Deployment of a Snowplow Driver-Assist System

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16. Abstract (Limit: 250 words)

Snowplow operators are often tasked with clearing snow from roadways under challenging conditions. One such situation is low visibility due to falling or blowing snow that makes it difficult to navigate, stay centered in the lane, and identify upcoming hazards. To support snowplow operators working in these conditions, University of Minnesota researchers developed a snowplow driver-assist system that provides the operator with visual and auditory information that is suitable for low-visibility situations. A lane-guidance system uses high-accuracy Global Navigation Satellite System (GNSS) and maps of the roadway to provide information to drivers about their lateral positions. A forward-obstacle-detection system uses forward-facing radar to detect potential hazards in the roadway. The design of the system, and in particular its interface, is guided by extensive user testing to ensure the system is easy to understand, easy to use, and well liked among its users.

The system was deployed in two phases over the 2020-2021 and 2021-2022 winter seasons. In total, nine systems were deployed on snowplows across Minnesota, four in the first winter season and an additional five in the second. Participating truck stations represented all eight MnDOT districts as well as Dakota County. Over the course of the deployment, additional user feedback was collected to identify system strengths and areas for improvement. The system was found to be a cost-effective addition to snowplows that increase driver safety, reduce plow downtime, and increase driver efficacy for plowing operations, thus providing support to operators working in demanding, low-visibility conditions.

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FINAL REPORT

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EXECUTIVE SUMMARY

Snowplow operators are often tasked with clearing snow from roadways under challenging conditions. One such situation is low visibility due to falling or blowing snow. This makes it difficult to navigate, stay centered in the lane, and identify upcoming hazards. Additionally, operators must drive in these conditions while also managing other monitoring and operational tasks related to plowing snow and spreading deicing agents. Operating in this environment is critical in clearing roadways and supporting emergency vehicles but is challenging and stressful for operators.

To support snowplow operators in these conditions, University of Minnesota researchers developed a snowplow driver-assist system that provides the driver with lane guidance and forward-obstacle-detection feedback that is suitable for low-visibility situations. The lane-guidance system uses a Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver and high-accuracy maps of the roadway to provide information to the drivers about their lateral positions. The forward-obstacle-detection system uses forward-facing radar to detect potential forward obstacles and alerts the drivers to their presence. Information about the plow's position within its lane and the presence of forward obstacles is provided to the driver through a display that uses a series of shapes that illuminate accordingly. This snowplow driver-assist system supports plow operators by allowing them to perform their jobs more safely and effectively in poor visibility.

This work was carried out in two phases with the system deployed over two winter seasons. In the first phase, work was done to integrate and evaluate the lane-guidance and forward-obstacle-detection systems and to conduct iterative user-centered design and testing on an LED-based display to ensure an appropriate design that supports operators' recognition of the lane guidance and hazard warning icons and auditory cues in a wide range of environmental conditions. The resulting system was deployed on four trucks over the 2020-2021 winter season. The research team developed, tested, and assembled the systems that were installed on each truck and created the high-accuracy digital maps required to enable the lane-guidance system. Operator feedback about the system's performance was collected throughout the winter season through usability testing. System enhancements or modifications were developed based on operator input.

As a part of the first phase, the research team evaluated the placement of the display within the snowplow cab and investigated luminance and color perception of the display under different ambient lighting conditions. This study simulated ambient lighting levels for day and night driving and tested the sensitivity and perception of brightness for different colors across varying intensities. Additionally, user testing in the 2020-2021 winter season deployment showed that the LEDs in the display may not always fully illuminate the shapes for low-display luminance settings. Specifically, in cases where the system was being operated with very little ambient light, it could be difficult for drivers to determine if certain symmetric shapes indicated a left or right deviation from the centerline. Even with these limitations, the system had very high user acceptance among operators.

In the second phase, additional system improvements were implemented based on feedback from the first winter season. These improvements included identifying a lower-cost GNSS receiver, integrating it

into the system, redesigning the system display to increase flexibility and clarity and to further improve the performance of the forward-obstacle-detection system. The phase two system was deployed on five new snowplows and select system updates were applied to the initial four deployed snowplows. All nine plows were deployed in the 2021-2022 winter season and driver feedback was again collected through usability testing. Overall, operators reported high satisfaction with the system to support plowing during low-visibility conditions. This support not only included lower mental workload and stress, but also a noticeable difference by operators in the lower frequency that the system-equipped plows were involved in run-off-the-road events or stalled vehicle strikes compared to other plows.

The new LCD design developed in the second phase provided more flexibility than the LED-based display in handling low ambient light conditions so that even in total darkness one could tell where one was located laterally with respect to the lane center. Using simple triangular shapes, the lane boundary guidance system on the relatively small LCD display provided sufficient information to allow the operators to determine their lateral lane positions up to four feet to the right or left with respect to the lane center, in one-foot increments. The design was such that the light intensity could be adjusted in software. The display provided information as to whether the vehicle was on a mapped route and whether the GNSS-sensed vehicle position reception was reliable. Three rectangular indicators on the same display above the lane-guidance system, alert the driver to a hazard to the left, straight ahead or to the right of the front plow.

The new LCD display can present any visual information needed in the future without hardware changes as the previous display would have required. This flexibility will ensure that the system can be modified for future use cases such as four-lane road segments, which may require a different presentation of lane-guidance information.

Feedback from the 2020-2021 winter season deployment showed that in some situations, the obstacle detection system was too sensitive and generated false positives. As such, improvements were made to the system, which included modifying the mounting configurations of the radar units, tuning the existing detection algorithms, and introducing filtering algorithms into the forward-obstacle-detection software. Because false positives in the right lane were still an issue in several locations, a radar visualization tool was developed during the second phase to identify the issues and help develop improved filters. The early results using the radar data visualization software seemed to indicate that it may be a useful tool for qualitatively analyzing the radar's performance. It provided metrics and visuals that can inform future filter development.

Multiple radar filter candidates are in development and this tool will aid in designing and perfecting these filters. Amplitude threshold filtering has been tested and early results show that it is effective at removing unwanted hits, particularly false positives in the right-hand channel. Additional development of the software should allow quicker testing and tweaking of filter candidates through redrawing the visualized data from a prerecorded dataset. This visualization tool will be used to investigate occurrences of false positive warnings, collect data, and identify any patterns that will be used to design an improved filter.

Feedback was collected from operators on all nine plows. Operator feedback was collected through usability testing to determine the efficacy and guide revisions to the new system display. A/B testing with and without the system was conducted to collect objective measures of system success. Lastly, an overall system assessment was conducted by soliciting feedback from drivers at the end of the season to determine system likes, dislikes, and potential future improvements.

The driver-assist system now integrates the lower cost RTK GNSS receiver, high-accuracy digital maps, forward-facing radar, and the display described above with supporting hardware including communications, networking, and power devices. The software that controls the system runs on a Raspberry Pi, a low-cost micro-computer. All system components except for the radar, antennas, and the display are mounted on an aluminum plate, so the system can easily be installed behind the driver's seat or elsewhere in the cab.

The snowplow driver-assist system is a cost-effective addition to snowplows that increase driver safety, reduce plow downtime, and increase driver efficacy for plowing operations, thus providing support to operators working in demanding, low-visibility conditions. The system is well-liked and quantitative measures of operator performance show that it provides valuable and measurable assistance to operators. Future work will seek to further improve the obstacle detection system and develop a system for using truck station staff to map additional snowplow routes at high accuracy.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Snowplow operators are often tasked with clearing snow from roadways under challenging conditions. One such situation is low visibility due to falling or blowing snow. This makes it difficult to navigate, stay centered in the lane, and identify upcoming hazards. Additionally, operators must drive in these conditions while also managing other monitoring and operational tasks related to plowing snow and spreading deicing agents. Operating in this environment is critical in clearing roadways and supporting emergency vehicles, but it is challenging and stressful for operators.

To support snowplow operators in these conditions, a driver-assist system (DAS) was developed to provide real-time feedback to drivers about their surroundings. The system incorporates a real-time kinematic (RTK) Global Navigation Satellite System (GNSS) and high-accuracy maps of the roadway to provide information about the truck's position within the lane. In addition, a forward-facing radar detects and warns the operator about obstacles ahead of the truck. This information is communicated to the driver through an LCD screen mounted on the dashboard and audio alerts.

This project follows and builds on previous work by the research team that implemented the first version of this system (Liao et al., 2018). Originally the system was designed to provide assistance with not only lane keeping but also echelon plowing (also called gang plowing) and backing up. Based on feedback from operators and other project stakeholders, it was determined that the system would be most helpful if it focused on the lane keeping assist functionality.

The initial implementation of the system used RTK GNSS and high-accuracy maps and provided feedback to the driver through a LED light bar. The system was tested on a single snowplow in the Minnesota Department of Transportation's (MnDOT) Metro District on a stretch of MN 25 between Belle Plaine and Green Isle, Minnesota. User feedback collected through interviews and ride-alongs indicated that the operators liked the system and found it to be useful in low-visibility conditions. That project also resulted in recommendations for future improvements focused primarily on improving the display. These recommendations led to the project objectives described below.

1.2 PROJECT OBJECTIVES

The goal of this project was to expand on the system designed in the previous project by adding forward-obstacle-detection functionality to the system, improving the display, deploying the system at multiple sites across the state, and continuing to engage with snowplow operators, technicians, supervisors, and other project stakeholders to evaluate the system and determine benefits and opportunities for improvement.

Forward obstacle detection was developed and added to the system to provide information to the driver about potential hazards ahead of the snowplow. The primary goal was to alert the operator to the presence of a slow or stopped vehicle ahead of the plow that otherwise wouldn't be visible in low-

visibility conditions. A visual or auditory alert would notify operators of the hazard and allow them to brake or steer to avoid striking another vehicle with their plow blade or plow wing. Due to the nature of operating in heavy snow conditions, it was determined that the alerts would be informed by a forward-facing radar.

The operator display underwent a number of significant design changes. Through user testing, operators said that they wanted a simple display that was capable of providing various warnings and informational notices. Consideration was given to ensuring that the display was clearly visible in both dark (e.g., nighttime) and bright (e.g., daytime snow) conditions.

A multi-year, multi-site deployment was conducted. The system was first deployed on two additional MnDOT snowplows and one Dakota County plow for the 2020–2021 winter season. For the 2021–2022 winter season, the system was further deployed on an additional five MnDOT snowplows such that each of the eight MnDOT districts were represented along with Dakota County.

Lastly, user feedback was collected throughout the project to both guide the development of these new features and to evaluate the acceptance and efficacy of the system. Snowplow operators and other project stakeholders guided the design by participating in interviews and focus groups aimed at evaluating mockup and prototype interfaces. Field operational testing was conducted to gather information about user acceptance, identify system strengths as well as system limitations based on real-world usage. Objective measures were collected to quantify driver performance with and without the system.

1.3 REPORT ORGANIZATION

This report documents work performed as part of this project. CHAPTER 1: provides an overview of the project's motivation, background, prior work, and the objectives of this work. Chapter 2 describes the functionality of the system and its components as they exist at the end of the project. Chapter 3 describes the development of the forward-obstacle-detection warning interface. Chapter 4 describes the system deployment over the 2020–2021 winter season. Chapter 5 documents the operational usability testing that was performed over the 2020–2021 winter season. Chapter 6 discusses the system improvements that were implemented in preparation for the 2021–2022 winter season deployment. Chapter 7 describes the system deployment over the 2021–2022 winter season. Chapter 8 discusses the deployment testing that was performed over the 2021–2022 winter season. Chapter 9 is a discussion of the project's major findings, benefits, and recommended future work.

CHAPTER 2: SYSTEM OVERVIEW

The snowplow driver-assist system provides feedback to the operator about their position within the lane and potential hazards ahead of the plow. This information is communicated to the operator through visual and audio interfaces that alert them if the vehicle is leaving the lane or approaching an obstacle at an unsafe speed.

The lane-guidance system incorporates high-accuracy digital maps and an RTK GNSS receiver to determine the vehicle's position within the lane. The receiver uses a cellular modem to receive GNSS corrections data from a continually operating reference station (CORS) network. The forward-obstacle-detection system uses a forward-facing radar mounted on the top of the snowplow to identify potential hazards in the snowplow's path. This information is provided to the operator through an LCD screen mounted on the dashboard and a speaker mounted behind or next to the operator. Figure 2.1 illustrates the major system components.
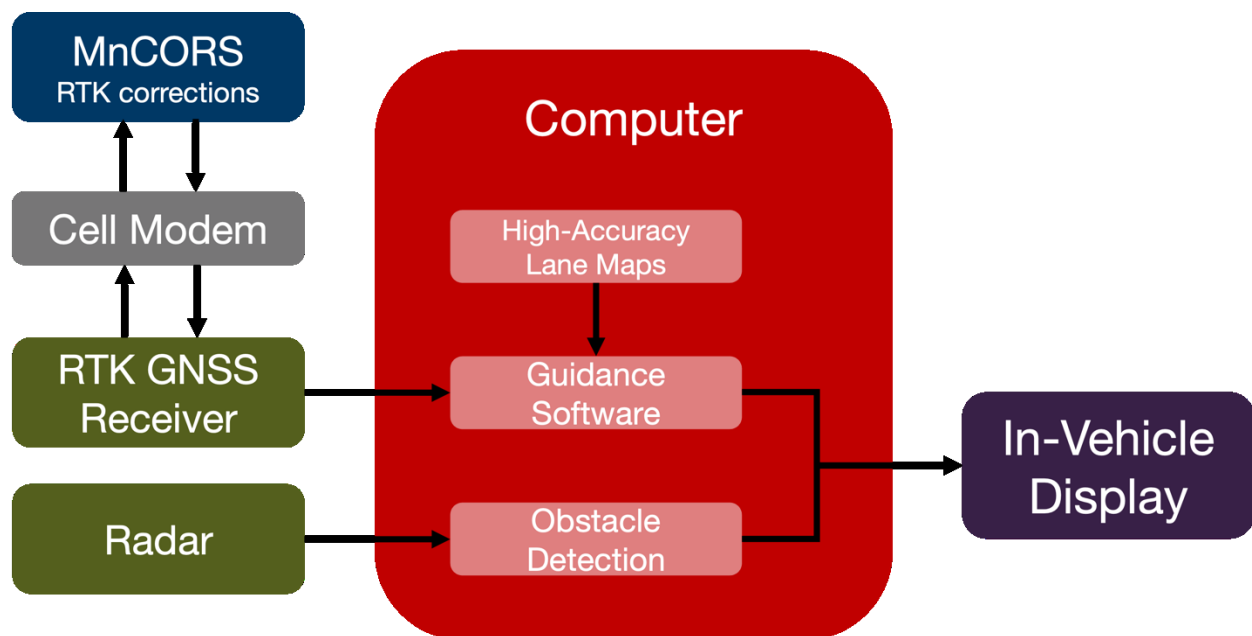
Figure 2.1 Snowplow DAS Overview Diagram

2.1 LANE GUIDANCE

The lane-guidance system provides information to the operator about the snowplow's position within the lane so that the operator can stay centered in the lane and avoid run-off-road crashes. This is accomplished with a high-accuracy map that is collected ahead of time and an RTK GNSS receiver. The receiver provides a highly accurate measure of the plow's absolute position in world coordinates (i.e., latitude and longitude). The map provides local context for the latitude, longitude coordinates so that a deviation from the lane centerline can be calculated.

The RTK GNSS receiver is the key hardware component in the lane-guidance system. Current deployments use a Swift Navigation Duro Inertial GNSS receiver (Swift Navigation, 2023). This receiver communicates with the Minnesota Continually Operating Reference Station (MnCORS) Network (MnDOT, 2023) through a cellular modem providing internet connectivity. This allows the receiver to determine the snowplow's position with an approximate accuracy of 1-3 cm. The receiver also provides measures of the vehicle's speed, the quality of the position fix, and the vehicle's heading as determined by its movement history. Position fixes are provided by the receiver at a 10 Hz update frequency. The receiver is mounted inside the snowplow's cab behind or next to the driver and its antenna is mounted on the roof of the snowplow cab. Figure 2.2 shows the GNSS antenna as well as the radar mounted on top of the snowplow.

Figure 2.2 GNSS antenna and radar mounted on top of snowplow

High-accuracy digital maps are used to transform the raw latitude and longitude coordinates from the GNSS receiver into a useful, localized measurement of lateral deviation from the lane centerline (i.e., the midline between a lane's painted fog line and the road's painted centerline). The process by which the maps are created is detailed in the final project report by Liao et al. (2018). In short, the maps are generated from vehicle path data collected with an RTK GNSS receiver capable of receiving corrections data from MnCORS. A vehicle drives along the centerline of a lane multiple times and then these paths are averaged together to generate a route map. In a departure from the protocol described in that report, maps collected under this project contain only the lane centerlines but no additional information about protected turn lanes or bypass lanes.

The software for the lane-guidance system first projects the latitude, longitude pairs into the UTM 15N coordinate reference system. This is a projected, cartesian coordinate system that is valid over the

entire state of Minnesota. This allows for more convenient geometry calculations including distance and bearing.

Next, the position and heading information is used to identify whether the vehicle is on a known and mapped route. A snowplow is considered to be on a route if it is within 5 m of a route and is within 60 degrees of facing in the correct direction to travel along the route.

The vehicle position and heading are also used to calculate a predicted position for the snowplow based on a 0.5 second look-ahead distance. This is to say that the predicted position is an estimate of where the vehicle will be in 0.5 seconds if it continues traveling at the same speed and in the same direction. The predicted position is used to determine an offset from the lane centerline based on the vehicle's current route. The offset is a measure of the lateral deviation from the lane centerline.

2.2 FORWARD OBSTACLE DETECTION

The forward-obstacle-detection system provides the operator with information and warnings based on the presence and relative position of potential hazards ahead of the snowplow. The system uses a forward-facing radar that is mounted on the top of the snowplow's cab.

The radar used in the forward-obstacle-detection system is the Aptiv ESR 2.5 (AutonomouStuff, 2023). It incorporates two scanners with a 50 ms update rate. The long-range scan has a range of 175 m and a horizontal field of view of ± 11 degrees. The medium-range scan has a range of 60 m and a horizontal field of view of ± 45 degrees. The radar provides a list of detected targets each with a position and speed relative to the vehicle.

Targets are filtered using a number of criteria. Targets are excluded if they are closer than 10 m or further than 174 m from the radar. They are also excluded if they are beyond 30 degrees in either direction from center. The radar also provides a measure of the strength of the returned signal reflected off the object. The software filters targets with return signals weaker than -20 dB. Potential obstacles are reported as being in the left, center, or right channels. These correspond to 12 ft lateral distances such that the center channel extends 6 ft laterally to the right and left of the vehicle. Right and left channels correspond to an object between 6 ft and 18 ft to the right or left of the vehicle, respectively. Targets beyond 18 feet from center are excluded.

2.3 OPERATOR DISPLAY

The operator display is the primary interface through which the system provides feedback to the driver about their lane position, the presence and location of forward obstacles, and the operational state of the system.

The visual display is a Waveshare 11.9 in LCD screen (Waveshare, n.d.). It has a wide screen format with approximate dimensions of 2.7 in by 10.5 in and a resolution of 320 pixels by 1480 pixels. The display is mounted on the dashboard or above the windshield (near the operator's sun visor). Figure 2.3 shows

the display mounted on the dashboard and Figure 2.4 shows an illustration of the display with all shapes lit up.

Figure 2.3 Driver display mounted on dashboard
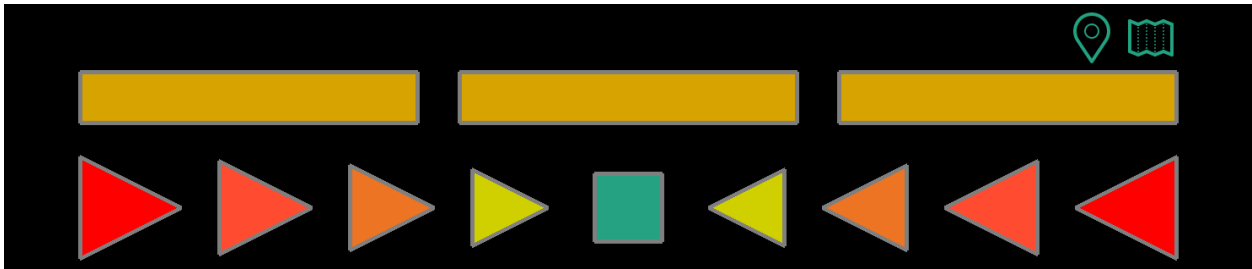
Figure 2.4 In-Vehicle Driver Display

A map status icon, located in the upper right corner of the display, indicates the availability of a high-accuracy digital map. When the icon is colored green, the system has a map for the vehicle's current location. When the icon is colored red, the system does not have a map for the vehicle's current location. This may be due to the vehicle not being on a mapped route or the system is unable to resolve its position with enough accuracy to determine whether it is on a mapped route.

A GPS status icon is in the upper right corner of the display. When the icon is colored green, the system has a high-quality (RTK fixed integer solution) GNSS position fix. When the indicator is colored red, the GNSS has a lower quality or no position fix.

The visual indicators for the hazard warning system are located above the lane boundary guidance system (on the same display) to improve the safety of plow operators under poor visibility conditions. Three rectangular indicators alert the driver to a hazard that is either to the left, in front of, or to the right of the front plow. When a hazard is detected approximately 5 to 3 seconds away from the plow, one of the directional bars will turn amber. The hazard warning bars will turn red and an audible alert will sound when the object is 3 to 2 seconds away from the plow. When the hazard is within 2 seconds or less to the plow, the hazard warning will flash red and an audible alert will increase in intensity. Further experiments are still needed to determine whether an audible alert should or should not sound for any hazards detected to the left of the plow (on a 2 way - 2 lane road). Additionally, the hazard warning system will still operate even when there is no GNSS satellite information available.

