



# Development of Driver Assistance Systems to Support Snowplow Operations

Final Report

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CTS 18-14

**CENTER FOR  
TRANSPORTATION STUDIES**

UNIVERSITY OF MINNESOTA

## Technical Report Documentation Page

1. Report No. CTS 18-14	2.	3. Recipients Accession No.	
4. Title and Subtitle Development of Driver Assistance Systems to Support Snowplow Operations		5. Report Date August 2018	
		6.	
7. Author(s) Chen-Fu Liao, Nichole L. Morris, Jacob Achtemeier, Lee Alexander, Brian Davis, Max Donath, and Gordon Parikh		8. Performing Organization Report No.	
9. Performing Organization Name and Address Department of Mechanical Engineering University of Minnesota 111 Church St. SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS#2016013	
		11. Contract (C) or Grant (G) No. (c) 99008 (wo) 204	
12. Sponsoring Organization Name and Address Center for Transportation Studies University of Minnesota 200 Transportation and Safety Building 511 Washington Ave. SE Minneapolis, MN 55455		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes <a href="http://www.cts.umn.edu/Publications/ResearchReports/">http://www.cts.umn.edu/Publications/ResearchReports/</a>			
16. Abstract (Limit: 250 words) 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. Driver assist systems were considered for 3 applications: gang plowing, backup assist, and lane boundary guidance. We evaluated the system performance and position accuracy of commercially available Dedicated Short Range Communication (DSRC) Onboard Units (OBU) for gang plowing. Our results indicated that the positioning accuracy of the OBUs was inadequate for providing the plow operator with sufficient information to maintain spacing between two vehicles. The backup assist system and lane boundary guidance system were developed and successfully deployed to support snowplow operations. Human factors studies were also conducted using a driving simulator to better understand the needs prior to designing an appropriate Human Machine Interface (HMI) for these plow operations. The radar-based backup assist system was installed on a snowplow that operates on Highway 169. The backup assist system provides an audio warning to the operator to look at the display from a rear-view camera when an object is detected. The Global Navigation Satellite System (GNSS)-based lane boundary guidance system was developed to assist plow operations when visibility is poor and lane boundary cues are limited. The lane boundary guidance system was installed on a second snowplow operating on MN-25 running between Belle Plaine and Green Isle. The lane boundary guidance received the most positive feedback from operators and is recommended for further development.			
17. Document Analysis/Descriptors Driver support systems, Snowplows, Human machine systems, Satellite navigation systems, Global positioning system		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 134	22. Price

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## **August 2018**

Published by:

Center for Transportation Studies

University of Minnesota

200 Transportation and Safety Building

511 Washington Ave. SE

Minneapolis, MN 55455

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## **ACKNOWLEDGMENTS**

The authors would like to thank MnDOT for sponsoring this project. We would like to acknowledge the assistance from the members of the TAP committee (Cory Johnson, John Bieniek, Jay Emerson, Ray Starr, and others) Sue Lodahl and Steve Lund from the Office of Maintenance, Jim Kommer and Jim Northway from the Oakdale truck station, plow operators from the Cedar Ave. truck station, and Bruce Thompson and his staff from the Shakopee truck station.

# TABLE OF CONTENTS

<b>CHAPTER 1: Introduction</b> .....	<b>1</b>
1.1 Connected Vehicles and DSRC.....	2
1.2 Driver Assist Systems.....	3
1.3 Report Organization .....	3
<b>CHAPTER 2: Human Factors Study</b> .....	<b>5</b>
2.1 Introduction.....	5
2.1.1 Part 1 - The HMI for the Operator of a Follower Plow during Gang Plowing .....	5
2.1.2 Part 2 – Interface Display Testing for a Backup Assist System.....	6
2.1.3 Part 3 – An HMI for Lane Boundary Guidance .....	6
2.2 Design and Evaluation of HMI For Gang Plow Operators.....	7
2.2.1 Method.....	8
2.2.2 Results .....	15
2.2.3 Conclusions and Recommendations .....	25
2.3 Interview of Truck Operators Regarding Backup Assist Interface Display .....	26
2.3.1 Participants.....	27
2.3.2 Results .....	31
2.3.3 Overall Themes regarding the Design Options .....	31
2.3.4 Conclusions.....	33
2.4 Simulation Study and Usability Test of Lane Boundary Guidance User Interface.....	34
2.4.1 Lane Boundary Guidance Interface Simulation Study and Usability Test .....	34
2.4.2 Experimental Lane Boundary Guidance System Interface Designs .....	35
2.4.3 Method.....	38
2.4.4 Results .....	42
2.4.5 Conclusions.....	49
2.5 Summary of Findings and Recommendations.....	51