Figure 2.5 through Figure 2.9 illustrate how the display would indicate the snowplow's lateral position within the lane as it moves from centered to 4 ft to the left of center. Lateral deviations to the right of the lane centerline would have similar, although mirrored, indications. All these figures show the hazard warning bar turned on as if a hazard is detected to the left of the plow.
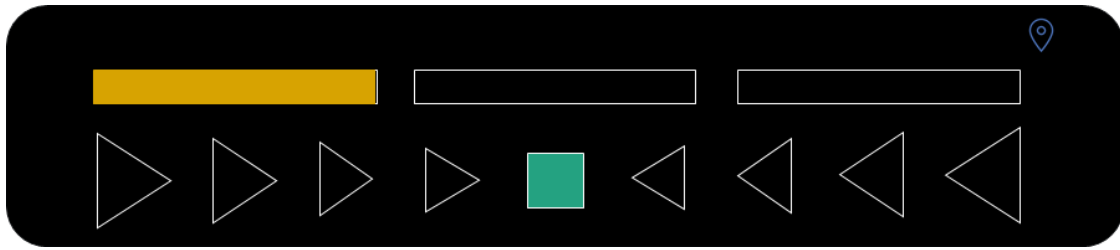
Figure 2.5 Display when snowplow is centered within lane
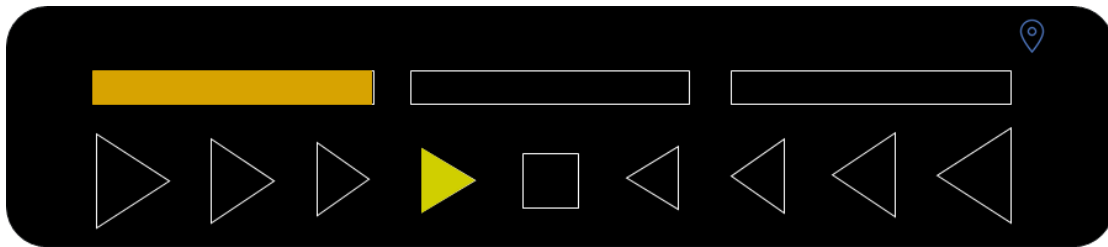
Figure 2.6 Display when snowplow is 1 ft to the left of lane centerline
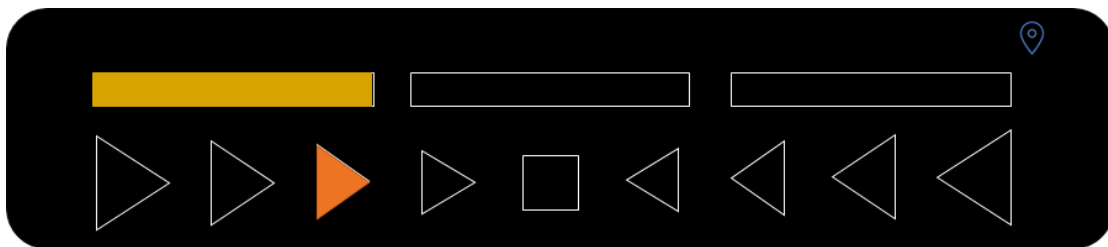
Figure 2.7 Display when snowplow is 2 ft to the left of lane centerline
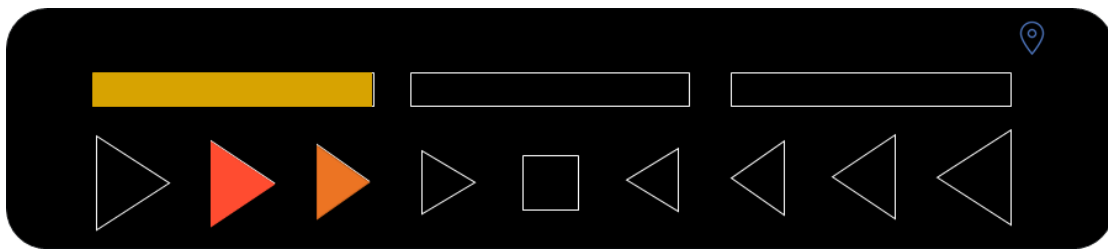
Figure 2.8 Display when snowplow is 3 ft to the left of lane centerline
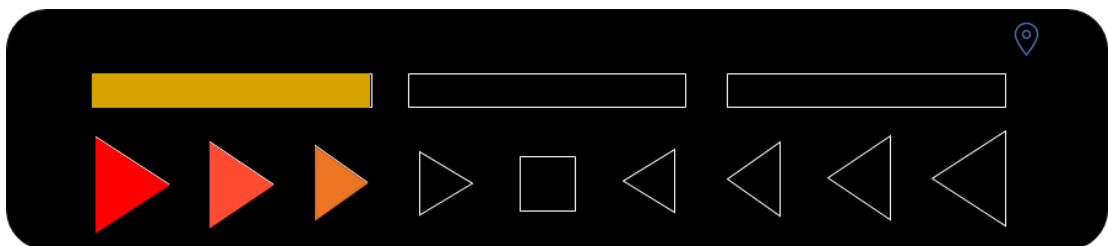
Figure 2.9 Display when snowplow is 4 ft to the left of lane centerline

2.4 OTHER SYSTEM COMPONENTS

The driver-assist system components are all mounted on a board that is installed either behind or next to the operator's seat. The exceptions are the operator display, which is mounted on the dashboard or above the windshield, and the radar, GNSS antenna, and modem antenna which are mounted on the roof of the cab.

The interior system components include the GNSS receiver, a cellular modem, a networking switch, and various power supply and distribution components. Additionally, the system's Raspberry Pi 4 computer is mounted here. Figure 2.10 shows the components mounted inside the cab.
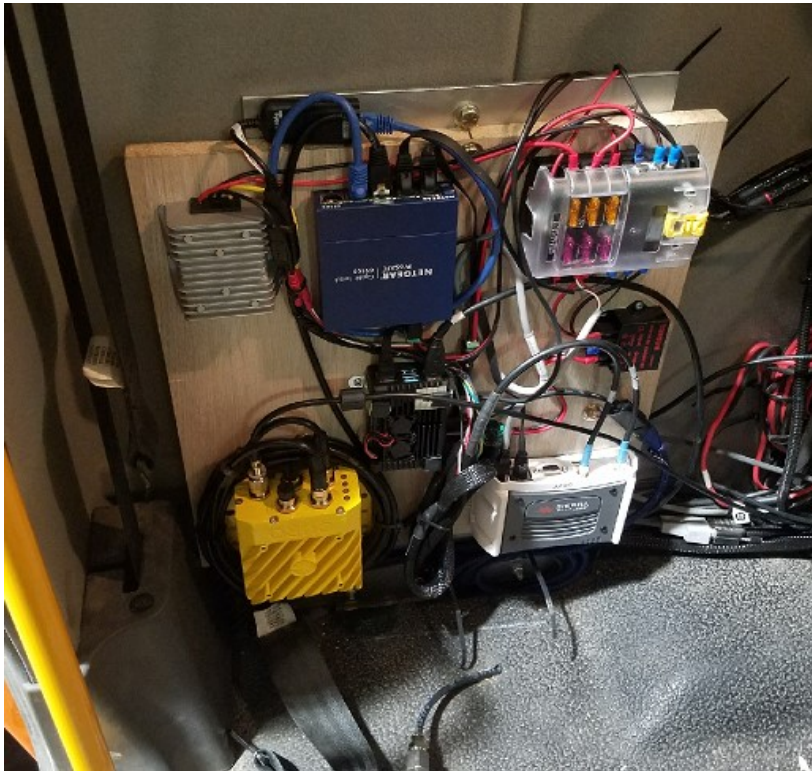
Figure 2.10 Interior System Components

CHAPTER 3: FORWARD OBSTACLE WARNING INTERFACE

One goal of this project was to extend the existing snowplow driver-assist system by adding a radar-based forward-obstacle-detection system to provide alerts to the operator about hazards in the roadway ahead of the snowplow. The goal of this system was to support operators working in low visibility weather and lighting conditions to reduce the risk of colliding with stopped or slow-moving vehicles.

To alert drivers in a clear and understandable way, the interface was developed through a series of user-centered design options that would best support operators and have high user acceptance. Initial iterative design and formative testing was done through a series of brief remote interviews with operators. Candidate designs were further evaluated through two rounds of remote user testing. This work led to a novel design of a user-centric forward-obstacle-detection warning interface based on user feedback and suggestions.

3.1 INITIAL DESIGN DEVELOPMENT

Seven interface designs were prototyped in Microsoft PowerPoint to enable initial user feedback interviews. The goal of this formative testing was to assess the feasibility, function, and acceptance of the designs. Prototype designs were constructed using PowerPoint animation features to simulate the states of the display corresponding to different warning severities. Several changes were made to the overall design throughout this process and novel designs were mocked up in real-time based on user feedback and suggestions. Table 3.1 presents a single representative image and brief description of each of the seven initial interface designs. Additionally, the last row shows an extra design that was developed during the first testing process. For additional information about the designs, refer to Appendix A.

Table 3.1 Forward Obstacle Warning Interface Designs

Description	Representative Image
Triangle Indicator (Solid or Flashing) Outside Lane Guidance	
Exclamation Indicator (Solid or Flashing) Outside Lane Guidance	
HAZARD Indicator Above Lane Guidance	
Alternating Flash Indicator	
Vehicle Indicator Outside Lane Guidance	
Vehicle Indicator (with Looming Bars) Outside Lane Guidance	
Snowplow Indicator Above Lane Guidance	
Location Bar Indicator Above Lane Guidance	

These designs were evaluated through Zoom video interviews with six participants representing the Morris (District 4), Sleepy Eye (District 7), Shakopee (Metro District), and Hastings (Dakota County) truck stations. Most participants (83%) reported no prior experience with the lane boundary guidance system. Participants in this study varied in years of experience working as snowplow operators, with three reporting fewer than five years of experience, two with six to 10 years of experience, and one with over 10 years of experience.

Participants were provided with a brief background on the snowplow driver-assist system which included a video demonstration of the lane-guidance system. They were then asked to rank the designs and provide additional feedback about features of the designs they liked, disliked, or found confusing. Participants were also asked to provide any suggestions for improvement and to indicate the likelihood that they would use the system.

Several designs consistently received support from participants. Overall, participants preferred a hazard warning design that would 1) flash when a hazard was detected, 2) identify the location of the hazard in relation to the snowplow (especially in low visibility conditions), 3) have a symbol that would clearly indicate a warning, and 4) was simple and easy to interpret.

Designs were scored based on participant rankings where a design ranked 1st place would receive 3 points, 2 points for 2nd place, 1 point for 3rd place, 0.5 points for 4th place, and 0.25 points for 5th place. Note that not all participants elected to rank the 4th and 5th place ranking. Scores were then added together across all participants. Participants consistently reported a preference for three designs: Location Bar Indicator (8.5 points), Triangle Indicator (7 points), and Vehicle Indicator (7 points).
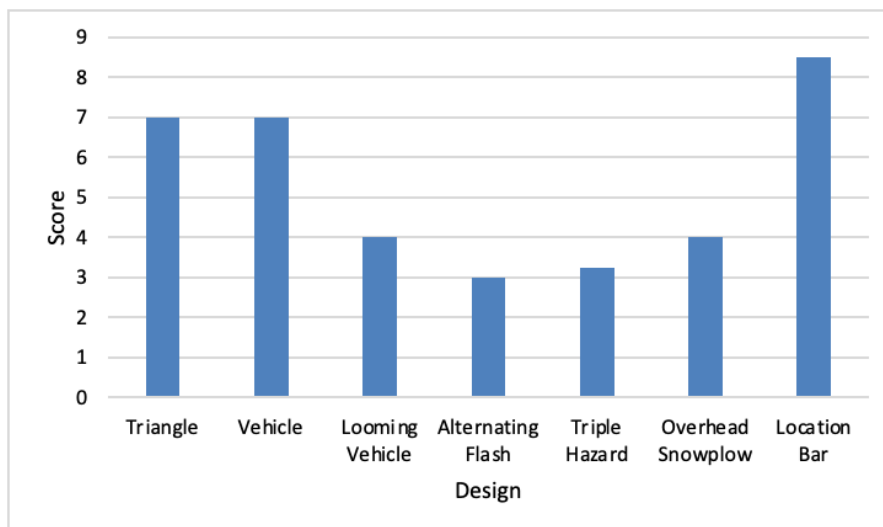
Figure 3.1 User Preference Scores for Initial User Interviews

Participants were also asked to provide feedback about the alert sounds that would accompany the visual warnings. They indicated that they would like to be alerted with a sound if a hazard was detected within their trajectory path, and that an audible alert would be most useful during low visibility (i.e., whiteout) conditions. Due to the number of sounds and alerts that currently exist within the cab of the

plow, it was important that the alert effectively capture participants' attention. Participants expressed a preference to have a sound with a looming effect that would beep faster as they approached the oncoming hazard and stressed the importance that the sound was not overly sensitive (i.e., triggered too frequently or unnecessarily). Additionally, participants indicated that they would like to only be alerted when a hazard was within the plow's trajectory (i.e., to the right, center, or left of the plow) and expressed they wanted the ability to control the volume of the audible alert.

3.2 DESIGN ITERATION AND FINAL USER TESTING

The three most preferred designs from the previous round of testing were further evaluated in a final round of testing. These designs included the flashing location bar indicator, the flashing triangle indicator, and the flashing vehicle indicator. Five participants from the initial round of testing (i.e., representing the Morris, Sleepy Eye, Shakopee, and Hastings truck stations) and two additional operators were recruited to participate in the final round of user testing.

Each of the designs were integrated into a first-person simulation video to demonstrate the feedback provided by the lane guidance and forward-obstacle-detection systems operating on a completely snow-covered road in low-visibility and whiteout conditions. The videos were created from a simulation model of US 169 between Jordan and Belle Plaine, Minnesota. In total, nine, 30-second videos were created for this test. Each video began showing the snowplow traveling at 20 mph and slightly deviating to the left and right of the centerline (i.e., displayed through movements on the lane boundary guidance system). In all videos, the visibility was restricted to 100 ft.

For each of the warning designs, three videos were created which presented a stalled vehicle directly in front of the plow, to the left of the plow, and to the right of the plow. During the simulation, the forward obstacle warning indicator flashed according to the stalled vehicle position (i.e., front, left, or right) and played a sound alert that increased in frequency as the plow approached the obstacle. Figure 3.2 through Figure 3.4 show sample screenshots of the videos demonstrating the different warning interface designs. Appendix B presents screenshots of each video design with warning indicators and the corresponding stalled vehicle position (i.e., front, left, or right).

Figure 3.2 Screenshot of right warning indicator

Figure 3.3 Screenshot of center warning indicator

Figure 3.4 Screenshot of left warning indicator

Participants were asked to rank the three designs in order of preference. Each design received a score based on the participants' preference rankings with 1st place receiving 3 points, 2 points for 2nd place, and 1 point for 3rd place. There was strong support for the Location Bar Indicator, receiving a score of 16, compared to the triangle and vehicle indicators, receiving scores of 14 and 11, respectively, see Figure 3.5.
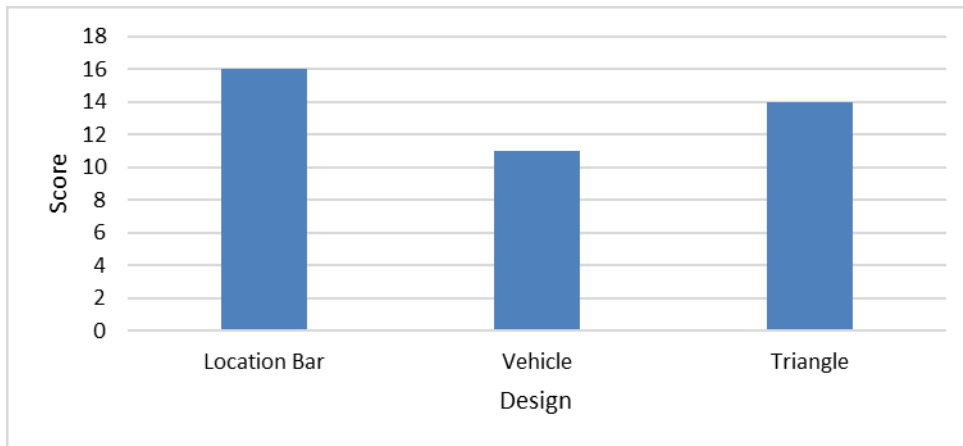
Figure 3.5 User Preference Scores for Final User Testing

Participants reported high user acceptance for the location bar design, stating that it was simple and easy to understand. There were minimal frustrations or concerns regarding this design. Participants felt this design would be useful in capturing their attention, as each bar was larger than either the vehicle or the triangle indicator, which was helpful and easy to use. Some users felt that the triangle or vehicle indicator could be confusing to users since it was in-line with the other icons of the lane-guidance system. The Location Bar Indicator offered greater appeal since its information was held on a separate line. Notably, not all users rated the Location Bar Indicator as their most preferred design and instead

15

preferred the Triangle Indicator. The feedback received regarding this preference tended to focus on the overall height of the system. The users preferred the Triangle Indicator (and the Vehicle Indicator as a second option) because they did not add to the overall height of the display. The additional inch(es) that the bar icons would add to the original design were seen as a limitation of the design.

Overall, participants reported that they were likely to use the hazard warning system during low visibility and whiteout conditions. There was also strong support for the system's ability to identify the location of the hazard relative to the plow (i.e., to the right or left).

3.3 USER TESTING FINDINGS

Generally, there were minimal frustrations or concerns reported while reviewing the concept for the hazard warning system presented during either round of testing. The ability to detect a hazard's location relative to the plow is expected to be useful for improving plow efficiency and allow operators to maintain a desired path on the roadway, especially under low visibility plowing conditions.

Overall, there was strong support and preference for the flashing Location Bar indicator design. The design of the hazard warning system can be integrated as a simple look-ahead notification to alert drivers using visual and audible feedback of hazards on the roadway while driving in low visibility conditions. Importantly, incorporating a hazard warning feedback system is critical to ensure the enhanced ability to operate a snowplow during whiteout conditions does not result in operators colliding with stalled vehicles that are otherwise impossible to detect on the roadway during adverse weather conditions.

CHAPTER 4: 2020 – 2021 SYSTEM DEPLOYMENT

The first system deployment under this project was warried out during the 2020 – 2021 winter season. This involved updating the system for previously deployed systems, identifying and mapping routes for the new districts, and installing the system on three new trucks for a total of four trucks. Additionally, training materials were created to provide a brief overview of the lane-guidance system and the newly implemented hazard warning system to provide operators with an explanation of system benefits and the features of the system and its controls.

4.1 DEPLOYMENT SITES

Four snowplow driver-assist systems were deployed over the 2020 – 2021 winter season. This included a snowplow that had previously been deployed under a prior project. The system on this truck was updated to ensure consistency with the other, newly installed systems. Three new systems were procured, constructed, and tested before installing them on snowplows at the Morris (District 4), Sleepy Eye (District 7), and Hastings (Dakota County) truck stations.

To support the three new deployments, routes were identified in each of the three new districts that would be digitized. Routes were considered that were primarily two-lane, undivided highways that were in areas where blowing snow conditions were known to occur. Routes were selected based on feedback from truck station supervisors, district leadership, and other project stakeholders. Once the routes were finalized, they were mapped based on the previously established protocol. Table 4.1 summarizes the routes selected for the 2020-2021 winter season. Note that the additional routes for the 2021 – 2022 winter season are shown in Table 7.1.

Table 4.1 2020-2021 Routes

District	Truck Station	Route	Route Start	Route End	Length
District 4	Morris	MN 28	MN 9 (Morris)	MN 7 (Beardsley)	39 mi
Metro District	Shakopee	MN 25	Mile Post 15 (Green Isle)	Mile Post 4 (Belle Plaine)	11 mi
District 7	Sleepy Eye	US 14	MN 4 (Sleepy Eye)	US 71 (Sanborn)	22 mi
Dakota County	Hastings	CR 42	MN 55	US 61	5.5 mi
		CR 54	CR 91	CR 68	6.8 mi
		CR 62	CR 89	MN 316	5.1 mi
		CR 91	CR 54	US 61	9.1 mi

The routes shown in Table 4.1 were mapped over the summer of 2020. System equipment was procured, assembled, and bench tested prior to installation in the snowplows in the late summer and early fall of 2020. After installation, the systems underwent a functional, on-road test to validate the maps and ensure the system was working properly.

4.2 TRAINING MATERIALS CREATION

A tutorial video and accompanying PDF document were created to provide operators with a brief overview of the snowplow driver-assist system, explain system benefits, and provide information on the display and controls. The video includes animations with voice over instructions and is 3 minutes and 15 seconds long. The eight-page PDF tutorial consists of screenshots from the video tutorial and the same information as the video tutorial.

The tutorial describes the benefits of the system (i.e., better decision making, increased safety) and provides information about how to interpret the system's display. The content described the system's lateral position information (i.e., the position indicators) and reviewed differences between each of the position indicators present on the display. Lastly, the tutorial includes information about how the system will respond to cases of temporary loss of GNSS signal or roads that are not digitally mapped.

The tutorial also includes content on the benefits and use of the hazard warning system. This consists of information on how hazards are detected on the roadway, interpreting the rectangular indicators (i.e., left, center, right), and understanding notifications about visual and audible alerts. The tutorial also describes the possibility of experiencing non-critical warnings, which alert the driver to look for an object that may not be a true hazard (e.g., roadside signage) and false alarms (i.e., a warning due to noise from the system's radar).

CHAPTER 5: 2020 – 2021 OPERATIONAL USABILITY TESTING

Field observations of the lane boundary guidance system and a newly implemented hazard warning system were completed to assess operator perceptions and user acceptance of the system while plowing in various weather and ambient lighting conditions. Users showed strong support for the lane boundary guidance system and requested both additional systems be made available for other trucks and that the mapping system be expanded across more routes. However, there was mixed feedback with using the hazard warning system, with some operators reporting the system was satisfactory, while others reported the system had frequent false alarms.

Additionally, the field observations completed with snowplow operators revealed a potential design limitation regarding the ability to correctly identify the appropriate position indicators in low illumination plowing conditions. As such, several design options varying in indicator size, shape, and color were developed and reviewed by operators to address this potential design limitation.

5.1 HUMAN FACTORS FIELD OBSERVATIONS

Human factors field observations evaluated lane boundary guidance and hazard warning system usability under a range of snowy weather conditions. A modified remote evaluation was developed, due to COVID-19 precautions, to focus the evaluation of the hazard warning system with snowplow operators from four truck stations using the system. A total of five participants were recruited. The hazard warning system was evaluated through the remote testing to assess user satisfaction and to validate the accuracy of the system in detecting various hazards on the roadway. Findings from remote usability testing found high user acceptance of the Lane Boundary Guidance System.

Users strongly communicated how much the system assisted them in their plowing duties and requested additional systems for other trucks and/or additional mapping to expand where their currently equipped truck could operate. However, conditions and exposure to the hazard warning system's user acceptance were unclear, with some locations reporting satisfactory performance of the system, while others reported frequent false alarms. Overall, operators did not have enough exposure to the hazard warning system under low visibility conditions to assess the usefulness of the system in their plowing duties.

5.1.1 Methods

Retrospective interviews using video reviewing were completed because they were determined to be the best and safest option given COVID-19 restrictions prohibiting in-person ride alongs. Researchers monitored weather conditions for the four truck stations (i.e., Sleepy Eye, Shakopee, Dakota County, and Morris). When snowy weather was forecasted in one of the four identified areas, researchers contacted plow operators by email and/or telephone to request video footage be recorded. Operators were provided with specific instructions to secure their devices inside the cab of the plow, prior to leaving the parking lot, to ensure that the video would capture both the roadway as well as the Lane

Boundary Guidance System. In the absence of any winter storms, the research team worked with operators to collect video of driving the study route under clear conditions to serve as a substitute.

Once video footage was collected, researchers met with operators over Zoom conference software to review the video footage and conducted a semi-structured interview. Operators were asked to walk through their experiences in the video and describe things they liked or disliked, points of frustration or confusion, and provide recommendations for improvement. The video footage reviewed during interviews with operators included video footage of various weather (e.g., blowing snow, windstorm, during snow fall) and lighting conditions (e.g., overcast day, nighttime). Figure 5.1 shows screenshots of reviewed video footage. The total time to complete the video review and interview was approximately 30 minutes.

Figure 5.1 Screenshots of recorded video footage reviewed during interviews

5.1.2 General System Feedback

Overall, operators indicated high user acceptance and buy-in for the system. Operators reported feeling safer plowing with the system, were more confident plowing with the system on, and felt the system effectively captured their attention. Several operators reported using the system as a validation tool to verify their position in the roadway, particularly while plowing on snow-covered roadways. One operator reported he continuously kept the lane-guidance system running and only turned it off when plowing on routes that were not mapped. When the system was working, it was perceived to be extremely beneficial and received strong support from operators. Several of the operators indicated that other operators in their truck stations were very interested in additional systems for other trucks and to have the digital mapping expanded to allow the use of the existing guidance systems on more roadways. Excerpts from the interviews highlighting the high user acceptance of the system are listed below.

Quotes from snowplow operator interviews:

> *"The system was a godsend."*
>
> *"We love it."*
>
> *"Without the system, it would be almost nearly impossible to do the job."*
>
> *"Once you get used to using the system, it is hard to go back."*
>
> *"I use it every time I'm out. It is always running."*

5.1.3 Lane-Guidance Feedback

While the general feedback of the lane-guidance system was positive, one issue was uncovered. One operator raised an issue with the appearance of the display at night. While driving at night, this operator preferred to turn off all in-cab lights and dim the LED display to its lowest possible setting at night. The resulting experience was that there was not enough ambient light present in the cab to view the full display, but rather, only the illuminated single shape indicator was visible.

This is problematic because the left side and right-side yellow circles (i.e., ±1 foot from centerline) would be indistinguishable when only blackness surrounds the display (see Figure 5.2). Further, the three inward-facing triangles would lose their specificity from one another until greater than four feet out of center had been reached. Other operators were contacted to determine if this was a problem experienced by others, but no other operators reported using the system under this extremely low ambient lighting condition.
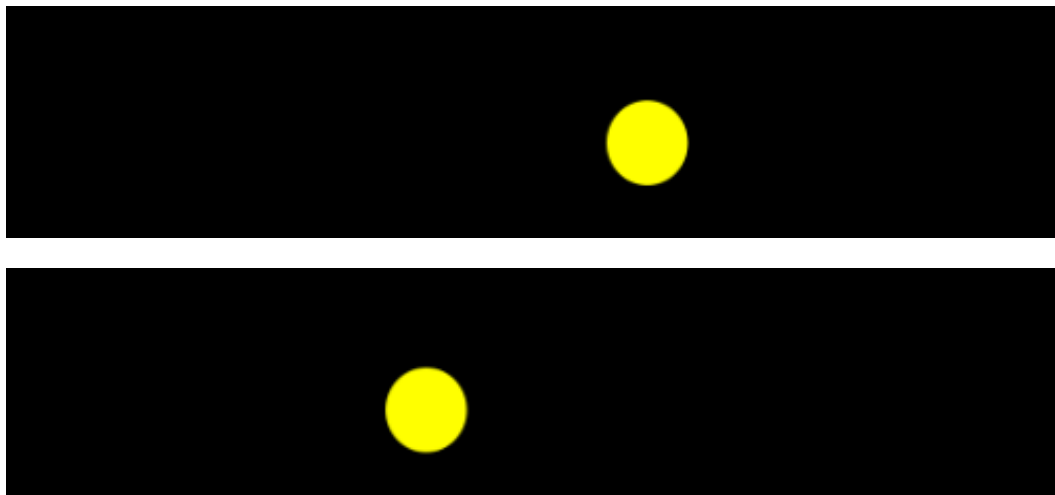
Figure 5.2 Example of lane-guidance indicator showing single yellow circle in total darkness

5.1.4 Forward Obstacle Detection Feedback

Overall, operators reported feeling less confident with the hazard warning system than the Lane Boundary Guidance System. Operators reported they felt less confident with the hazard warning system because they were less familiar with the system and because they had experienced detection errors with the system (i.e., false alarms). Additionally, operators reported that errors tended to occur more often on the right channel indicator of the hazard warning system and that the right channel identified non-hazard objects (e.g., signposts, mailboxes, poles) as hazards during plow routes. There were also observed errors related to the center channel detection sensitivity and potentially missed hazards on the roadway (e.g., failure to detect vehicles on the roadway). This suggests that the reliability of the center channel for detecting hazards may need further evaluation.

Several issues were also identified with the audible alert of the hazard warning system. Operators reported instances of the audible alert not working at all throughout some plow shifts, and often turned the volume down or all the way off as they felt the audible alert was less useful than the visual alert of the hazard warning system. Additionally, if the system was experiencing many false alarms or flashing frequency, operators indicated that they turned the volume down or off on the system. However, operators also reported that the audible alert sound was easily distinguishable amongst other sounds in the cab, effectively captured operator attention, and would be most useful during low visibility plowing conditions and at the latter part of a long shift.

Although operators reported some hesitation in the current hazard warning system, they indicated that their confidence and trust in the system would improve with more experience with the system and through increased reliability (i.e., reduced false alarm rate). Operators reported they were generally satisfied with the response time of the hazard warning and its ability to detect hazards on the roadway, and the system would be particularly useful during low visibility conditions as well as during longer plowing shifts (i.e., 8 to 12-hour shifts).

5.2 LANE GUIDANCE INTERFACE MODIFICATIONS

The potential design limitation revealed in the field observations lead to the development of three design solutions with position indicators that varied in size, shape, and color to better identify the position indicator in low illumination conditions. Specifically, the designs were developed to address the design limitations relating to its use at night at full dim with no interior cab lights turned on. The design modification options included changes in color gradation, size of the position indicators, and changing the 1-foot indicator from a yellow circle to a yellow triangle to better indicate the plow's position relative to the centerline when plowing during low illumination conditions (i.e., at night). The three design solutions were mocked up and evaluated by snowplow operators.

5.2.1 Methods

Participants were selected from the same truck stations from the usability testing to participate in the online study evaluating design modification options. Six participants completed the study representing all four participating truck stations.

Each of the three design modification options were mocked up to show the full sequence (i.e., each lane position indicator) with the modifications using Microsoft PowerPoint to address the design limitations of the original design. The full sequence of Option 1, Option 2, and Option 3 described below are presented in Appendix D. The pattern of illumination was changed so that further deviation beyond 2 ft. from center would maintain the previously illuminated red triangles so that more information is visible as the truck goes further out of lane (e.g., all three triangles illuminated at 4ft from center). The first design option (Option 1) included additional color gradation of the 2 ft., 3 ft., and 4 ft. (i.e., triangle) position indicators, a 10% reduction in size from the outermost (i.e., 4 ft.) position indicators towards the centerline indicator (i.e., green square), and changing the shape of the 1-foot indicator (i.e., yellow circle) to a yellow triangle to better clarify the position of the plow relative to the roadway in low illumination conduction. The second design option (Option 2) included only the size and shape changes made in the first design modification, and the third design option (Option 3) included only the shape change.

Three videos were created for pairwise comparisons of the design modifications. The videos began by presenting the full design modifications (i.e., with all position indicators illuminated) and then demonstrated the entire sequence of the lane-guidance system (i.e., each position indicator). After the sequence was displayed, a final slide presented the two full design modifications. See Appendix D for the full sequence of design options.

A brief survey was developed to evaluate each of the three candidate designs. Participants were presented with the three pairwise comparison video presentations in random order. After reviewing each of the pairwise comparisons, participants were asked to rate which of the two presented designs they preferred the most. Next, participants were asked to indicate whether they detected size differences, color differences, size and color differences, or were unsure if there were any differences presented in the two design options. Lastly, participants were asked to rank all three design options from their most preferred design to their least preferred design. They were also asked to provide any additional comments they had about each of the options and to share any additional information they thought was important about the system or that needed design changes.

5.2.2 Results

Preferences and participant accuracy for detecting differences were examined for each of the three pairwise comparisons. When comparing Option 1 and Option 2, 60% of participants preferred Option 1 and 80% accurately detected color and size differences. When comparing Option 2 and Option 3, 60% of participants preferred Option 3, with 40% accurately detected size differences. Lastly, when comparing

Option 1 and Option 3, participants reported an equal preference for Option 1 (50%) and Option 3 (50%), with 83% accurately detected color and size differences.

Participants were asked to rank their preferred design modification. Each design received a score based on participant preference, which allowed for summation of votes for 1st place (3 pts), 2nd place (2pts), and 3rd place (1 pt). Participants reported strong support for Option 1, receiving a score of 11, compared to Option 2 and Option 3, receiving scores of 7 and 6, respectively, see Figure 5.3. Participants showed strong support for a design that included both changes in color and size. Additionally, participants indicated that they would prefer an even stronger contrast between the colors, thought the smaller size of the position indicators would be particularly helpful at night or in low illumination conditions, and suggested that it would be useful to increase the spacing between the each of the position indicators.
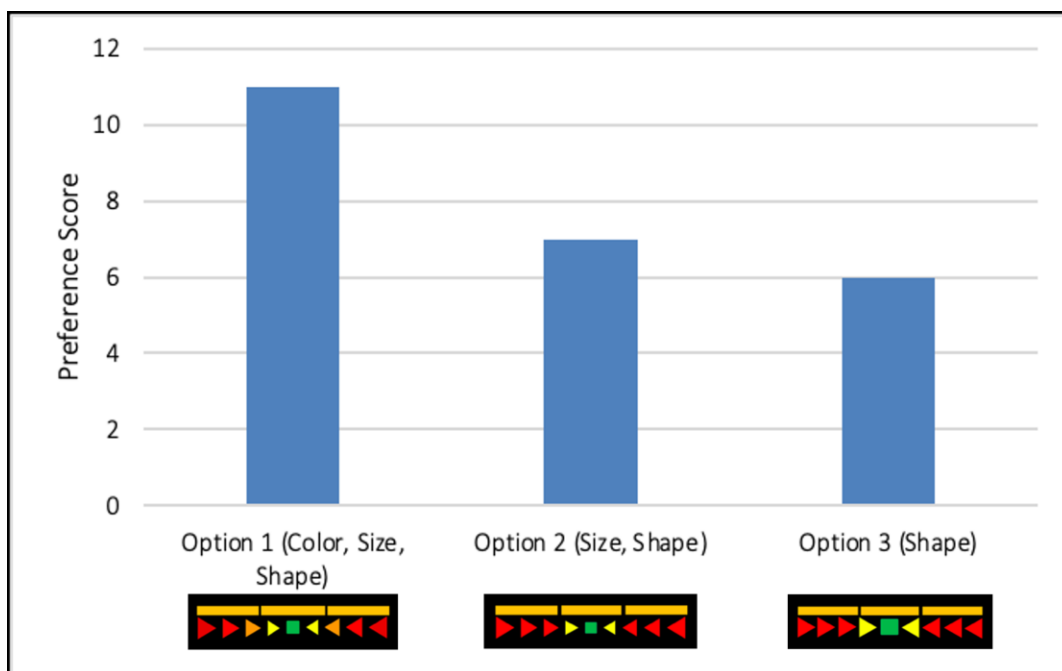
Figure 5.3 Option Preferences for Lane-Guidance Modification

5.3 FINDINGS

The purpose of the field observations was to evaluate the system under real-world conditions. Overall, operators showed strong support for the system, indicating they felt the system was useful, felt safer plowing when using the system, and thought the system was fairly accurate throughout the winter season. Operators also reported they felt the system was easy to learn and indicated that other operators were interested in using the system.

A key finding from the field observations was a potential design limitation of the existing lane-guidance system where in low illumination conditions (i.e., a dark cab at night) it was difficult to determine the position of the truck relative to the lane centerline. Specifically, confusion was reported about the

plow's position when the one-foot indicator (i.e., yellow circle) was dimly illuminated while plowing at night. A design modification incorporating size, shape, and color gradation changes was developed to address this design limitation.

CHAPTER 6: 2021 – 2022 SYSTEM REDESIGN

User feedback collected over the 2020 – 2021 winter season showed that the snowplow driver-assist system's reception among operators was extremely positive. Based on in-depth user testing and by working with project stakeholders, a number of system enhancements were identified to be implemented for the 2021 – 2022 winter season deployment. These included improving the system software, redesigning the operator display, and performing diagnostic work to increase forward-obstacle-detection accuracy.

6.1 SOFTWARE IMPROVEMENTS

To support improvements in system hardware and project data needs, a number of software enhancements were identified and implemented to support the 2021 – 2022 winter season deployment. These included updating the system software to work with a new computer and GNSS hardware, update software dependencies to the latest suitable versions, and expand system functionality to allow for remote data collection.

The snowplow driver-assist system software is organized into a number of modular components written in Python which each implementing a single, small piece of the system's functionality. These components read input either directly from hardware devices (e.g., GNSS, radar, etc.) or from other components, process this input, and then pass their output to the next components that need it. This inter-process communication (IPC) is performed by a Redis (Redis Ltd., 2023) instance that runs on the Raspberry Pi computer. Figure 6.1 shows an illustration of the system components and the information shared between them.
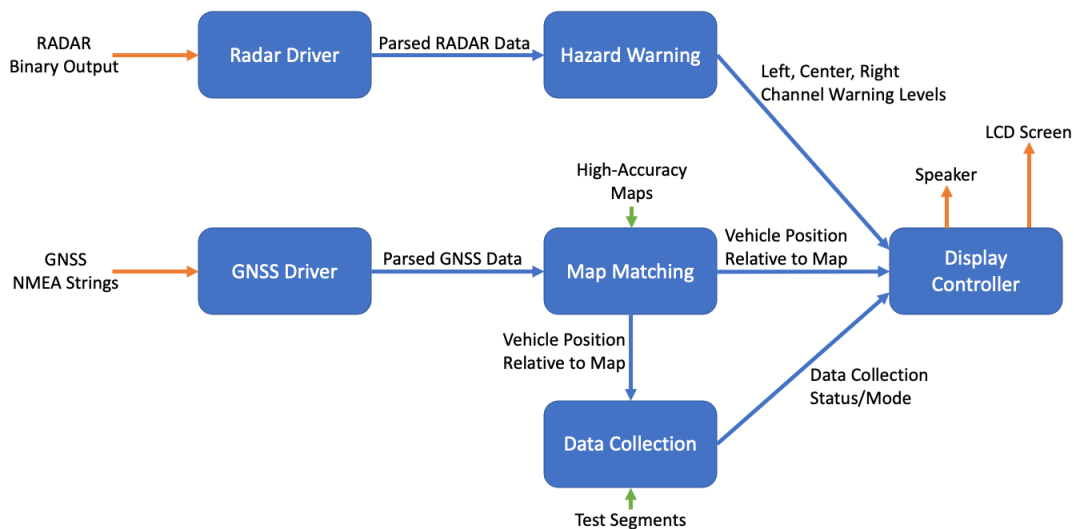
Figure 6.1 Snowplow Driver-Assist System Software Diagram

6.1.1 Swift Duro Inertial Receiver

The four snowplow driver-assist systems deployed in the winter 2020-2021 used Trimble BX982 or BX992 RTK GNSS receivers. In parallel with mapping efforts to support these deployments, data was collected to determine the accuracy and reliability of a Swift Duro Inertial GNSS receiver. Based on the results of this testing, this receiver was determined to be suitable and the additional 5 plows deployed in the winter 2021-2022 were specified to use this receiver instead of the more expensive Trimble units.

To support this change, the GNSS driver software was modified to enable the use of this new receiver. The Trimble receivers and the Swift Duro Inertial are capable of outputting NMEA 0183 sentences, a standardized message protocol for devices including GNSS receivers. Because of this, major software modifications were not necessary. It is noted that Swift recommends using the Swift Binary Protocol (a proprietary binary format) but to ensure interoperability with Trimble and Swift receivers, it was determined that all receivers would be configured to use NMEA 0183 and the software would be written to support that output.

One difference that needed to be accounted for in the GNSS driver was the manner in which the vehicle's heading was determined. Vehicle heading is used in map matching algorithms to determine the vehicle's predicted offset when using a lookahead distance and to check that the plows heading matches the road segment on which it is currently traveling. Both Trimble receivers are capable of operating with two antennas which allows the system to calculate a GNSS-based vehicle heading (i.e., the compass direction in which the vehicle is pointed). This is computed within the receiver by comparing the difference in positions between the two antennas. However, the Swift Duro Inertial is only capable of using a single antenna. Because of this, the receiver is only capable of providing an estimated heading based on the vehicle's movement history. In the case of ground vehicles, the measurements provided by these two techniques are typically very similar. To accommodate this change and to ensure parity between systems using different receivers, it was determined that all receivers would be configured to provide the heading as estimated by vehicle movement history.

6.1.2 Raspberry Pi 4 and Raspberry Pi Operating System Upgrades

Another hardware change that was implemented for the 2021-2022 winter season was upgrading the systems' computers from the Raspberry Pi 3 to the newer and more powerful Raspberry Pi 4 (Raspberry Pi Foundation, 2023). The Raspberry Pi 4 is a small, inexpensive, single board computer that is used to run the software that powers the snowplow driver-assist system. Using this new model required that the software be upgraded and tested to run on the newest version of the Raspberry Pi Operating System (OS).

No major issues were encountered upgrading to the newest version of the Raspberry Pi OS. Development and testing work focused mainly on upgrading and testing software libraries upon which the snowplow software depends and ensuring that in upgrading these dependencies, no regressions or other breaking changes were introduced.

The snowplow driver-assist system is currently designed to run on a Raspberry Pi 4 Model B (4GB RAM) running the April 4, 2022 release of Raspberry Pi OS Lite based on Debian 11 (bullseye). The system software uses the default 3.9.2 Python interpreter. All other binary dependencies are the default for this version of the operating system.

6.1.3 Remote Data Collection and System Monitoring

To support project data needs related to operator performance measurement, additional system software was developed to record select system metrics that could be used to enable a quantitative measure of how the system aids driver performance.

For each deployed snowplow, the research team identified a three-mile portion of its mapped route that would serve as the experimental test area. When the snowplow operates on these test areas, the system automatically begins logging additional vehicle parameters to file. When the vehicle leaves the test area and continues onto other portions of the mapped route or other unmapped routes, the system stops logging these parameters. This behavior was selected so as to limit the volume of data that needed to be stored, transmitted, and analyzed.

To determine the effect of the driver-assist system on driver performance, an ABA experimental design was developed. Under this design, the three-mile test area was split into three 1-mile segments. When driving the first and third segments, the system would operate as normal, providing feedback to the driver. When driving the middle segment, the system would not provide any feedback, only showing a message indicating that the driver is in an experimental test area.

This was accomplished by adding in two key software features. The first was the ability for the system to collect additional vehicle state information and write this data to a file so it could be remotely transmitted to the research team. The logged data was collected primarily from the map matching component which is responsible for combining the vehicle's position (as provided by the GNSS receiver) with the digital map to determine whether the vehicle is on a mapped segment and if so, its deviation from the lane centerline. This data was combined with additional, experiment-specific fields such as which experimental segment (i.e., which of the three 1-mile segments) the vehicle was traveling.

The second key software feature added to enable this experiment was the function to disable the driver display so that performance metrics could be collected when the system was operating normally (i.e., with the driver assist on) as well as when the system was not providing feedback to the driver. In addition to logging vehicle data, the data collection component was designed to send a message to the display software indicating whether the display should be shown or not shown. When the display was not shown to the driver, due to traveling through the second mile of the experimental test area, a message was shown to the driver indicating they were in an experimental test area. This message is shown in Figure 6.2.

DISPLAY DISABLED FOR TEST SEGMENT

Figure 6.2 Experimental Test Area Message

6.2 DISPLAY IMPROVEMENTS

Operational field testing conducted over the 2020 – 2021 winter season indicated that the LED light bar display design could be modified to improve readability. User testing showed that the design was well liked and provided a benefit to operators plowing in difficult weather conditions. However, it was also determined that the display had low shape readability when the LED light bar was set to a low luminance setting and when operated with low ambient lighting in the cab, a condition extremely common during nighttime plowing operations.

Readability was determined to be low in these conditions for two key reasons. The first was that under low luminance settings, the LEDs inside the light bar would not always fully illuminate their bounding shape resulting in a dim circle in the center of the shape. This made it difficult to determine the difference between different shapes that were not also colored differently.

The two yellow circle indicators to the left and right of the green center square indicator identify when the vehicle is 0.5 to 1.5 ft away from the lane centerline to the left or right respectively. When one of these indicators is shown, it can be challenging for drivers to differentiate between the left and right indicator in low ambient lighting conditions because there is little or no reference to determine where the lit shape is relative to the other shapes.

New display designs were investigated and prototyped to identify a design that would both maintain the high user acceptance of the old design but also mitigate the readability issues encountered in certain lighting conditions. Based on these constraints, it was determined that an LCD screen would be used to show the same shape-based indicators as were shown on the LED light bar display. The key advantage of such a display is its ability to fully light up the shapes leading to higher readability even in low luminance settings. Additionally, an LCD would also allow for a greater level of flexibility in changing the indicators' colors, shapes, sizes, positions, etc. which is of particular use as the system and its display undergo further user testing.

6.2.1 Hardware

The hardware display selected was a Waveshare 11.9" LCD. It has an ultra-wide screen aspect ratio with a resolution of 1480 by 320 pixels. A housing unit was designed for the display to provide protection for the display and its connectors as well as to provide a sturdy body that could be used for mounting in the

snowplow cab. Figure 6.3 shows the display in its enclosure. 3D printing was used to produce a custom display enclosure. The blue cable shown is an HDMI cable that connects to the Raspberry Pi computer. The black cable shown is a USB cable that provides power to the display. A rear view of the enclosure is shown with the backplate removed in Figure 6.4. This view shows the display electronics inserted into the display enclosure design.

Figure 6.3 LCD screen in a custom designed prototype enclosure

Figure 6.4 Display electronics in enclosure without backplate

6.2.2 Interface Design

The design of the interface was created to be as similar to the LED light bar design as possible while still making some improvements on shape readability. Figure 6.5 shows the display when no indicators are lit noting that the edges of the shapes are purposely drawn in the image to provide context.
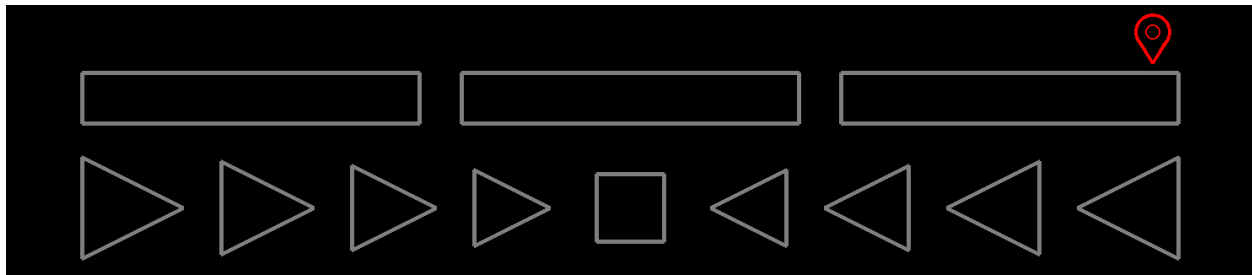
Figure 6.5 Display when no indicators are lit

Figure 6.6 shows the display when all indicators are lit noting that this situation would not happen during the operation of the system. It is shown here to illustrate the positions and colors of indicator shapes.
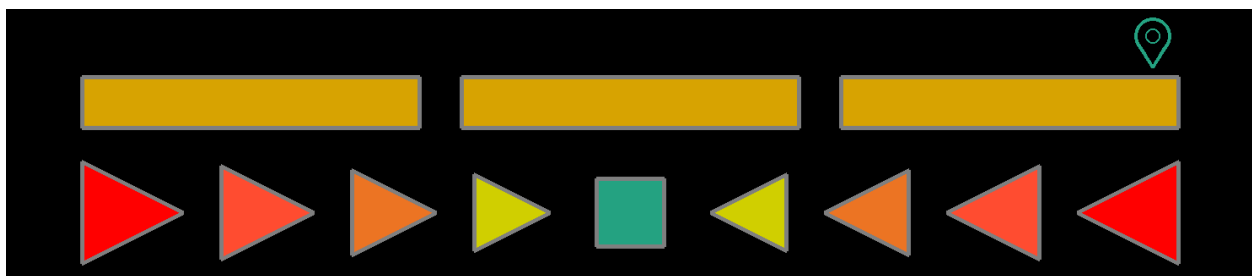
Figure 6.6 Display showing all indicators

6.3 FORWARD OBSTACLE DETECTION PERFORMANCE IMPROVEMENTS

Feedback collected from operators over the 2020 – 2021 winter season indicated that in some cases, there were forward-obstacle-detection alerts displayed when there was not an obvious corresponding hazard in the real world. To better understand these situations and provide a foundation for making future system improvements, it was determined that better software tools were necessary to aid in the investigation of these issues and to facilitate the evaluation of new software algorithms designed to increase the performance of the system.

To support this work, sample data was collected simultaneously from the radar as well as a video camera such that the radar data and video data could be synchronized in post processing. Visualization software was created to display a top-down, 2D representation of the radar data alongside a forward-facing video. The data visualization includes markers to indicate longitudinal and lateral distance from the radar. Individual radar returns are shown in the visualization with arrows indicating their speed relative to the radar and numbers indicating either the time to collision or the strength of the return. Figure 6.7 shows a sample frame from the software showing the video on the left and the top-down, 2D representation on the right.

Figure 6.7 Sample frame from visualization software

The early results using the radar data visualization software seem to indicate that it may be a useful tool for qualitatively analyzing the radar's performance. It provides metrics and visuals that can inform future filter development.

CHAPTER 7: 2021-2022 SYSTEM DEPLOYMENT

The second system deployment under this project was for the 2021 – 2022 winter season. This involved updating the computer and display for previously deployed systems, updating user training material for new system functionality, identifying and mapping routes for new districts, and installing the system on five new trucks for a total of nine trucks.

7.1 DEPLOYMENT SITES

A total of nine snowplows were deployed over the 2021 – 2022 winter season. This included the four snowplows previously deployed over the 2020 – 2021 winter season. Systems on these trucks were updated with the newer Raspberry Pi 4 computer and the newly designed operator display and enclosure. Five new systems were procured, constructed, and tested before installing them on snowplows at the McGregor (District 2), Ada (District 2), Paynesville (District 3), Dodge Center (District 6), and Willmar (District 8) truck stations.

Routes were identified in each of the five new districts to be digitized. Similar to the previous deployment, routes were considered that were primarily two-lane, undivided highways in areas where blowing snow was expected to occur. Routes were proposed by district staff and selected by project stakeholders. Table 7.1 summarizes the routes selected for the 2021-2022 winter season marking previously digitized routes in grey and new routes with white. Note that in District 7 and Metro District, new routes were added in addition to the existing routes. Figure 7.1 shows a map of the routes for the 2021 – 2022 winter season deployment.

Table 7.1 2021-2022 Routes

District	Truck Station	Route	Route Start	Route End	Length
District 1	McGregor	MN 210	US 169	MN 73 (Cromwell)	36 mi
District 2	Ada	MN 200	US 75 (Hendrum)	MN 9 (Ada)	14 mi
		MN 75	CR 39 (Perley)	CR 3 (Shelly)	19 mi
District 3	Paynesville	MN 55	County Line (Brooten)	MN 23 (Paynesville)	22 mi
District 4	Morris	MN 28	MN 9 (Morris)	MN 7 (Beardsley)	39 mi
Metro District	Shakopee	MN 25	Mile Post 15 (Green Isle)	Mile Post 4 (Belle Plaine)	11 mi
		MN 13	MN 19	CR 2	8 mi
		MN 21	MN 19 (New Prague)	CR 66 (Jordan)	8 mi
District 6	Dodge Center	MN 56	US 14 (Dodge Center)	MN 60 (Kenyon)	17 mi
District 7	Sleepy Eye	US 14	MN 4 (Sleepy Eye)	US 71 (Sanborn)	22 mi
		MN 4 (S)	MN 30	US 14 (Sleepy Eye)	21 mi
		MN 4 (N)	US 14 (Sleepy Eye)	MN 19 (Fairfax)	16 mi
		MN 68	MN 67 (Morgan)	MN 4	12 mi
District 8	Willmar	US 71	MN 7 (Blomkest)	MN 23 (Wilmar)	10 mi
		MN 7	MN 23 (Clara City)	US 71 (Blomkest)	17 mi
Dakota County	Hastings	CR 42	MN 55	US 61	5.5 mi
		CR 54	CR 91	CR 68	6.8 mi
		CR 62	CR 89	MN 316	5.1 mi
		CR 91	CR 54	US 61	9.1 mi
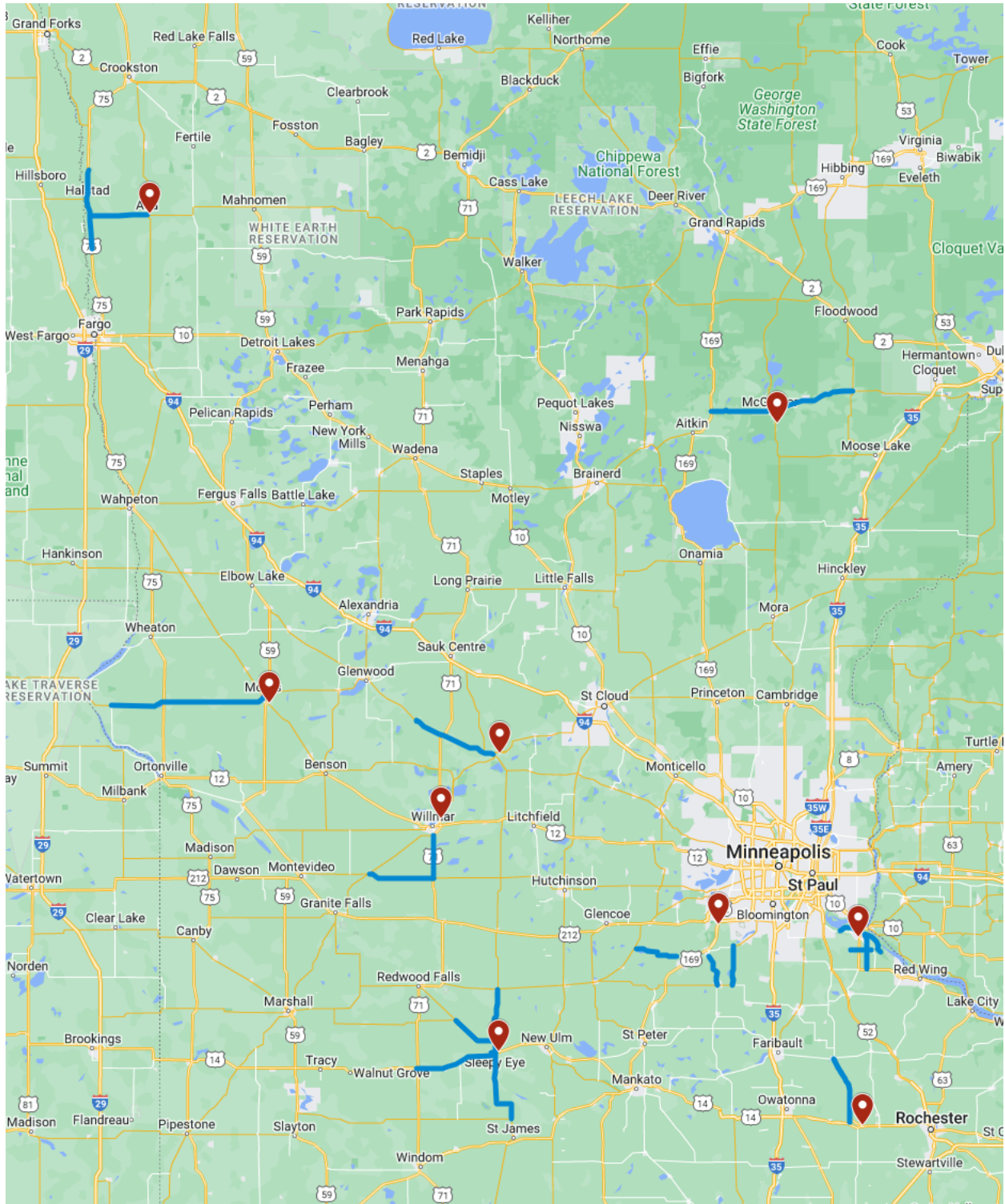
Figure 7.1 2021-2022 Route Map

Routes were mapped over the summer of 2021 using the previously established protocol. System equipment was procured, assembled, and bench tested prior to installation in the snowplows in the late summer and early fall of 2021. After installation, the systems underwent a functional, on-road test to validate the maps and ensure the system was working properly.

7.2 UPDATE TO TRAINING MATERIALS

An updated snowplow driver-assist system tutorial PDF was created to provide operators with a brief overview of the revised lane-guidance system and forward-obstacle-detection system. The seven-page PDF tutorial describes the benefits of the system (i.e., better decision-making, increased safety) and provides information about how to interpret the system's display. See Appendix E. Lastly, the tutorial includes updated information about how the system will respond to cases of temporary loss of GPS signal or roads that are not digitally mapped. Figure 7.2 shows a sample screenshot from the tutorial showing the icon indicating a loss of GPS signal.
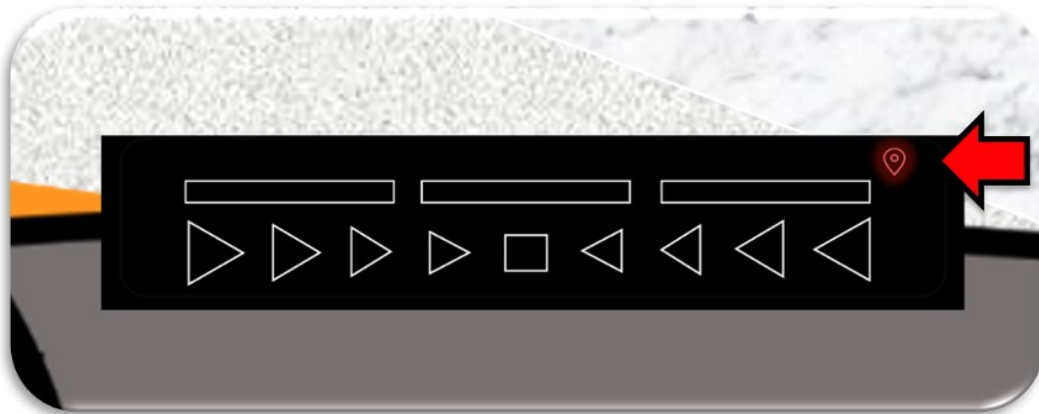
Figure 7.2 Screenshot of tutorial demonstrating loss of GPS signal

CHAPTER 8: 2021 – 2022 DEPLOYMENT TESTING

This chapter summarizes the 2021-2022 deployment testing research activities including the display user testing, system usability testing, and an operator performance test.

First, user display testing of the Lane Boundary Guidance System was performed to assess user satisfaction and acceptance of the system and to determine optimal placement of the Lane Boundary Guidance System. The outcome of this work helped to identify key design preferences and placement from operators that are recommended for implementation.

Next, the research team used a mixed-methods approach to conduct a final round of system usability testing, which consisted of both creating an online survey and conducting a series of virtual interviews over Zoom conferencing software. The findings from the system usability testing provided validation that the lane boundary guidance system has good usability and high user acceptance. Most frustrations and suggestions for improvement were related to system reliability and hardware changes. Suggestions for improvement included improving and extending the system's GPS/mapping capabilities, reducing the amount of noise (i.e., false alarms) from the hazard warning system, and adding distinguishable controls for powering the system on/off and adjusting display brightness.

Finally, an operator performance test sought to evaluate how the lane boundary guidance system improves the process of maintaining lane keeping for snowplow operators on real roadways. Thus, the operator performance test sought to evaluate whether the lane boundary guidance system improves the process of maintaining lane keeping for snowplow operators while plowing on real roadways compared to plowing without the use of the system (i.e., the normal, unassisted method). The findings from this operator performance test demonstrate some evidence that there are differences in both lane position and truck speeds when operators are supported by the lane boundary guidance system compared to unsupported. However, the complexity of evaluating operator performance using the lane boundary guidance system requires additional data to better model each individual run and more completely assess operator performance under true low visibility winter conditions across a range of roadway infrastructures.

8.1 DISPLAY USER TESTING

The research team developed multiple design modifications for the revised Lane Boundary Guidance System to test with snowplow operators. These design modifications included overall system display designs, brightness adjustment designs, and icon indicator designs (i.e., mapping and GPS icons). Finally, the research team collected operator preferences for the system display placement inside of the cab.

8.1.1 Methods

8.1.1.1 Participants

In total, 12 participants were recruited from four MnDOT truck stations. Four participants had previous experience with the system. The research team met with operators at their truck stations or virtually over Zoom for approximately one hour to discuss design options for the overall system, brightness adjustments, icon design options, and system placement preferences. Table 8.1 presents a summary of recruited participants.

Table 8.1 Recruited participants for display user testing

Truck Station	N
Dodge Center (District 6)	6
Sleepy Eye (District 7)	1
Shakopee (Metro)	2
Wilmar (District 8)	3
TOTAL	**12**

8.1.1.2 Materials

Each of the design modification options were mocked up to show the full sequence (i.e., each lane position indicator) and five levels of brightness (i.e., dim to bright) with modifications using Microsoft PowerPoint. The PowerPoint presentation was loaded onto the LCD display system to present to operators during the rounds of user display testing.

Overall Display Design. In Chapter 4, user feedback revealed a potential design limitation of the existing Lane Boundary Guidance System such that low illumination conditions (i.e., a dark cab at night) resulted in an inability to determine the position of the plow relative to the centerline. For the 2021-2022 testing, two designs (Design A and Design B) of the overall system were developed in Microsoft PowerPoint to determine the how to best display lateral position information to operators regarding their lane position when no other roadway cues are available). Table 8.2 presents an overview of the two system design options. The first design (i.e., Design A) provides lateral position information using a single indicator to indicate the position of the left plow edge relative to the centerline when the left plow edge is on the centerline, and one, two, three, or four feet to the right or the left of the centerline. As the indicator shifts outward with greater lane deviation, the illuminated icons increase in size and the color shifts from yellow to red along the visible color spectrum. Additionally, when the left plow edge is more than four feet from the centerline, the outermost red triangle will begin flashing.

The second design (i.e., Design B) uses the same lateral position information with a single indicator to indicate the position of the left plow edge relative to the centerline when the left plow edge is on the centerline, one foot to the right or left of the centerline, and two feet to the right or the left of the centerline. However, when the left plow edge is three feet to the right or the left of the centerline, the two-foot indicator (i.e., orange triangle) and the three-foot indicator (i.e., red-orange triangle) were

displayed. Similarly, when the left plow edge was four feet from the centerline, the two-foot, three-foot, and four-foot (i.e., red triangle) indicators are displayed. Finally, when the left plow edge is greater than four feet to the right or the left of the centerline, the two-foot, three-foot, and four-foot indicators flash simultaneously.

Table 8.2 Overview of System Display Design Options

Position of Left Plow Edge	Design A	Design B
On the centerline		
1 foot right or left of centerline		
2 feet right or left of centerline		
3 feet right or left of centerline		
4 feet right or left of centerline		

Brightness Adjustment Design Options. Three designs were developed to determine which type of display design would best provide feedback to operators that an adjustment was made to the system brightness. Five changing levels of brightness using changes in color saturation, the presence of dark space, or a combination of both to indicate the five brightness levels were developed. The first design (Design 1) consisted of five levels of brightness that increase in both brightness and saturation using the filled-in indicator shapes for each level of brightness. The second design (Design 2) consisted of a cutout design with five levels of brightness that fill in as brightness levels increase. Finally, the third design (Design 3) consists of the same cutout design but uses a combination of the first two designs (i.e., Design 1 and Design 2), such that as brightness of the system increases, the position indicators both fill out and increase in saturation. The brightness adjustment controls were placed horizontally at the top left-hand corner of the display and were designed to be adjusted using the touch-screen function, with brightness increasing from left to right. The five brightness levels are displayed between the seven brightness icons, with the lowest brightness setting (i.e., the far left) and the highest brightness setting (i.e., the far right). Figure 8.1. presents the five brightness levels in the top left corner. See Table 8.3 for an overview of each of the designs by brightness level.

Table 8.3 Overview of Brightness Adjustment Options

Brightness Level	Design 1	Design 2	Design 3
1			
2			
3			
4			
5			

GPS and Mapping Icons. Two icons were initially selected to indicate when GPS and Mapping features of the system were available. The icons are placed at the top right corner of the display. The icons are illuminated in green to indicate that GPS and Mapping features were functional. Additionally, several icon designs were developed to indicate the GPS and Mapping features were not functional by modifying the GPS and Mapping icons. The non-functional design options included changing the icon color from green to red and adding a red slash diagonally through the GPS and mapping icons. See Figure 8.1 and Figure 8.2.

Figure 8.1 Screenshot the five brightness levels (see top left corner) and of GPS and Mapping icons indicating GPS and mapping are available (the icons are in the upper right corner)
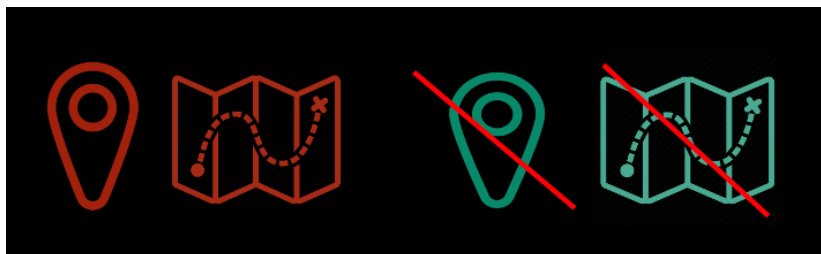

Figure 8.2 Screenshots of non-functional icon design options

8.1.1.3 Procedure

The research team met with participants at their home truck stations or virtually over Zoom for the user display testing. First, participants were provided with a brief overview of the system including its functions and features. Next, participants viewed each of the display design options and were asked to provide their feedback on their likes and dislikes about each design. Participants were also asked about each to describe what they thought the GPS and Mapping icons indicated, and how the icon should provide information about the system status. After viewing the design options during in-person testing, researchers brought the system into the garage to determine optimal placement preferences inside of operator trucks. During virtual testing, optimal placement was discussed after viewing pictures of the system mounted to various places. Participants were asked to provide any additional feedback and suggestions for improvement of the system and were thanked for their time.

8.1.2 Results

8.1.2.1 General Feedback

Overall, participants showed strong support and liking for the design of the Lane Boundary Guidance System, stating that they thought the design was 'cool' and thought the ability to adjust the screen by touch was a good idea. However, some participants also expressed concerns about being able to adjust the touch screen when they were plowing on rough roads and that the screen may be hard to tap and stated that the ability to adjust the brightness using the touch screen may vary due to individual difference factors (e.g., hand size). Additionally, because of differences in brightness comfort preferences, participants felt that the system should have as many options (i.e., levels) for adjusting brightness as possible to satisfy a range of ambient lighting conditions and operator preferences. Those who had previously used the system said they preferred to keep a knob to adjust the brightness of the screen but were still accepting of the touch screen option. Some suggestions for improving the touch screen design included placing the brightness adjustment as a sliding, vertical adjustment and enlarging the touch target points to increase sensitivity of the system.

8.1.2.2 Lane Boundary Guidance Feedback

Overall, operators expressed a strong preference and liking for Design B (i.e., additive triangles) because it provided more information about where the truck was relative to the centerline. Several participants indicated that Design A might be confusing because there was no additional information to tell the driver where the left plow edge was in the roadway (i.e., relative to the centerline). Additionally, operators reported that they liked Design B better because it would be easier to identify their position in the roadway with a quick glance or peripheral vision to quickly determine the plow's position.

8.1.2.3 Brightness Adjustment Design Feedback

Overall, the majority of participants reported a strong preference for the brightness adjustment design that uses filled-in indicator shapes (i.e., Design 1). Participants felt that the cut-out designs of Design 2

and Design 3 may not capture their attention as much as Design 1 because there was too much dark space. However, a few participants felt that they may have to shut off or dim some of the other system screens in their truck cab because of the brightness of the lane boundary system. Operators expressed that so much light was in the cab of the truck from other systems that sometimes it was difficult for them to see outside the truck (i.e., the roadway).

8.1.2.4 Icon Feedback

Operators felt that the green color of the GPS and Mapping icons was representative of the system status and indicated the system was working. When asked what type of feedback would be most useful to indicate the system was not working, operators suggested that the icons be marked with a red slash or that the green color change to a red color to indicate there was no mapping available or the GPS was not working. One participant suggested that the mapping and GPS icons disappear when the system is not functioning. Operators reported they thought both the mapping and GPS icons were intuitive and easy to understand. In fact, one participant mentioned that the color of the icons was consistent with other icons currently used in their truck (e.g., Force America).

8.1.2.5 Lane Boundary Guidance System Truck Placement Preferences

Several options were reviewed for placement of the Lane Boundary Guidance System on the truck. The majority of operators thought the system would be best suited to be placed in the center of the dash, to the right of the steering wheel above the Force America/AVL systems. See Figure 8.3. Additionally, operators did not feel that the extra height of the new system would be an issue while plowing. However, a few operators expressed concern about placing the system in the center of the dash, because they felt other systems in their truck would distract them from focusing on the Lane Boundary Guidance System. These operators felt the system would be better placed over the steering wheel so that it was directly in front of them.

Figure 8.3 Preferred Placement for the Lane Boundary Guidance System

8.1.3 Final Design Recommendations

Overall Design. The purpose of display user testing was to evaluate the revised Lane Boundary Guidance System through a series of user testing. The outcome of this work resulted in a final design recommendation of the revised Lane Boundary Guidance System that was recommended for implementation. Overall, operators showed strong support for the system and preferred a design that used size, shape, and color (i.e., Design B) to provide lane position feedback. See Figure 8.4 for an example of the final design recommendation. See Appendix F for additional images of the final design.

Figure 8.4 Image of Final Design at 4 feet to the left of the centerline

Brightness. The feedback on the brightness adjustment design options revealed a strong preference for using the filled-in position indicators that changed in saturation to indicate the level of brightness (i.e., Design 1, see Table 8.3). The recommended brightness adjustments, completed by altering the color

saturation of the icons, required software coding changes that were not feasible to be completed prior to the initial system deployment. Updated software releases may include this modification in the future. Alternatively, a physical control that would allow the operator the ability to reduce the brightness of the display hardware could be added to the system. However, this hardware change was also not feasible prior to initial deployment but could be implemented in future system modifications.

In the interest of presenting a display that is comfortable and visible across multiple luminance conditions, the research team conducted an internal beta test of the display under a range of luminance conditions (e.g., bright office building, dark room with no windows). The brightest icons were deemed visible under the brightest condition; although, it was noted that the display was prone to catching reflections of objects in the room (i.e., glare). Under the darkest condition, with viewers fully dark adapted, the green and yellow icons were deemed slightly too bright for comfortable viewing. To accommodate more comfortable viewing, brightness level 4 (see Table 8.3) was selected for green and yellow icons. A combined brightness setting was selected and was considered acceptable for initial deployment of a fixed brightness level until brightness adjustments are possible within the system software or hardware. The recommended color and brightness levels for the initial display are shown in Table 8.4, listing the colors in red, blue, green (RGB) intensity and in hexadecimal (HEX) coding language.

Table 8.4 Revised Brightness Recommendations by Indicator Position, RGB, and HEX

Indicator	RGB	HEX
Green Square (Centerline)	36,162,129	24A281
Yellow Triangle (1 ft from centerline)	208,207,0	D0CF00
Orange Triangle (2ft right or left of centerline)	236,116,35	EC7423
Red-Orange Triangle (3ft from centerline)	255,76,48	FF4C30
Red Triangle (4ft from centerline)	255,0,0	FF0000
Amber Hazard Warning (left, center, right)	215,163,1	D7A301

Icons. Based on user feedback and current system functionality, the revised Lane Boundary Guidance System display was reduced to one icon to indicate the presence or absence of mapping and GPS. The mapping and GPS position icon indicator should be colored green to indicate that the GPS signal is working and that there is a map available of the roadway. The map indicator will change to red when there is no map available for the roadway due to either a temporary loss of GPS signal or because the current roadway has not been digitally mapped.

8.2 SYSTEM USABILITY TESTING

The final round of system usability testing consisted of follow-up with operators throughout the 2021-2022 season to understand how operators adapted to using the revised lane boundary guidance system, user satisfaction and acceptance, and whether there were any user frustrations or concerns with the revised system (e.g., glare). A mixed-methods approach was used to complete the final round of system usability testing using, which included virtual interviews and online feedback forms.

8.2.1 Methods

8.2.1.1 Participants

A total of 20 participants, including snowplow operators and supervisors from eight MnDOT truck stations and Dakota County completed interviews with the research team. Although the research team sought to complete interviews with the primary operators using the modified lane boundary guidance system, several interviews consisted of both operators and their supervisors. Operators had various levels of experience using the system while plowing, ranging from only two to three times to over 20 times. Additionally, operators reported they had used the system while plowing in various weather conditions (e.g., blowing snow, whiteout conditions, clear day). For system placement, all truck stations except for the Morris (D4) truck station had the lane boundary guidance system installed on the dash of their trucks, i.e., either directly on the dash or above other dash mounted displays. The Morris (D4) truck station has the system installed on the ceiling of the truck, near the driver's side visor. Table 8.5 presents a summary of recruited participants and usability testing method(s) for each truck station.

Table 8.5 Summary of recruited participants and usability testing method(s) for each truck station

Truck Station	Virtual Interview	Online Feedback	# of Operators
McGregor (D1)	✓		2
Ada (D2)	✓		1
Paynesville (D3)	✓		2
Morris (D4)	✓		2
Metro District		✓	2
Dodge Center (D6)	✓		2
Sleepy Eye (D7)	✓		2
Willmar (D8)	✓		2
Dakota County	✓		2
Total			**17**

8.2.1.2 Virtual Interviews and Online Feedback

The research team met with operators and some supervisors from truck stations virtually over Zoom for approximately thirty minutes to discuss operators' experience with the system throughout the season, including their likes and dislikes, concerns, frustrations, and suggestions for improvement. The research team also constructed a brief online survey via Qualtrics that was emailed to each of the participating truck stations to collect user feedback about the lane boundary guidance system, including many of the same metrics of usability collected during the interviews. Participants completed interviews and online feedback through the Winter 2022 (i.e., January to April) season.

8.2.2 Results

8.2.2.1 General System Feedback

Overall, the modified lane boundary guidance system was well received by operators across all truck stations. Although some operators had limited experience with the system due to differences in installation periods, all operators reported that they liked the system, found it easy to use, and felt it was useful for improving plowing efficiency and increasing operator safety, especially during low visibility conditions. Furthermore, the truck stations with first-time users of the system commented on the simplicity of the system's design and found it extremely easy to learn. Novice users of the system reported receiving training on the system through being briefed on the system's functions and features or after reviewing the PDF tutorial and reported both to be sufficient and useful. The feedback on the modified lane boundary guidance system is consistent with feedback received from previous interviews regarding the overall system usability.

Operators who had previously used the system in the 2020-2021 winter season indicated that they liked the LCD system display, the system's improvements, and preferred the subtleness of the system's dark background. Furthermore, they felt the LCD display made a big difference and liked how the system used outlines of the shape position indicators and had a darkened background rather than the gray solid shape cutouts used in the previous design.

8.2.2.2 System Display Feedback

System Placement. As previously discussed, all but one truck station had the lane boundary guidance system mounted on the dash in the cab of the truck. Operators reported they liked this placement of the system within the cab of the truck and often relied on the use of their peripheral vision to monitor the system's status. The one truck station that had the system placed overhead (i.e., on the ceiling) reported that they thought the placement helped reduce eye strain because they did not have to turn their head so much while plowing.

Evaluation of Display Brightness. Overall, the majority of participants reported that the system's display was visible and was of adequate brightness. Most operators reported working longer shifts that started either early in the morning (i.e., between 12am to 3am) and ended mid-day (i.e., between 11:30am to 12:30pm), or worked an evening shift that started midday (i.e., between 11:30am to 12:30pm) and ended later in the evening (i.e., between 8:30pm to 11:30pm). Operators were asked to report any issues with system glare and no issuers were reported. Thus, the positive feedback regarding the system's brightness settings and absence of glare issues suggests the overall brightness of the system was well-received.

Although most operators felt the brightness of the system was acceptable, a few operators felt that it would be useful to add a knob to adjust the brightness of the system because they either felt the system was too dim or too bright, especially when plowing during low ambient lighting conditions (i.e., early morning or late at night). Another operator felt the brightness of the overall system was at the right

setting except for the green square, which he felt could be made brighter. Additionally, several operators felt it would be useful to include an "on/off" switch on the system so they could turn the system off during non-plowing seasons (i.e., summer). Finally, because the operators use multiple displays with varying brightness while plowing, it is important to consider how the displays of other systems in the cab may compete for operator attention, especially while plowing during low visibility conditions when greater mental effort is required. Taken together, it is recommended that the future system improvements include two distinguishable controls for the brightness of the overall display and on/off functions.

8.2.2.3 Lane Boundary Guidance GPS/Mapping

There were several complaints about the system's overall GPS and mapping reliability expressed across several truck stations. Some operators reported that they had issues with the system functioning after the initial installation process, but reported that after the first few uses, the system's GPS was working reliably. Other operators reported that the system lost GPS signal when they were driving on curves or in some cases, one direction on the entire stretch of the mapped roadway. Additionally, modified paths of the digital map on road segments near turn lanes were raised as a potential area for improvement. One truck station indicated that the preferred first pass for clearing the road near a dedicated turn lane would be to drive straight through the turn lane rather than follow the path of the road around it. Such path alterations using operator input/preference should be considered in the future as maps are updated or expanded.

8.2.2.4 Hazard Warning Feedback

Operators consistently reported that the hazard warning system was unreliable or oversensitive when detecting potential hazardous objects on the roadway. Many operators reported that the system unnecessarily warned them of detected objects such as signposts, mailboxes, and in some cases, guard rails. A few operators noted that they do not pay attention to the hazard warning system because of the frequent false alarm rate but noted they would pay more attention to the hazard warning system when plowing in low visibility (i.e., blizzard) conditions. Because of the high reported false alarm rate, operators reported they often turned the volume of the system's audible alert down to a low level or turned off the volume completely because the constant beeping was annoying, and relied only on the visual cues (i.e., flash rates) while plowing.

Although operators felt the system was generally too sensitive and slightly annoying, they still felt the hazard warning notifications were useful, especially during snowing and blowing weather conditions. Furthermore, operators reported they liked receiving information about hazards both to the right and the left side of the plow. In fact, one operator reported that it was useful to have the system detect cars that were passing the plow's left side on two-lane roadways. Furthermore, despite the higher rate of false positives in the right warning channel, one operator strongly cautioned against removing this sensing function since multiple trucks without the warning system at their station had struck stalled vehicles on the shoulder with the plows wing during a blizzard event.

Notably, a few operators who had previously used the hazard warning system in the Winter 2020-2021 season felt that the hazard warning detection had greatly improved compared to the previous system. Nonetheless, as operators utilize other displays and systems with audible and visual alerts while plowing, careful consideration should be given to iterating the design of the hazard warning system and increasing the reliability of hazard detection sensitivity to ensure it is not placing increased workload on operators.

8.2.3 Conclusions

Overall, the findings from the final round of system usability testing suggest that the overall human-machine interface of the lane boundary guidance system consistently receives high user acceptance. Both novice and experienced operators find the system easy to use and very useful, especially when plowing in low visibility winter weather conditions. Across all truck stations, operators and supervisors expressed a strong liking for the system and requested additional routes to be mapped to extend the usefulness of existing systems as well as systems to be added to more trucks.

There are several system reliability-oriented issues and hardware changes that should be considered for further iteration before widespread implementation, including:

- Prioritize improving the overall reliability of the GPS and mapping system to reduce the amount of GPS signal loss along routes
- Improving the reliability of the sensitivity of the hazard warning detection system (i.e., reduce the number of false alarms)
- Adding a distinguishable control for adjusting the brightness to individual operator comfort level
- Adding an on/off power button so the system can be turned off during the off-season

8.3 OPERATOR PERFORMANCE MEASUREMENT

Throughout this work, the lane boundary guidance system has consistently received strong support, high user acceptance and user satisfaction. Specifically, operators report that the system improves plow efficiency and safety, especially when used during low visibility plowing conditions (e.g., during blowing snowstorms, at night). Although the system has received strong user support, it was important to demonstrate that the system improves operator performance by determining whether the system allows operators to better maintain lane position compared to plowing without the system. Thus, an operative performance study examined whether using the system improvers operators' ability to maintain a straight path on the roadway compared to plowing the normal method (i.e., without the use of the system).

8.3.1 Methods

8.3.1.1 Participating Truck Stations

Participating truck stations included six Minnesota DOT (MnDOT) truck stations and the Dakota County truck station. All data was collected on two-lane Minnesota roadways currently mapped by the lane

boundary guidance system. A total of 70 runs were sampled across the seven truck stations. Operator performance data from District 1 and District 8 are not included in this analysis because these two trucks were unavailable during the scheduled data collection period. Table 8.6 presents a summary of run characteristics by truck district.

Table 8.6 Summary of Run Characteristic by Truck District

Truck District	Run *n* (%)	Direction	Date(s)	Time of Day	Precipitation	Wind Speed
District 2	13 (18.6)	EB/WB	March 30, April 7, 13, 14	AM, Afternoon	Trace, Trace to .02	5-10 mph, 10-15 mph, 15-20 mph
District 3	6 (8.6)	EB/WB	March 22	Afternoon, PM	.04 to .08	5-10 mph, 10-15 mph
District 4	29 (41.4)	EB/WB	March 30, April 4, 6, 7, 11, 14	AM, Afternoon, PM	Trace, Trace to .02, .02 to .04	0-5 mph, 5-10 mph, 10-15 mph, 15-20 mph, 20-25 mph
Metro District	2 (2.8)	NB/SB	March 30	PM	Trace	5-10 mph
District 6	8 (11.4)	NB/SB	March 31, April 7, 8	AM, Afternoon, PM	Trace, Trace to .02	10-15 mph, 15-20 mph
District 7	7 (10.0)	NB/SB	March 30, April 7, 8	AM, Afternoon	Trace	5-10 mph, 10-15 mph
Dakota County	5 (7.1)	NB/SB	March 31, April 8, 15	AM, Afternoon	Trace	5-10 mph, 15-20 mph

8.3.1.2 Operator Performance Measures

Lane Position. Lane position was used as the primary dependent measure of operator performance. Lane position indicates the truck's lane position in feet. A value of zero indicates the truck's left plow edge is directly on the centerline, positive numbers indicate the truck's lane position is shifted to the right of the centerline, and negative numbers indicate the truck's lane position is shifted to the left of the centerline.

Speed. Speed is the measure of the truck's speed in miles per hour.

8.3.1.3 Run Characteristics

Direction. Direction identifies the direction for each run completed on the two-lane roadways, and were coded as eastbound, westbound, northbound, and southbound.

Time of day. Time of day was classified into four categories based on the timestamp data provided by the lane boundary guidance system to approximate various lighting conditions while plowing on the roadway. Categories included night (i.e., from 12AM to 6AM), morning (i.e., 6AM to 11AM), afternoon (i.e., 12PM to 5PM), and evening (i.e., 5 PM to midnight).

Weather. Hourly summaries of local climatological data were collected from the National Oceanic & Atmospheric Administration (NOAA) on hourly precipitation rates and wind speeds to better estimate roadway conditions from the recorded runs.

8.3.1.4 Roadway Characteristics

Roadway characteristics were documented for each three-mile segment using Google Maps. Roadway characteristics included the number of intersections along the three-mile route, the number of driveways leading to homes or businesses along the route, and the number of right turn lanes present within each three-mile route. See Figure 8.6.

Figure 8.5 Three Google Maps images of intersections, driveways, and right turn lanes along routes

8.3.2 Experimental Design

Prior to data collection, Google Maps was used to identify 21 roadway segments across seven participating truck stations' plowing routes, i.e., three segments per station. The criteria for each identified segment included segments that consisted of three-mile stretches of roadway that were isolated from major cities or towns and that all three miles of the identified segment were on a straight path of the roadway (i.e., without curves or turns). Although a concerted effort was made to ensure that each of the identified mile sections was on a straight path and away from major cities or towns, other roadway characteristics that may influence operator performance were documented, including the number of intersections, driveways to homes or businesses, and the number of right turn lanes present in each mile section.

Next, to reduce bias in the road segment selection, one 3-mile segment from each truck station was randomly selected as the experimental testing segment for each truck station. A software package for the experimental test segment was deployed to the lane boundary guidance system through an updated software package push to each participating truck station. During the second mile section (i.e., Mile 2), the lane boundary guidance system's feedback was suppressed and instead presented a message stating "TEST" to inform operators that the system was in testing mode and no lane guidance would be provided. This was done to notify operators that the system was still functional, but in the testing phase. The three-mile segments afforded a BAB reversal design in which the first and third mile could collect performance data with the lane boundary system providing operator guidance (i.e., B) and the second mile could collect performance data without providing system guidance to the operator (i.e., A). While there are limitations to this design, e.g., difficulty in assessing performance prior to intervention, this design was selected over a standard ABA reversal design due to ethical considerations regarding withholding effective treatments.

The software package collected GPS data and operator performance metrics within each segment by sampling lane position for the truck (in feet) using latitude/longitude coordinates every one-tenth of a second. Additionally, timestamps and truck speed (in miles per hour) were recorded for each data point. Data was collected on runs completed by truck stations on nine different days between March 22, 2022, and April 15, 2022.

Additionally, operator feedback during the data collection period revealed that there was variability across the individual runs. Because operators must make multiple passes to effectively clear the roadway (i.e., plowing from the centerline to the shoulder), the truck's position in the roadway varied across each individual run. In other words, trucks could be plowing in the shoulder on one of the runs, while on a different run they may have been plowing nearer to the centerline. Finally, the data collected during each run was during light snowy weather conditions (i.e., less than one inch of snowfall per hour) and none of the truck stations experienced a true snowstorm (i.e., whiteout conditions) during the data collection period. Thus, the average speed for each run is faster and may have a higher degree of variability than may be found during heavy snowstorms. Table 8.7 provides an overview of the experimental testing segments and route information.

Table 8.7 Overview of the Experimental Test Segment and Route Information for Each Truck Station

District	Route	Data Collection Start/End [Latitude, Longitude]	Intersections on Route	Driveways on Route	Right Turn Lanes
2	MN 200	47.295616, -96.746320; 47.295724, -96.682013	4	0	0
3	MN 55	45.490034,-95.103794; 45.46741, -95.051523	4	4	1
4	MN 28	45.558249, -96.554597; 45.558114, -96.491943	5	1	0
Metro	MN 13	44.641948, -93.501292; 44.684833, -93.500986	12	4	3
6	MN 56	44.053982, -92.899460; 44.097850, -92.899493	2	5	4
7	MN 4S	44.111018, -94.720032; 44.154896, -94.720461	3	6	0
Dakota County	CR 91	44.603943, -92.812813; 44.647035, -92.812812	3	14	0

8.3.3 Results

Although data was initially collected from seven truck stations, not all test runs contained complete data sufficient for analysis. Thus, after data cleaning, 10 runs were removed because of incomplete data and the final sample size consisted of 60 completed runs from five truck stations. Twenty percent (12) of the runs were from District 2, 10% (6) of the runs were from District 3, 46.7% (28) of the runs were from District 4, 13.3% (8) of the runs were from District 6 and 10% (6) of the runs were from District 7. Overall, there was considerable variation in both lane position and average truck speed observed across the 60 completed runs. See Figure 8.6 and Figure 8.7.
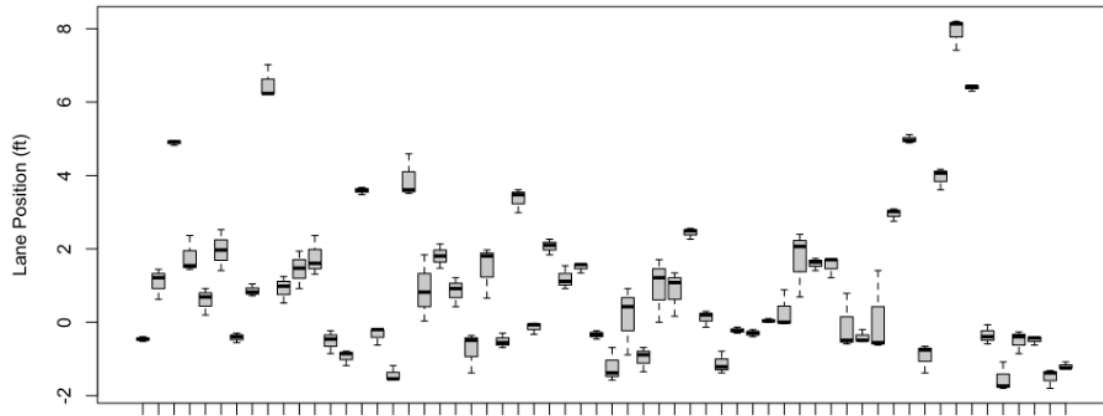
Figure 8.6 Boxplot of lane position (ft) by individual run (*N* = 60). Positive is to the right of the centerline
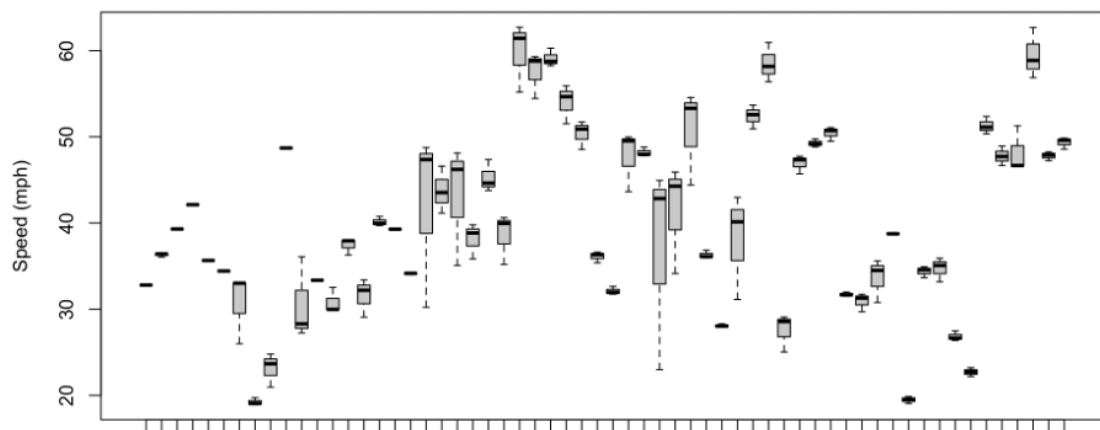

Figure 8.7 Boxplot of truck speed (mph) by individual run (*N* = 60).

Lane Position. A repeated measures analysis of variance (ANOVA) was computed to determine the effects of the lane boundary guidance system display mode (i.e., display on, display off, display on) on lane position within the 3-mile BAB segment. The differences between average lane position between mile segments were not statistically significant. However, lane position shifted slightly to the right of the roadway when the system was turned off (i.e., Mile 2) compared to when the system was turned on. Mile 1 (i.e., system on) showed an average lane position of .98 (*SD* = 2.13) feet away from the centerline, Mile 2 (i.e., system off) showed an average lane position of 1.09 (*SD* = 2.08) feet away from the centerline, and Mile 3 (i.e., system on) showed an average lane position of 1.03 (*SD* = 2.14) feet away from the centerline. This suggests that the change in the system display mode influenced lane position even if not statistically significant.

Speed. A repeated measures ANOVA was computed to determine the effects of display mode on truck speed within the 3-mile segment. The differences in speed between the display modes (i.e., within the 3-mile BAB segments) were not statistically significant, $F(2,118) = 2.85$, $p = .071$. However, average speed increased from Mile 1 (*M* = 39.58, *SD* = 10.37) to Mile 2 (*M* = 40.88, *SD* = 10.63) when the display

feedback changed from on to off, and then decreased when the display feedback was turned back on in Mile 3 (*M* = 39.99, *SD* = 10.32). This suggests that the change in the system display mode influenced operator speed; however, more data may be needed to show statistically significant differences. See Figure 8.8.
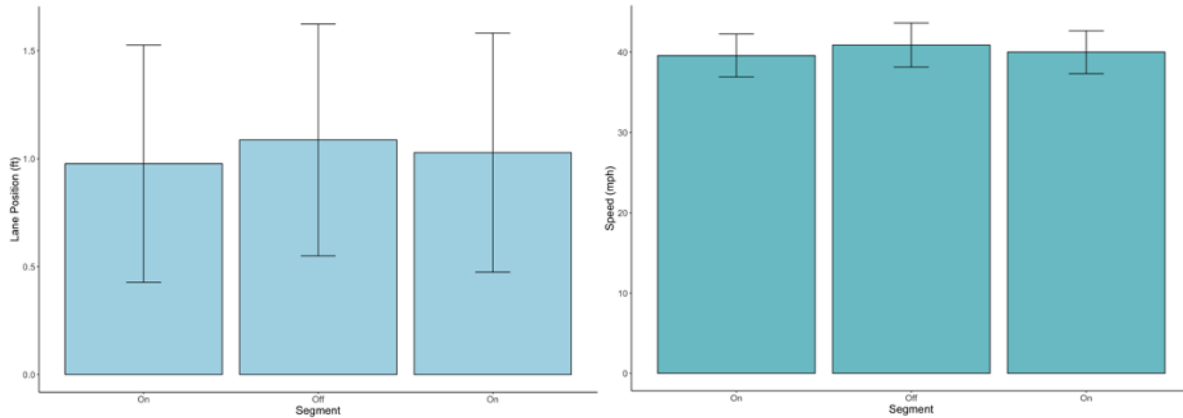
Figure 8.8 **Bar graphs of mean lane position (ft) with positive to the right of the centerline, and mean speed (mph) by BAB segment for all runs (*N* = 60).**

8.3.3.1 Effect of Number of Intersections, Driveways, and Turn Lanes

Finally, regression analyses examined which of the roadway features (e.g., number of right turn lanes, driveways, and intersections) were predictive of overall lane position and truck speed. Findings indicated that the more right turn lanes and fewer driveways on the three-mile BAB segment significantly predicted truck lane position to shift to the right of the centerline. Similarly, routes with more driveways appear to influence operators to shift the truck to the left, toward the centerline. In application, District 3 and District 6 were the only districts that had turn lanes, while all districts had driveways on their BAB routes. The number of right turn lanes and driveways may require operators to change their plowing maneuvers, especially as right turn lanes temporarily change the roadway from a two-lane road to a three-lane road. Further, given the directionality of the right turn lanes from the centerline, the operators may be shifting their trucks to the right to clear the turn lane of snow on the roadway. See Table 8.8.

Table 8.8 Regression Model Summary for Roadway Features on Lane Position (ft)

Characteristic	*ß*	*SE*	*t*	*p*
Turn Lanes	.746	.167	4.458	< .001
Intersections	-.514	.268	-1.915	.057
Driveways	-.505	.099	-5.063	< .001

Note. R^2 = .26, ΔR^2 = .25. Positive *ß* indicates associated lane positions shifted to the right.

For speed, all road characteristics significantly predicted truck speed. Specifically, fewer turn lanes predicted higher truck speeds, while more intersections and driveways predicted higher speeds. Having fewer right turn lanes on the three-mile BAB segment suggests operators may have been better able to maintain plowing speeds because they did not encounter temporary changes in the roadway due to turn lanes that would require them to lower their speeds. Routes with higher numbers of intersections and driveways appear to coincide with higher truck speeds. See Table 8.9.

Table 8.9 Regression Model Summary for Roadway Features on Speed (mph)

Characteristic	β	SE	t	p
Turn Lanes	-2.966	.799	-3.711	< .001
Intersections	4.623	1.281	3.608	< .001
Driveways	2.845	.477	5.972	< .001

Note. R^2 = .31, ΔR^2 = .30. Positive β indicates higher associated speeds.

8.3.4 Discussion

The results of this study found that operators shifted their lane position when using the lane boundary guidance system compared to when they could not use the system. While the direction or exact position of this shifting varied across routes and individual runs, these findings support previously collected data that found operators reported the system was useful in helping them maintain a desired lane position while plowing. The results also found that operators plowed at a slightly slower speed when using the lane boundary system compared to when they could not use the system. Not only would slower speeds support safer plowing and more efficient salting, but they would also slow the pace at which trucks may leave the road during a lane departure event. The changes in speed are in line with previous findings from the initial system deployment, in which operators reported the system allowed them to plow more efficiently and at higher speeds, especially when making their return pass (Liao et al., 2018). Overall, the small speed changes observed with the use of the system supports previous data which found operators reported to feel safer in their plowing operations when using the system, however more data may be needed to find statistically significant speed differences.

Notably, there was considerable variation across individual runs in lane position and average truck speed. Additionally, the presence of certain roadway characteristics (e.g., intersections, turn lanes) influenced lane position and truck speed. Taken together, the findings from this work suggest that measuring operator performance while plowing with the lane boundary guidance system is complex and requires additional data to better understand the influence of using the system on operator performance.

8.3.4.1 Limitations and Next Steps

There are several limitations to this work that may have contributed to the observed variability in lane position and speed. First, the number of completed runs was highly unbalanced across the five districts.

Although a closer examination of performance metrics by individual districts reveals that there is considerable variability amongst each participating truck station on lane position and truck speeds, these differences are likely due to varied weather conditions, varied lane clearing tasks, or random noise in the data.

Although run data was only collected on days that it was snowing, the current sample is also limited in capturing data on operator performance in true low visibility (i.e., whiteout snowstorm) winter conditions. During true low visibility winter conditions, operators plow at extremely slow speeds (i.e., 5-15 miles per hour) and rely heavily on the system when lane boundary cues are limited.

Future studies should collect additional data to provide a better understanding of operator performance, specific to individual districts. Additionally, it is important to collect comparison data of how operators normally plow while the system is on throughout the entire three-mile segment to better understand the influence of turning the system off. Finally, collecting data during true low visibility winter conditions with slower plowing speeds may provide better insight to understanding how the lane boundary guidance system improves operator performance. The methods used in this study (i.e., the BAB treatment design on a straight, 3-mile road segment) are expected to still be a practical and safe way to assess operator performance in true low visibility (i.e., whiteout) conditions since the standard for nearly all snowplow trucks in the state currently operate with no lane guidance feedback. Any future implementation studies should include dedicated tasks aimed at collecting ample data from all test trucks during low visibility weather conditions to supplement this study.

8.3.5 Conclusions

The goal of this work was to determine whether using the lane boundary guidance system improved operator performance while plowing on Minnesota roadways compared to plowing without the use of the system. Specifically, this work sought to understand whether using the lane boundary guidance system allows operators to maintain a straighter and desired path on the roadway (i.e., maintain appropriate lane position) when using the system compared to plowing without using the system, and to determine what, if any other factors influenced performance.

The findings from this operator performance study provide some support that operator performance changes with the use of the lane boundary guidance system's feedback compared to not using the system. Specifically, the use of the lane boundary guidance system's feedback shifts the average lane position and slows the average truck speed. Although the observed differences are relatively small, the implications of changing patterns of lane position by just a few inches or truck speed by a few miles per hour may greatly enhance plow efficiency and operator safety, especially while plowing under low visibility plowing conditions (i.e., during whiteout, blowing snowstorms). These results coupled with the results of the usability testing of previous tasks, which found high operator satisfaction with the system, suggests that the observed performance changes are indicative that the system supports operators to better maintain preferred truck lane position.

CHAPTER 9: CONCLUSIONS

Snowplow operators are often tasked with numerous monitoring and operational activities that they need to do simultaneously while removing snow and spreading deicing agents on the road. The University of Minnesota has developed a snowplow driver-assist system that provides the driver with lane guidance and forward-obstacle-detection feedback that is suitable for low-visibility situations. The lane-guidance system uses a Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver and high-accuracy maps of the roadway to provide information to drivers about their position within the lane. The forward-obstacle-detection system uses forward-facing radar to detect potential forward obstacles and alerts drivers to their presence. Information is provided to the driver through a display that uses a series of shapes that illuminate to provide information to the driver about the snowplow's position within its lane and the presence of forward obstacles.

This work was carried out in two phases with the system deployed over two winter seasons. In the first phase (i.e., winter 2020-2021), work was done to integrate and evaluate the lane guidance and forward-obstacle-detection systems and to conduct iterative user-centered design and testing on the LED-based display to ensure appropriate design that supports operator recognition of the lane guidance and hazard warning icons as well as auditory cues across a range of environmental conditions. The 2020-2021 system was deployed on four Minnesota snowplows during the 2020-2021 winter season. Driver feedback about the system's performance was collected through usability testing, and system enhancements or modifications were developed based on operator input.

In the second phase (i.e., winter 2021-2022), additional system improvements were implemented based on feedback received in the 2020-2021 winter season. These improvements included identifying a lower cost GNSS receiver, integrating it into the system, redesigning the system display to increase flexibility and clarity and to further improve the performance of the forward-obstacle-detection system. The 2021-2022 system was deployed on five new snowplows and select system updates were applied to the initial four deployed snowplows. All nine snowplows were deployed in the 2021-2022 winter season and driver feedback was again collected through usability testing. Overall, operators reported high satisfaction with the system to support plowing during low-visibility conditions. This support not only included lower mental workload and stress but also a noticeable difference by operators in the frequency that system-equipped plows were involved in run-off-the-road events or stalled vehicle strikes compared to other plows.

9.1 RESEARCH BENEFITS

The University developed a snowplow driver-assist system that provides lane guidance and forward-obstacle-detection feedback to the driver. Snowplow operators' consistent praise for the system provides compelling support for the overall system usability, especially while plowing during low-visibility conditions. The system allows operators to perform their jobs more safety by not only providing feedback regarding their position in the roadway but also uses a forward-obstacle-detection system to warn operators about stationary or moving obstacles in front of the snowplow on the roadway. Moreover, taking a user-centered approach in the design and iteration of system features (e.g., display

brightness, hazard warning alerts) results in a system that is perceived to be easy to use and widely accepted by snowplow operators.

It was determined that the Swift Duro Inertial GNSS receiver deployed on five snowplows in the second phase of the project (i.e., Winter 2021-2022) provided similar accuracies to that of the Trimble RTK GNSS receivers used by the initial four snowplows. The benefits of using this new GNSS receiver and antenna is cost. The driver-assist system now integrates a lower cost RTK GNSS receiver, high-accuracy digital maps, forward-facing radar, and the display described above with supporting hardware including communications, networking, and power devices. The software that controls the system runs on a Raspberry Pi, a low-cost micro-computer. All system components except for the radar, antennas, and the display are mounted on an aluminum plate so the system can easily be installed behind the driver's seat or elsewhere in the cab.

The new LCD design developed in the 2021-2022 phase provided more flexibility than the previous LED-based display in handling low ambient light conditions, so that even in total darkness one can tell where one is located laterally with respect to the lane center. Using simple triangular shapes, the lane boundary guidance system on the relatively small LCD display provides sufficient information to allow the operator to determine where they are laterally up to four feet to the right or left with respect to the lane center, in one-foot increments. The design is such that the light intensity can be adjusted in software. The display provides information as to whether the vehicle is on a mapped route and whether the GNSS-sensed vehicle position reception is reliable. Three rectangular indicators on the same display above the lane-guidance system, alert the driver to a hazard to the left, straight ahead or to the right of the front plow. Finally, the new LCD display can present any visual information that is needed in the future without hardware changes as the previous display would have required. This flexibility will ensure that the system can be modified for future use cases such as four-lane road segments, which may require a different presentation of lane-guidance information.

In the Phase 1 winter season deployment, it was determined that in some situations, the obstacle detection system was too sensitive and generated false positives. The outcome of the 2020-2021 system testing research activities suggested that the obstacle detection system was overly sensitive, resulting in false alarms. As such, improvements were made to the system, including a modification to the mounting configurations of the radar units, tuning the existing detection algorithms, and introducing filtering algorithms into the forward-obstacle-detection software. Additionally, a radar visualization tool was developed to identify these issues and improved filters. Preliminary results using radar data visualization suggest that it may be a useful tool for qualitatively analyzing radar performance.

Multiple radar filter candidates are in development, and this tool will aid in designing and perfecting these filters. Amplitude threshold filtering has been tested and early results show that it is effective at removing unwanted hits, particularly false positives in the right-hand channel. Additional development of the software should allow quicker testing and tweaking of filter candidates through redrawing the visualized data from a prerecorded dataset. This visualization tool will be used to investigate occurrences of false positive warnings, collect data, and identify any patterns, which will be used to design an improved filter.

9.2 COST-BENEFITS CONSIDERATIONS

The cost of a snowplow is approximately $275,000. The current equipment costs of the snowplow driver-assist system are on the order of $13,000. This does not include installation or any of the annual operational costs (such as the monthly charge for the modem or the time for high accuracy mapping of the snowplow routes). Each snowplow is a considerable investment of taxpayer dollars and this system (i.e., $13,000 per system) would increase the total cost by only 4.7% and is expected to ensure maximum use and value of each investment.

The Minnesota Department of Public Safety estimates that a typical property damage only crash could cost $4,600 and a minor injury crash costs $23,400 in total economic loss. The wear and tear, damage, and potential collision risks with other vehicles may be considerably reduced through the use of this system by reducing the risks of run-off-the-road crashes and vehicle-to-vehicle collision events. The demonstrated use of this system has shown that operators are better able to clear lanes of travel in fewer passes when using the lane-guidance system. This improved efficiency reduces fuel costs, labor hours, and better meets Minnesota's clear roads initiatives. Further, the wellbeing of snowplow operators may be improved through reduced stress, mental workload, or even injury from crashes.

9.3 STEPS FOR FUTURE IMPLEMENTATION

All snowplow routes with poor visibility can take advantage of this driver-assist system. The following implementation steps provide a guideline for MnDOT to improve the driver-assist systems after the completion of this project.

1. Service the nine deployed driverassist systems
2. Use the radar visualization tool developed in this project to further investigate and improve the performance of the forward-obstacle-detection functionality
3. Develop a procedure that will allow maintenance works to create, manage, and maintain high-accuracy digital maps that will work with the driver-assist system
4. Integrate the above into a system that can be deployed on a large scale, state-wide basis
5. Develop a user manual and technician manual for training MnDOT staff on the DAS
6. Identify a service provider that can provide for future system maintenance, upgrades, etc.
7. Explore methods to estimate annual costs to operate the system as well as an estimated initial cost or labor hours to install each unit
8. Identify the basis for selecting locations for further deployment of the DAS

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APPENDIX A
FORWARD OBSTACLE WARNING INITIAL DESIGNS

Multiple design changes were implemented for each of the main design alternatives. The images displayed in each of these figures below denote changes made to the design within the iterative process (as indicated by a blue arrow) and multiple states of that design (e.g., on/off, approaching hazard, or right/center/left hazard position).
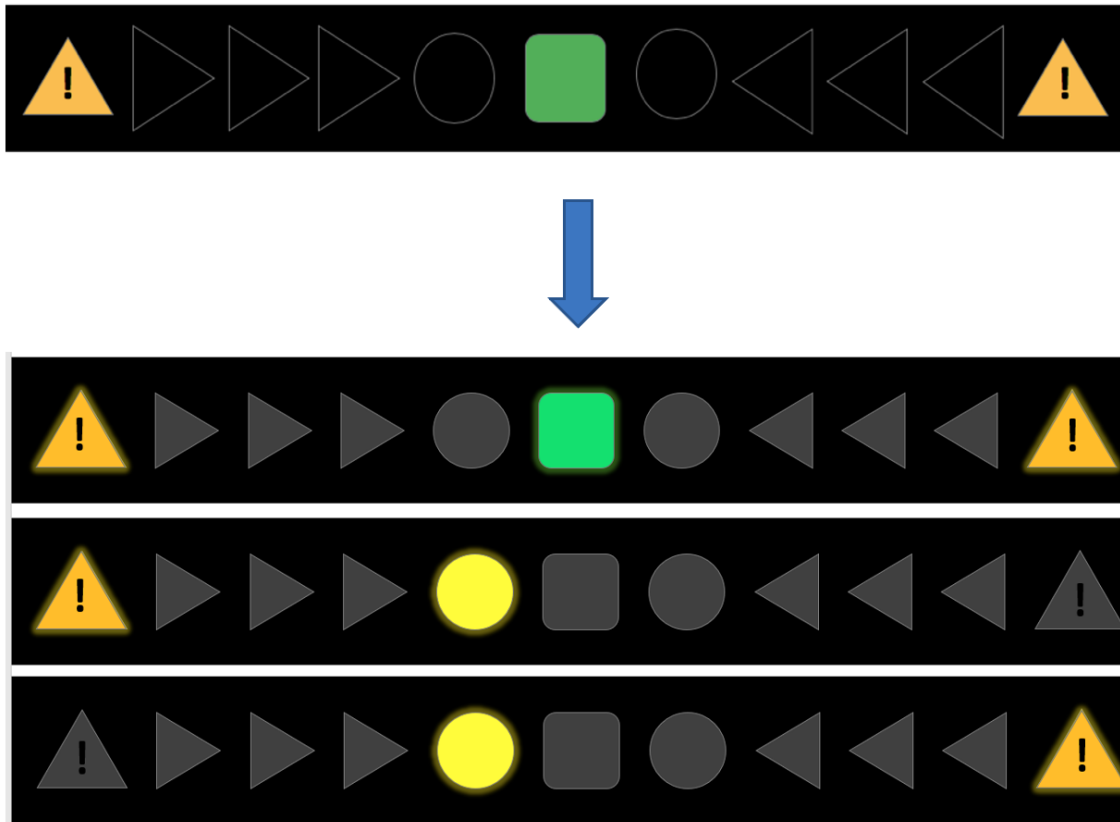
Note: Design changes were made to demonstrate glowing functions and to demonstrate hazard position through center (left and right triangles illuminated together), left (left triangle illuminated), and right (right triangle illuminated) hazard locations relative to plow.

Figure A-1 Triangle indicator on outer edges iteration
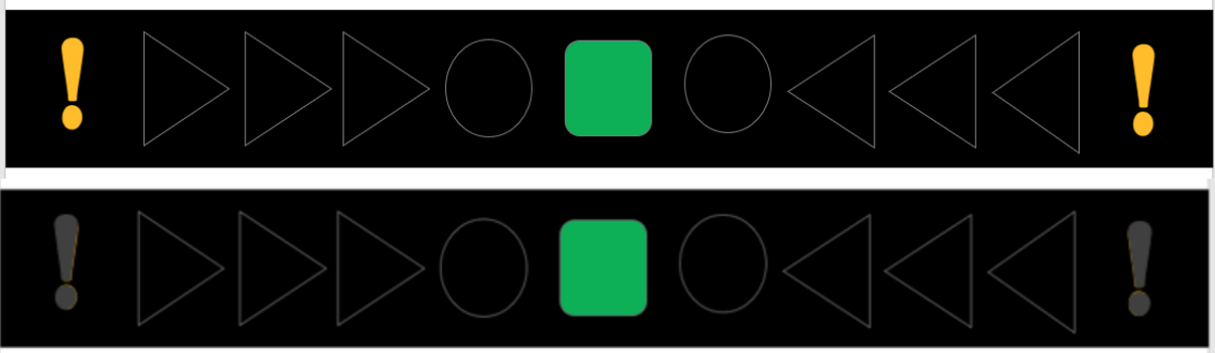
Note: Design was tested to include still or flashing functions and was eliminated from consideration during testing.

Figure A-2 Exclamation indicator on outer edges flashing/still
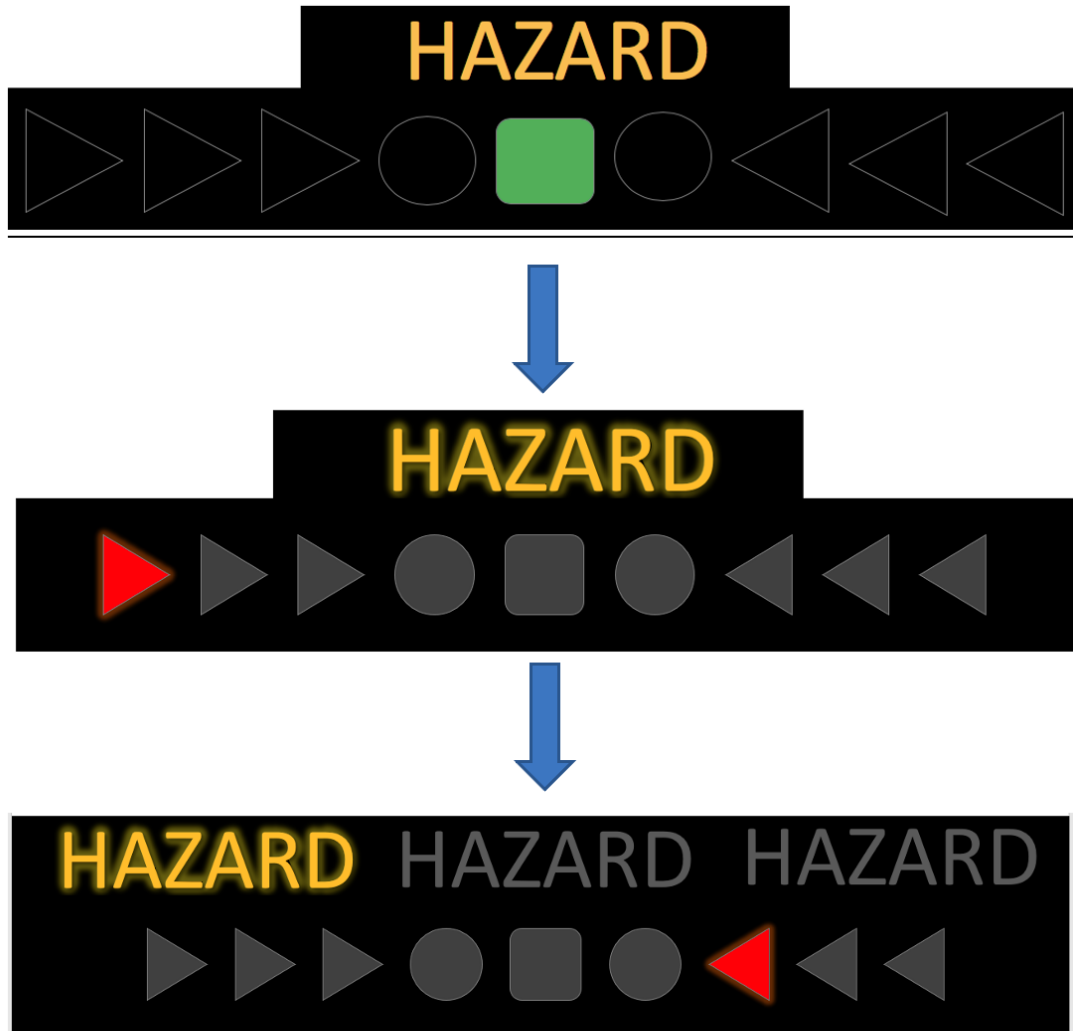
Note: Design changes were made to demonstrate glowing functions and to demonstrate hazard position through center (center HAZARD illuminated), left (left HAZARD illuminated), and right (right HAZARD illuminated) hazard locations relative to plow.

Figure A-3 Overhead hazard indicator iteration vs triple hazard warning indicator
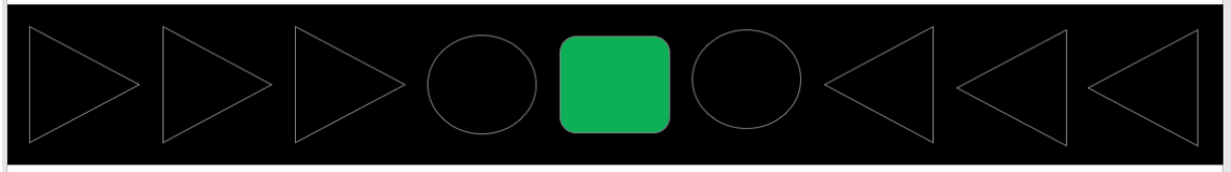
Note: Design was tested to use the existing lane guidance icons to alert the presence of a hazard. The design functions so that the current lane position indicator (see top image) alternates in being illuminated with the remaining unused icons. When the hazard is detected, all icons, except for icon denoting current lane position, are illuminated in amber and the current lane position icon is turned off (see bottom image). The flashing component is presented as the two appearances (top and bottom) alternate in turning on. This design was eliminated from consideration during testing.

Figure A-4 Alternating flashing indicator in on/off position
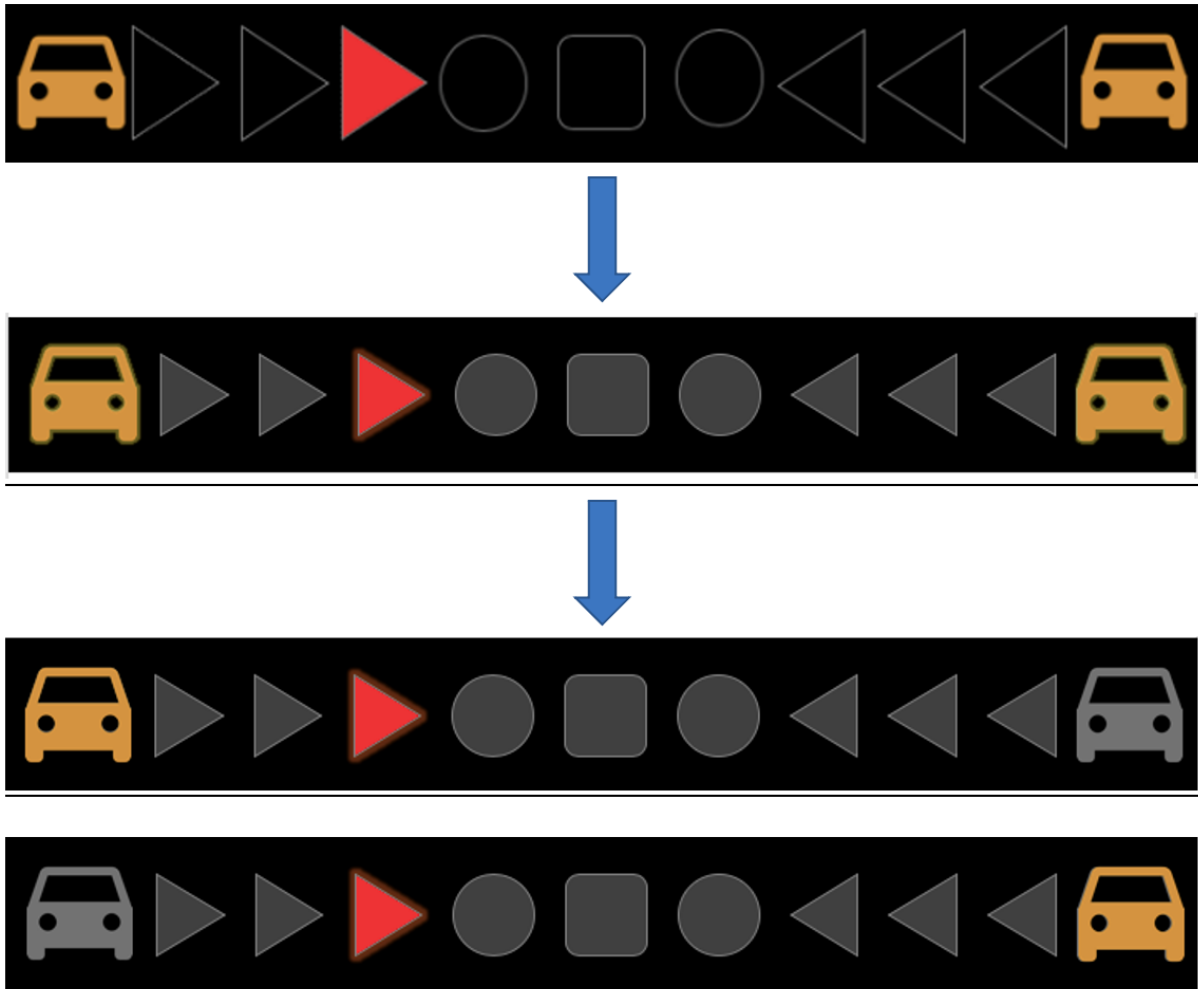
Note: Design changes were made to demonstrate glowing functions and to demonstrate hazard position through center (left and right cars illuminated), left (left car illuminated), and right (right car illuminated) hazard locations relative to plow.

Figure A-5 Flashing vehicle indicator on outer edges iteration and right/left hazard position
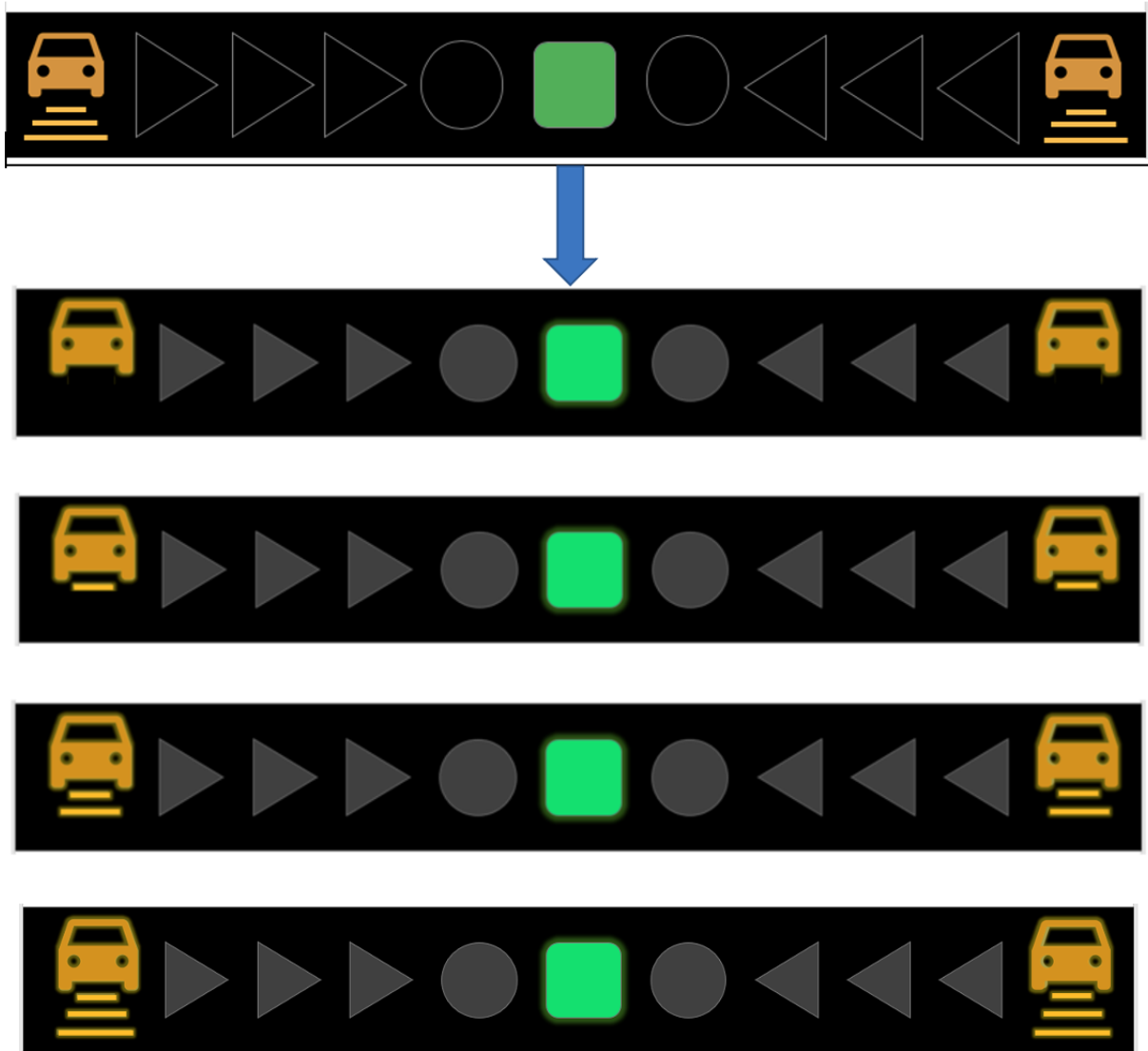
Note: Design changes were made to demonstrate glowing functions and remaining images demonstrate the multiple states of the design (with glowing functions) as the hazard approaches plow.

Figure A-6 Vehicle with looming bars on outer edges (Additional looming bars appear as hazard approaches)
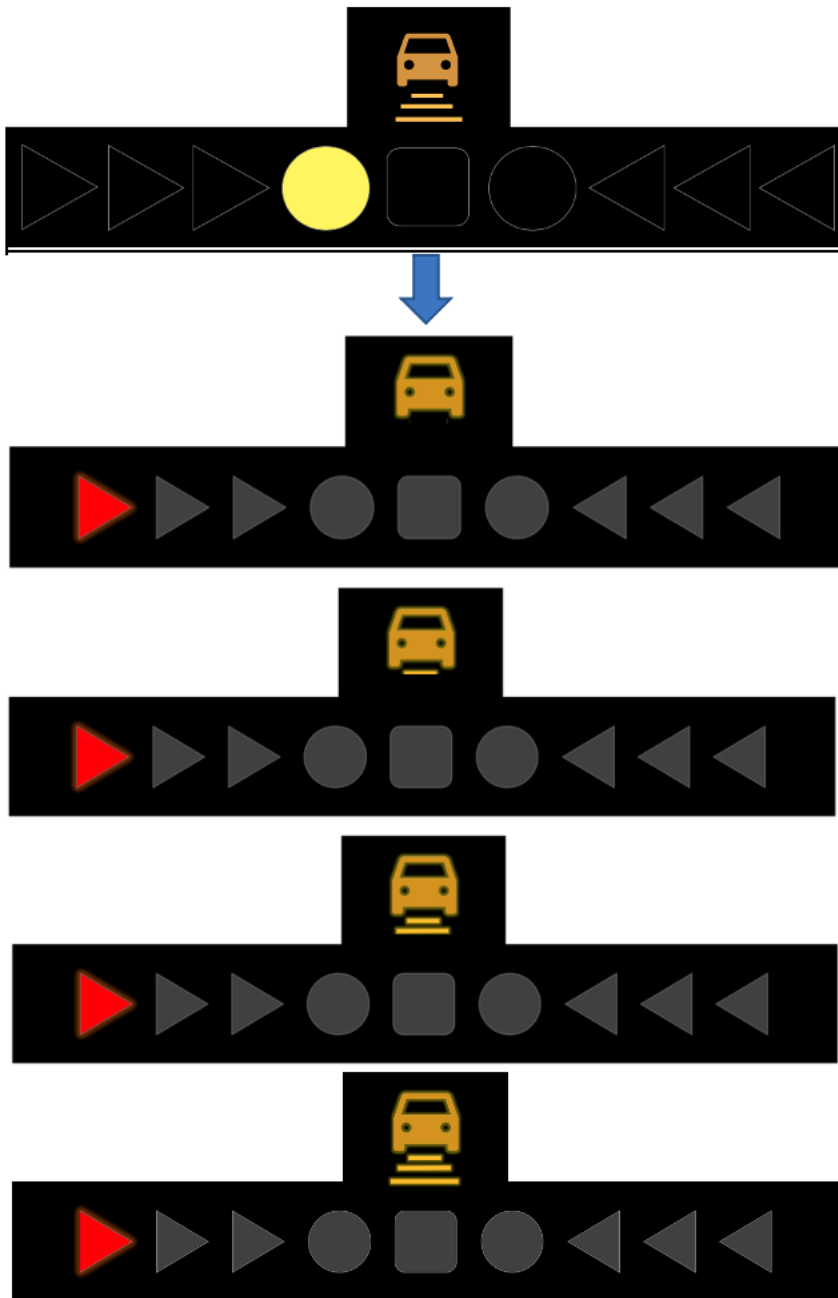
Note: Design changes were made to demonstrate glowing functions and remaining images demonstrate the multiple states of the design (with glowing functions) as the hazard approaches plow.

Figure A-7 Overhead vehicle indicator with additional bars appearing as hazard approaches
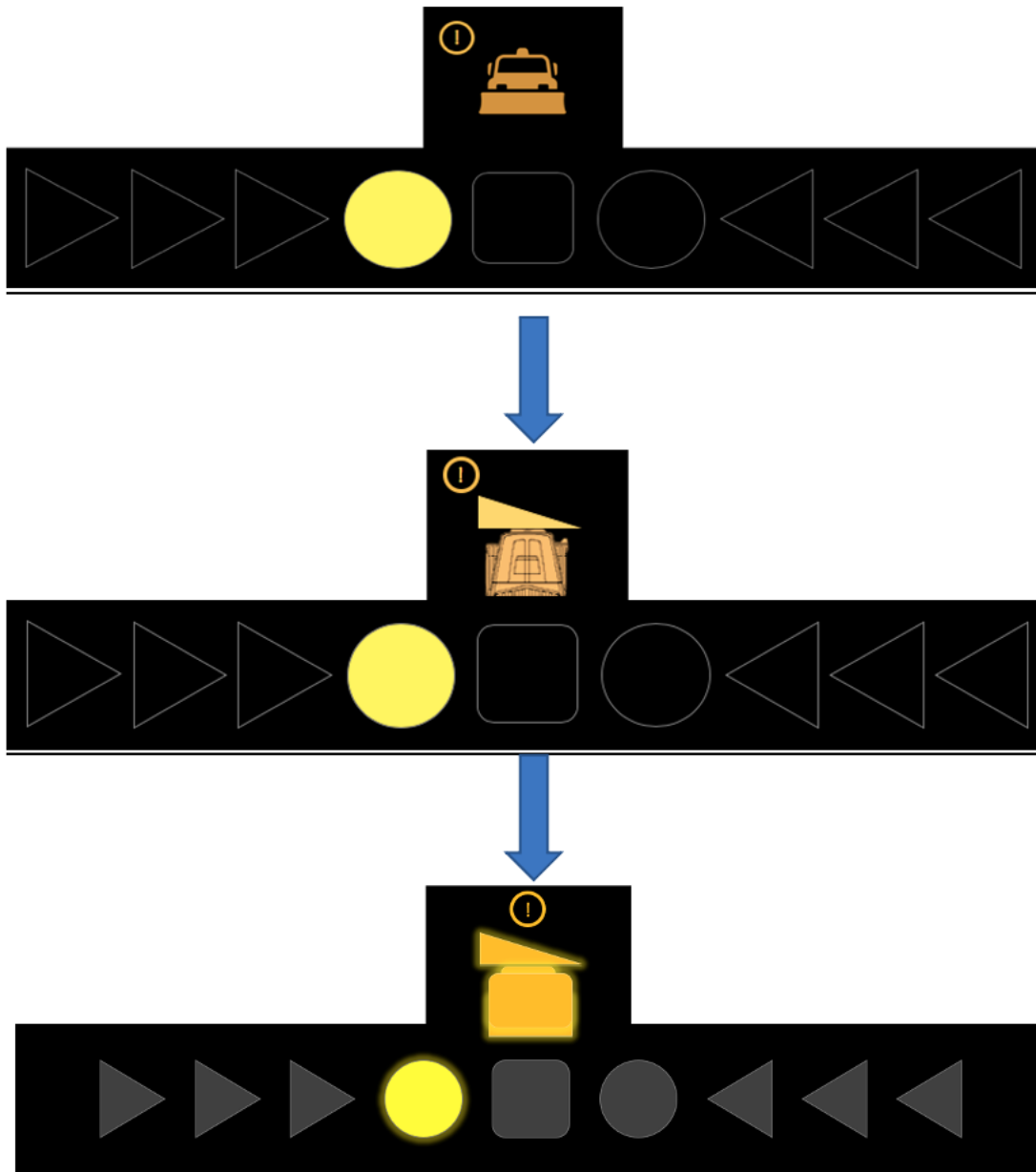
Note: Design changes were made to present a bird's eye of the snowplow and additional changes were made to demonstrate glowing function.

Figure A-8 Overhead snowplow indicator iteration (Exclamation above snowplow indicates lateral location)
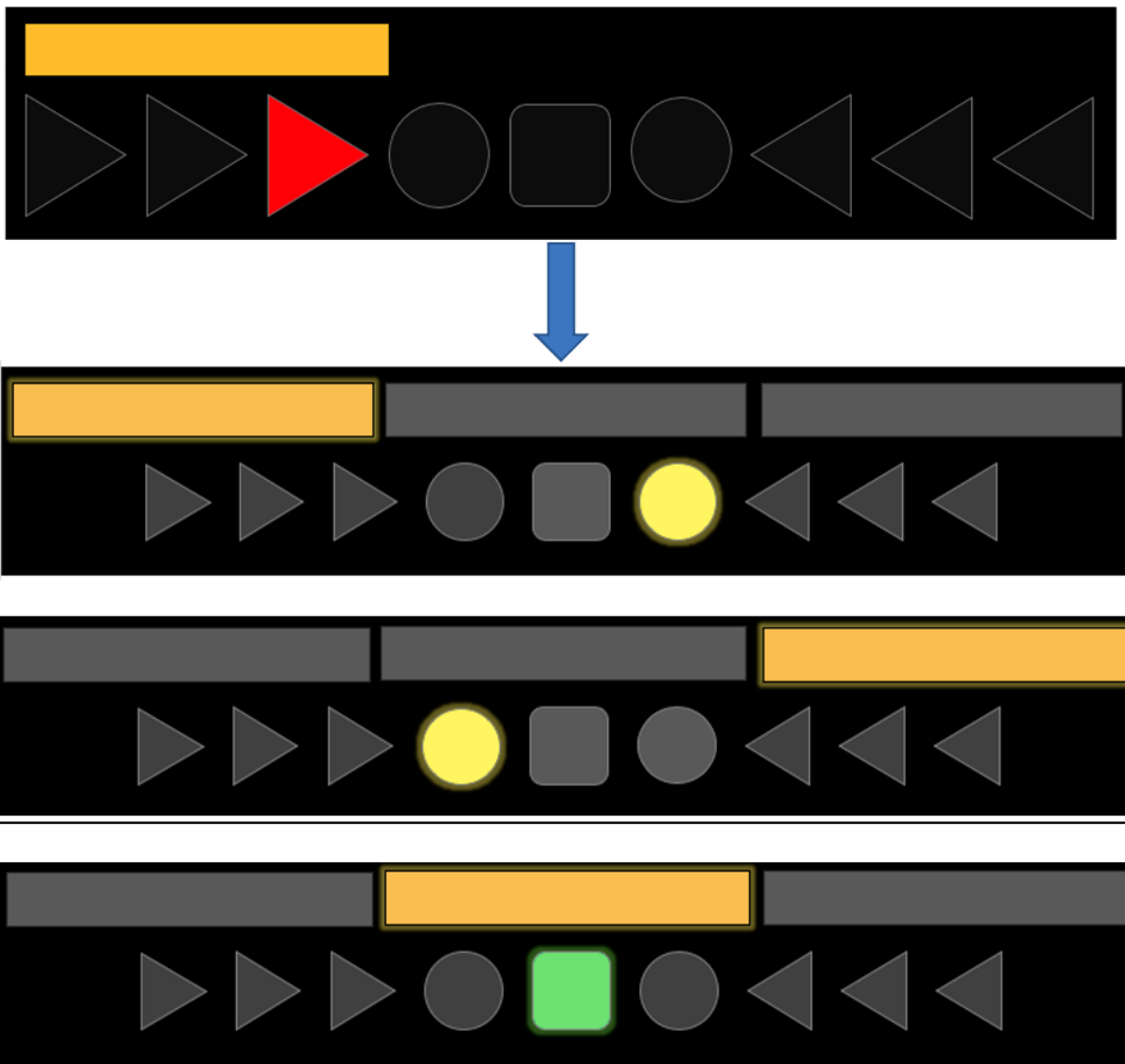
Note: This design was mock-up in real-time during testing based on operator feedback (i.e., first image) and was more fully enhanced (i.e., remaining images) for demonstration in subsequent testing.

Figure A-9 Flashing location bar indicator with left, right, and center hazard warning

APPENDIX B
FORWARD OBSTACLE WARNING DESIGN SIMULATOR TESTING

Figure B-1 Three screen shots of flashing vehicle indicator for center, left and right hazard

Figure B-2 Three screen shots of Flashing Location Bar indicator for center, left, and right hazard

Figure B-3 Three screen shots of flashing triangle indicator for center, left, and right hazards

APPENDIX C
HUMAN FACTORS FIELD OBSERVATIONS

Video Recording Instructions for Usability Test

Thank you for your participation in our research project. The process of improving the design of the lane-guidance system centers around the feedback of snowplow operators. Because we must interact virtually, we would like to review videos capturing snowplow operators using the system in low-visibility conditions rather. The reason we are asking for recordings of the plow route instead of live zoom meetings is to ensure that there are no additional distractions that would impact the safety of the driver while plowing in low visibility conditions.

You are welcome to follow the steps below to record videos whenever you experience low visibility conditions while plowing. Additionally, the University of Minnesota researchers will monitor weather conditions near the identified truck stations. When snowy weather conditions are detected, U of MN researchers will contact plow operators via telephone or email to request that they record the upcoming plow route in which they will later and use for a follow-up interview. After you are contacted by the researchers or determine the conditions are suitable, please take the following steps:

1. Prior to beginning your plow route, please be sure to secure your phone or tablet to the designated location within the cab of your plow.
2. Turn on your video and press record.
3. Using the provided mount from the engineering team should ensure that both the Lane Boundary Guidance System and view of the roadway are visible for the follow-up interview to help identify any problems with the system that may have occurred during the route or discuss instances where it was most useful.
4. Check that the Lane Boundary Guidance System is turned on and the sound is turned up.
5. Commence your plowing activities as usual.
6. After you have completed your plow route and have safely returned to your station or have come to a safe stopping place, you may stop recording the video. Ideally, capturing 15-20 of low visibility conditions with the system running should be sufficient, but capturing the entire route is also useful.
7. Contact University of Minnesota researchers to schedule a follow-up interview time to review the video footage. You will be provided with additional instructions for the interview.
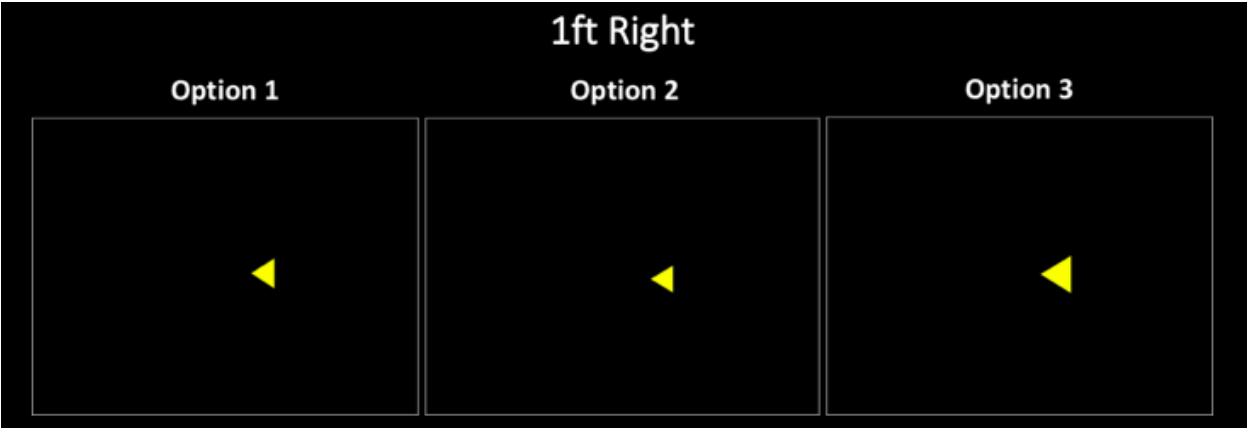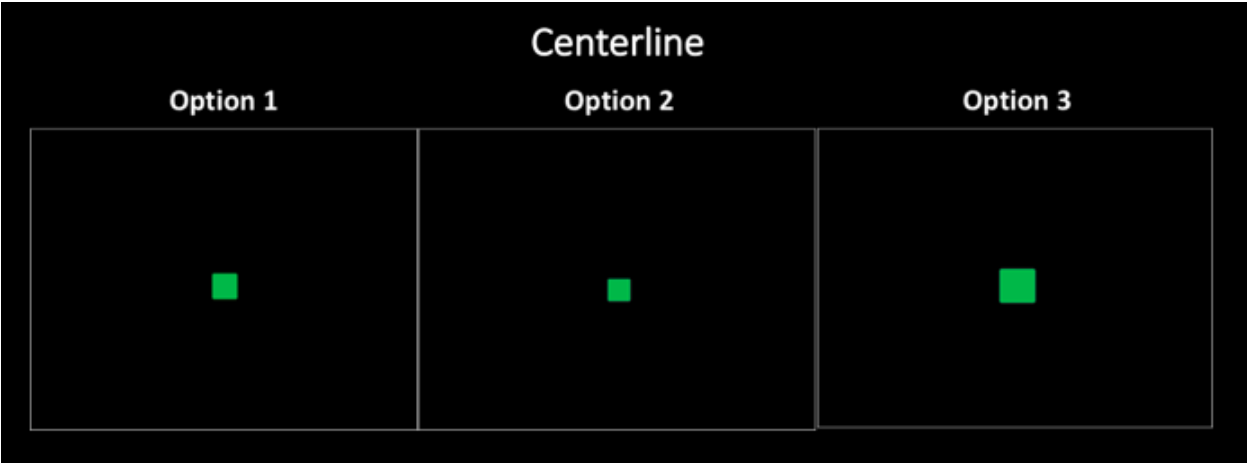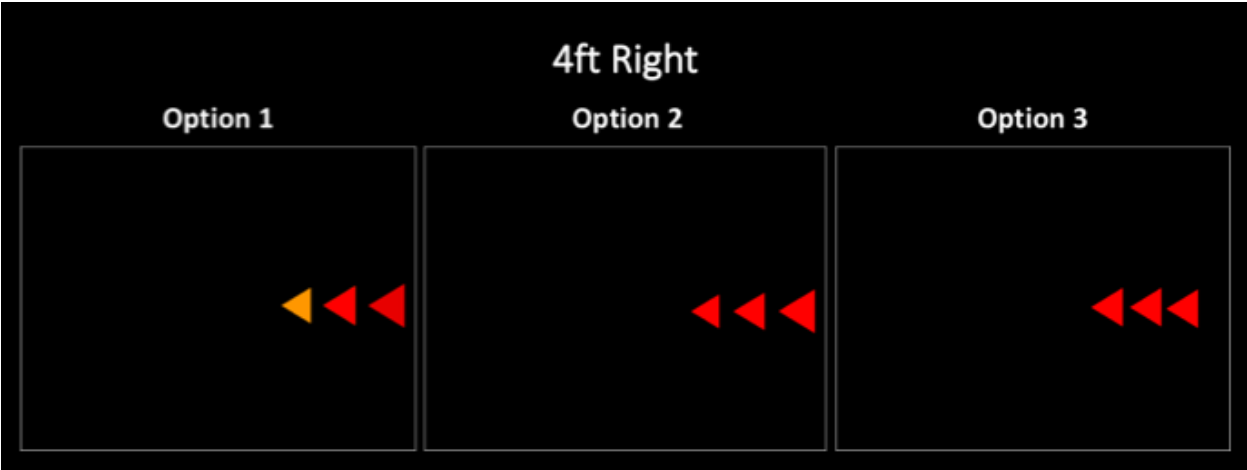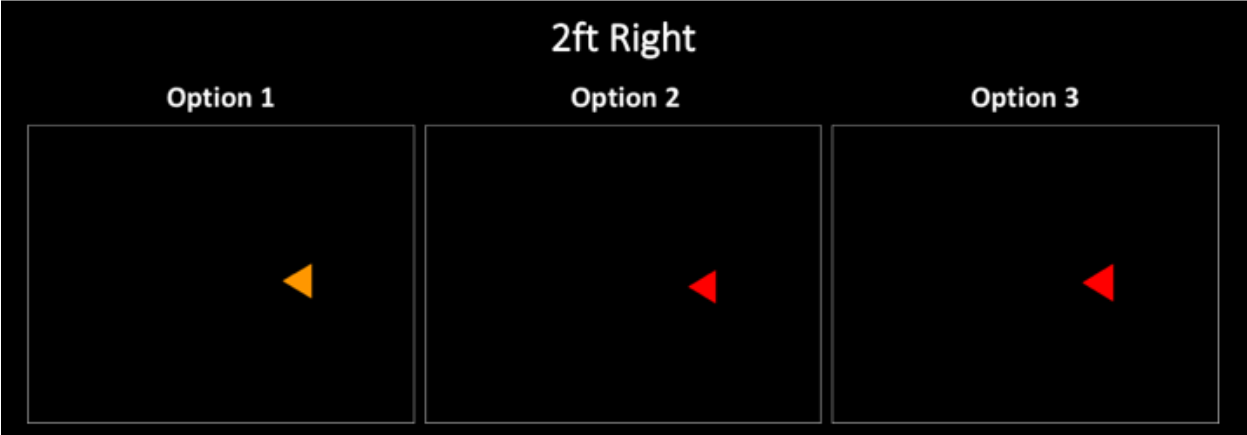
APPENDIX D
FULL VIDEO SEQUENCE OF LANE-GUIDANCE DESIGN MODIFICATIONS

The videos began by presenting the full design modifications (i.e., with all position indicators illuminated) and then demonstrated the entire sequence of the lane-guidance system (i.e., each position indicator). After the sequence was displayed, a final slide presented the full modifications. Each column represents what the operator would see on the video for each of the design options (i.e., Option 1, Option 2, and Option 3), moving from the center line, one foot to the left, two feet to the left, three feet to the left, four feet to the left, more than four feet to the left, the center line, one foot to the right, two feet to the right, three feet to the right, four feet to the right, and more than four feet from the right.

4ft+ Right

Option 1   Option 2   Option 3

All 3 Flashing
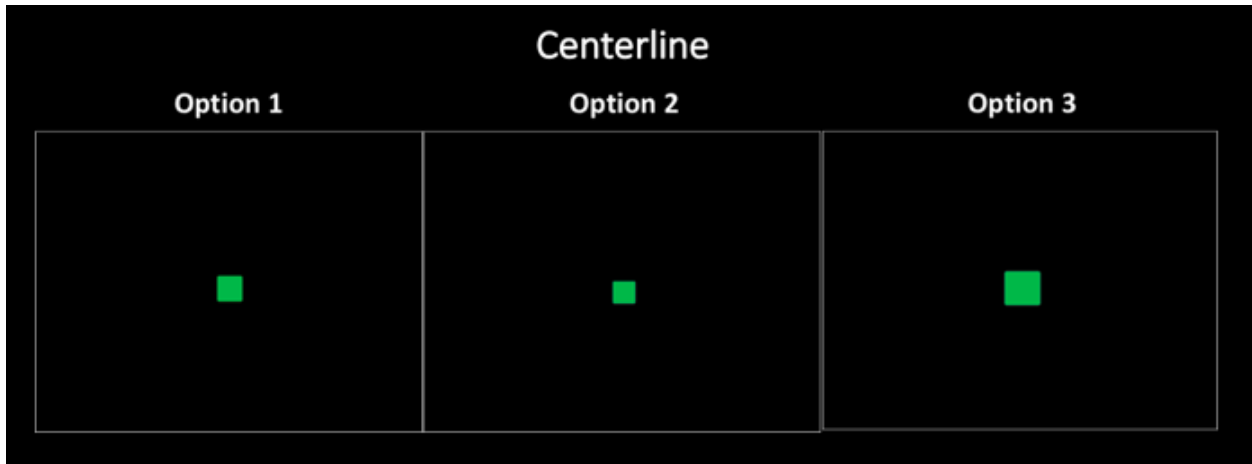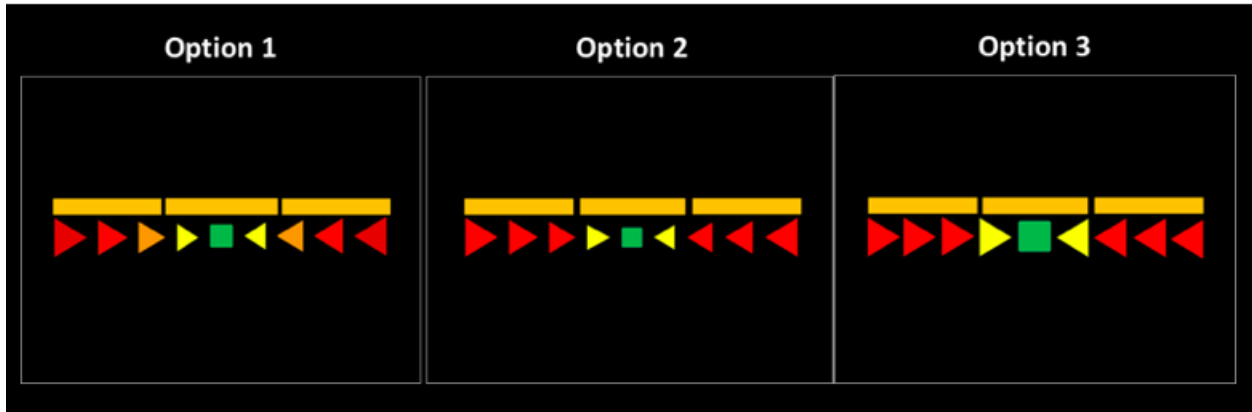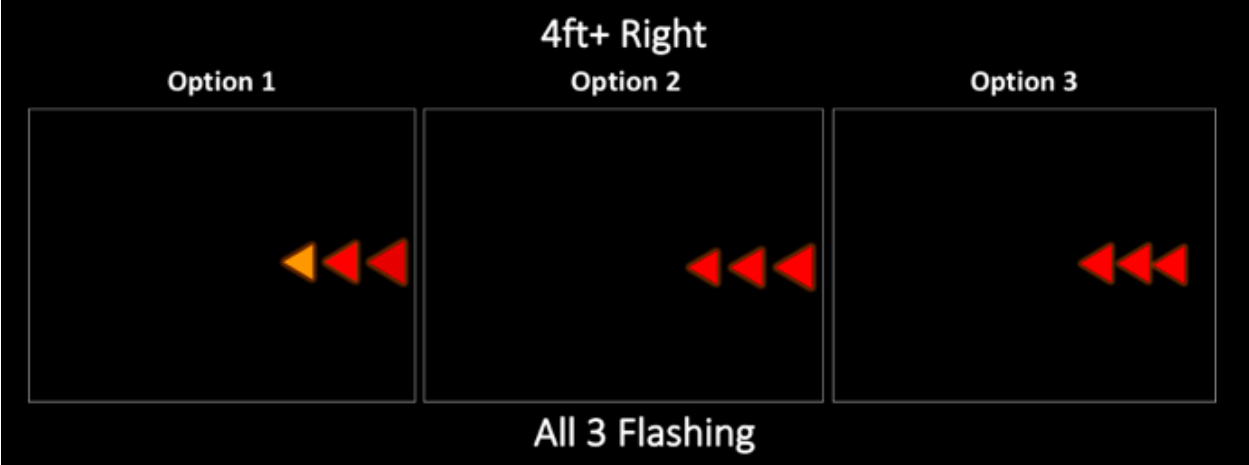
APPENDIX E

LANE BOUNDARY GUIDANCE SYSTEM PDF TUTORIAL

Lane Boundary Guidance System Tutorial

The lane boundary guidance system was developed to assist plow operators in making better decisions and performing their jobs safely and effectively when visibility is poor and lane boundary cues are limited.

The system uses a strip of colored shapes mounted to the dashboard or above the windshield of a snowplow to guide the driver. Lateral position information is provided to advise the plow operator about their lane position.

1
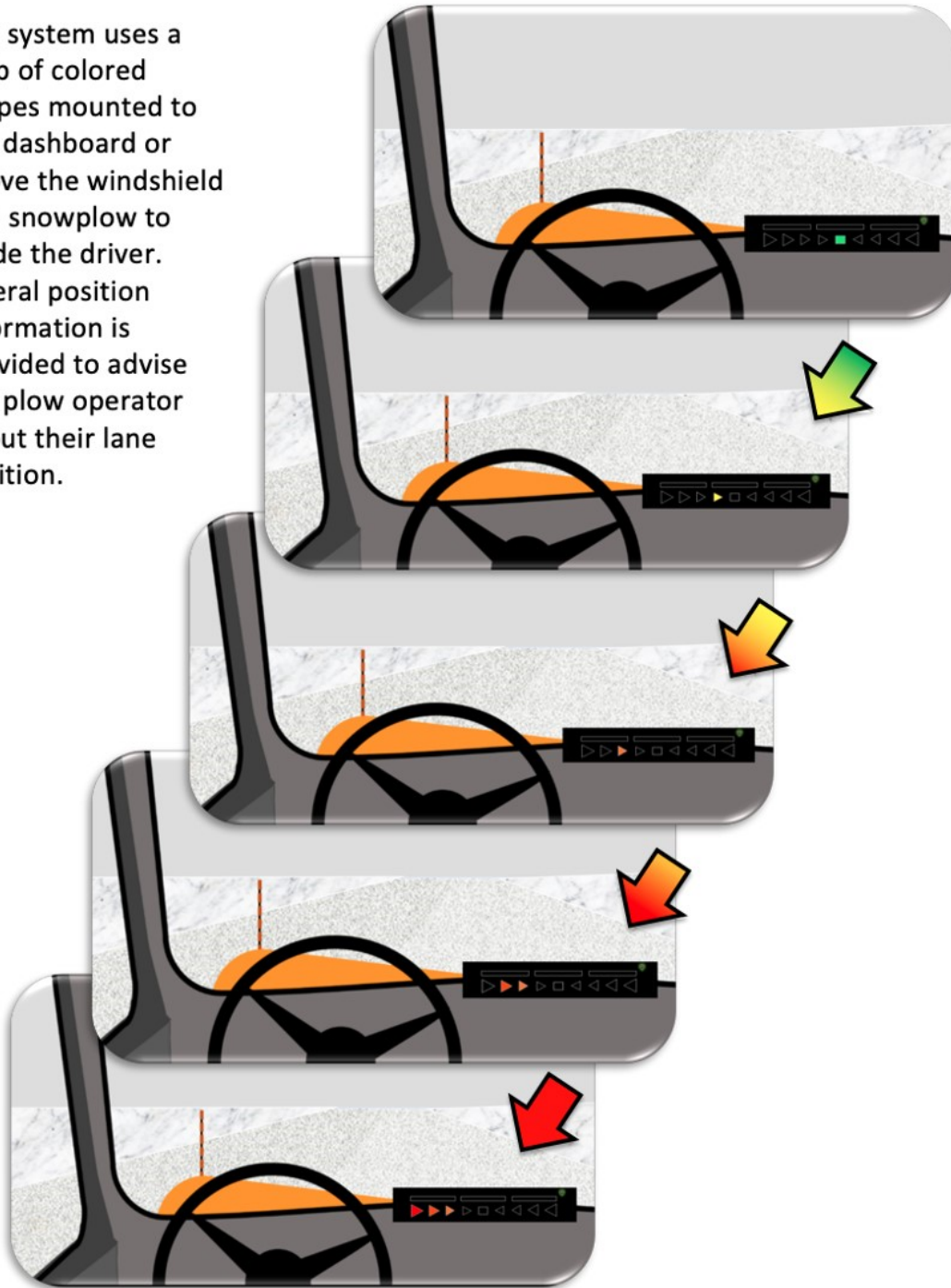
A **green square** indicates the left plow edge is *on the centerline*
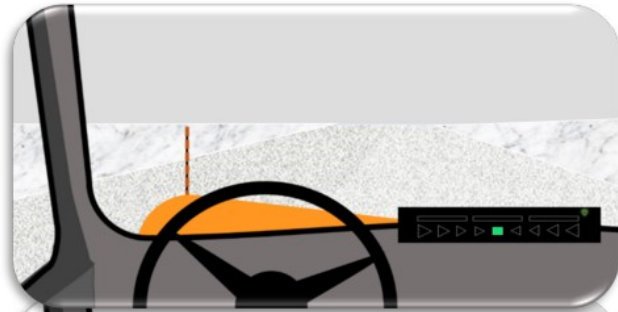
A **yellow triangle** indicates the left plow edge is *1 foot* to the *right* or the *left* of the centerline


An **orange triangle** indicates the left plow edge *is 2 feet* to the *right* or the *left* of the centerline

When the **orange triangle and red-orange triangle** are illuminated, the left plow edge is *3 feet* to the *right or left* of the center line.
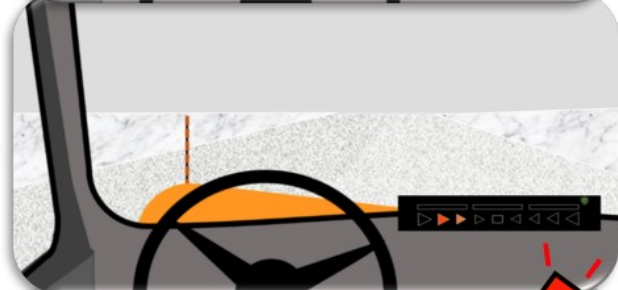
When the **orange, red-orange, and red triangles** are illuminated, the left plow edge is *4 feet* to the *right or left* of the center line. You'll notice the **orange, red-orange, and red triangles** flash when the plow edge has *exceeded 4 feet* from the centerline.

2
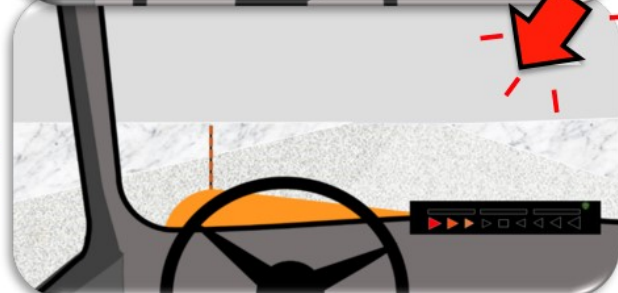
A map position icon is located on the upper right corner of the display.

When the **map position icon** indicator is colored **red**, there is *no map available* for the roadway. This may be due to temporary loss of GPS signal or because the current roadway has not been digitally mapped.

3

In addition, a hazard warning system is located above the lane boundary guidance system (on the same display) to improve the safety of plow operators under poor visibility conditions. Three rectangular indicators alert the driver to a hazard that is either to the left, in front of, or to the right of the front plow.

When a *hazard* is detected approximately *5 to 3 seconds away* from the plow, one of the directional **bars will turn amber**.

The hazard warning **bars will turn red** and an audible **alert will sound** when the *object* is *3 to 2 seconds away* from the plow.

When the *hazard* is within *2 seconds or less* to the plow, the hazard warning **will flash red** and an audible **alert will increase in intensity**.

4

The audible alert will not sound for any hazards detected to the left of the plow.

Additionally, the hazard warning system will still operate even when there is no GPS information available.

5

Occasionally, drivers may experience a non-critical warning or a false alarm warning from the hazard warning system. A non-critical warning would alert the driver to look for an object that may not be a true hazard, such as roadside signage. A false alarm may occur when a warning occurs in the absence of a true object. This may be due to noise from the system's RADAR.
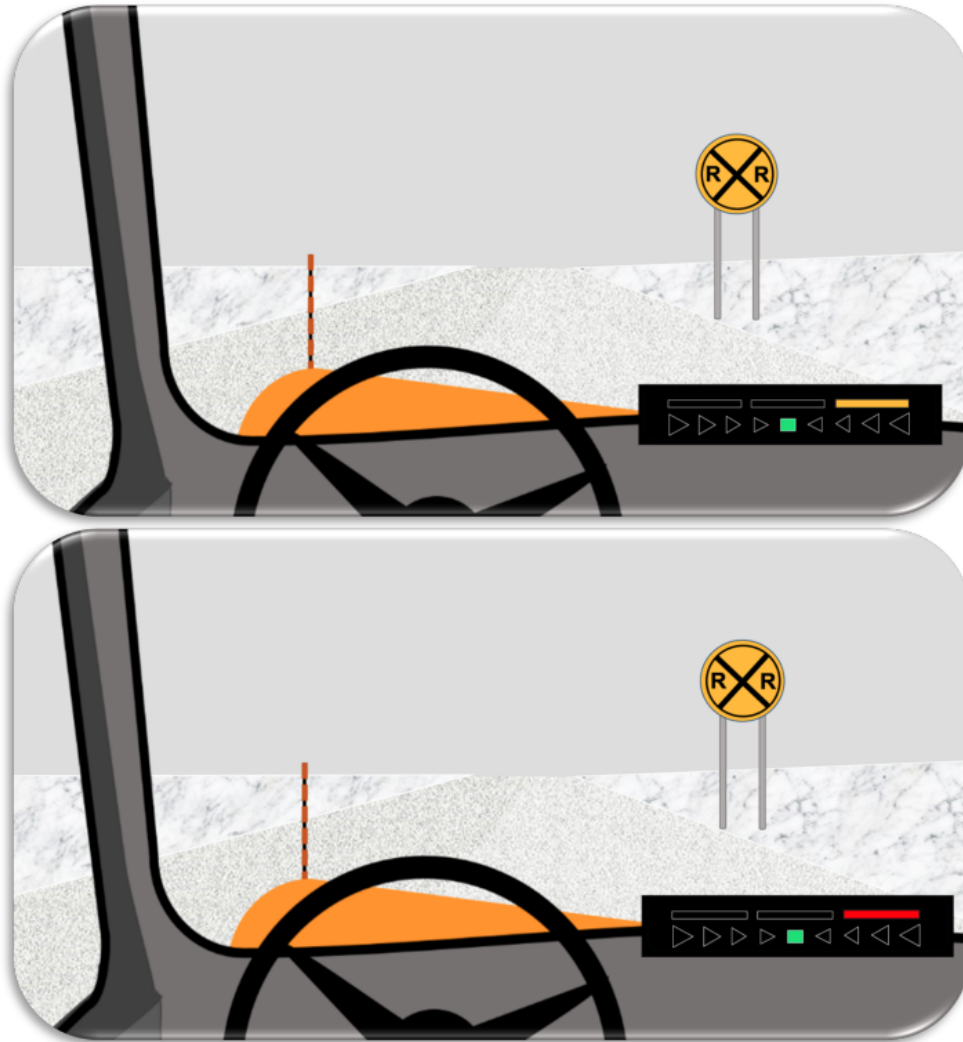
Thank you for your contributions to this research.

Your experiences, feedback, and recommendations will help us continue to make improvements to refine this system to one that optimally supports you during the most challenging winter conditions.

Questions or concerns about the lane guidance system should be sent to Nichole Morris: nlmorris@umn.edu; 612-624-4614
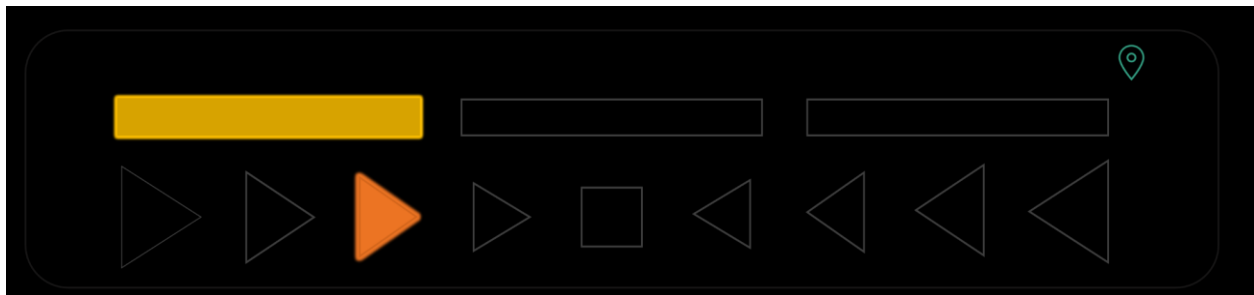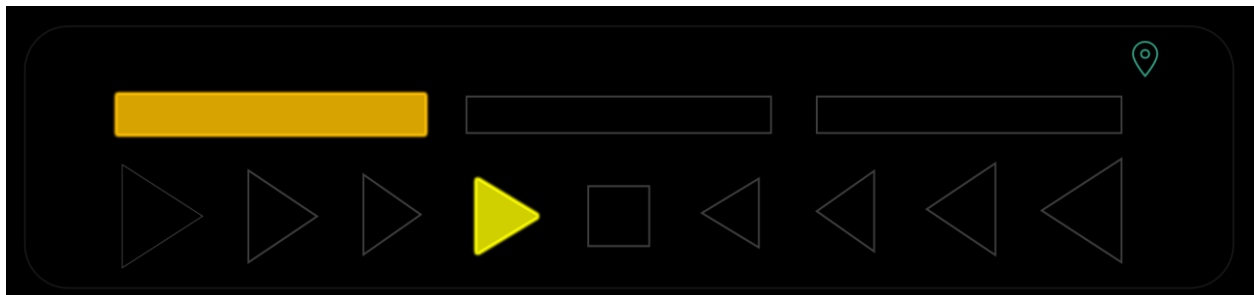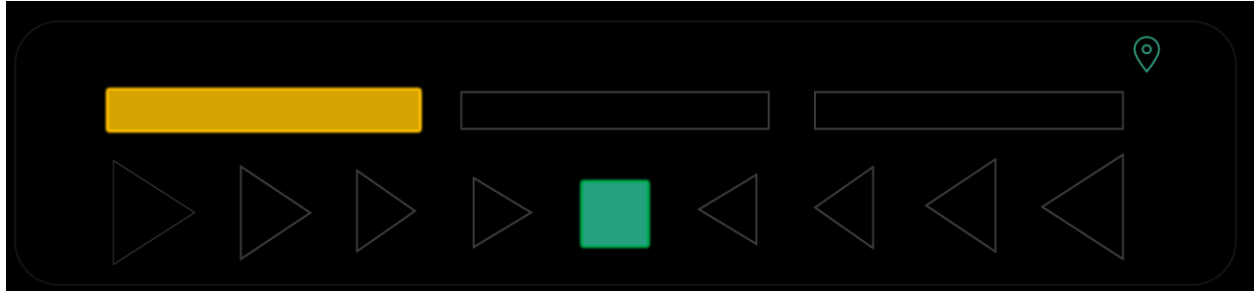
Thank You

M

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APPENDIX F

FINAL DESIGN RECOMMENDATIONS FOR THE LANE BOUNDARY GUIDANCE SYSTEM

The final design of the lateral position information is sequenced as follows: A single indicator indicates the position of the left plow edge relative to the centerline when the left plow edge is on the centerline (green square), one foot to the right or left of the centerline (yellow triangle), and two feet to the right or the left of the centerline (orange triangle).

However, when the left plow edge is three feet to the right or the left of the centerline, the two-foot indicator (i.e., orange triangle) and the three-foot indicator (i.e., red-orange triangle) were displayed. Similarly, when the left plow edge was four feet from the centerline, the two-foot, three-foot, and four-foot (i.e., red triangle) indicators are displayed. Finally, when the left plow edge is greater than four feet to the right or the left of the centerline, the two-foot, three-foot, and four-foot indicators flash simultaneously.