2.5.1 Design and Evaluation of an HMI for the Operator of a Follower Plow in Gang Plowing.....	51
2.5.2 Backup Assist Interface Display.....	51
2.5.3 Lane Boundary Guidance HMI.....	51
2.5.4 Summary .....	52
<b>CHAPTER 3: Evaluation of DSRC OBU to Support Snowplow Operations .....</b>	<b>53</b>
3.1 Evaluation of Relative Position Using DSRC OBU .....	53
3.2 Design and Setup of Experiments.....	55
3.3 Evaluation Methodology .....	58
3.4 Data Collection and Analysis.....	61
3.4.1 Position Accuracy between Two Savari ASD OBUs .....	61
3.4.2 Comparison of Position Error Using Two Vehicles .....	65
3.5 Summary and Discussion .....	72
<b>CHAPTER 4: Radar-Based Backup Assist System .....</b>	<b>74</b>
4.1 System Development.....	74
4.1.1 Introduction.....	74
4.1.2 Delphi ESR Radar .....	75
4.1.3 System Design and Methodology.....	75
4.2 System Installation and Testing.....	77
4.2.1 Scenario #1 .....	79
4.2.2 Scenario #2 .....	79
4.2.3 Scenario #3 .....	79
4.2.4 Scenario #4 .....	80
4.2.5 Scenario #5 .....	80
4.2.6 Scenario #6 .....	80
4.3 Summary .....	81
<b>CHAPTER 5: Lane Boundary Guidance System .....</b>	<b>83</b>
5.1 System Design and Development.....	83

5.1.1 RTK GNSS System .....	84
5.1.2 Digital Map .....	85
5.1.3 LED Display .....	89
5.2 System Installation and Testing on a Plow Truck .....	90
5.3 Summary .....	94
<b>CHAPTER 6: Field Observation and Interviews.....</b>	<b>95</b>
6.1 Observations.....	95
6.1.1 Initial Ride-along.....	95
6.1.2 Second Ride-along.....	96
6.1.3 Third Ride-along .....	98
6.2 Recommendations.....	99
<b>CHAPTER 7: Summary .....</b>	<b>101</b>
7.1 Backup Assist System.....	101
7.2 Lane Boundary Guidance System .....	102
7.3 Future Opportunities .....	103
<b>REFERENCES .....</b>	<b>104</b>
<b>APPENDIX A: System Usability Survey (SUS)</b>	
<b>APPENDIX B: Rating Scale Mental Effort</b>	
<b>APPENDIX C: Two sets of interviews of Maintenance Operators Regarding Backup Assistance</b>	
<b>APPENDIX D: Software Used for Testing the Savari Devices</b>	

# LIST OF FIGURES

- Figure 1.1 V2V subsystem components (from CAMP VSC4 consortium 2014 document)..... 3
- Figure 2.1 Picture of the simulator setup from the driver’s view..... 9
- Figure 2.2 Arrow task states displayed to the user..... 10
- Figure 2.3. System device setup for the initial design. .... 11
- Figure 2.4. Green zone for the initial design..... 12
- Figure 2.5. Yellow zone for the initial design..... 12
- Figure 2.6. Red zone for the initial design. .... 13
- Figure 2.7. Lateral red zone for the initial design. .... 13
- Figure 2.8. System state when the auditory warning occurred for the initial design. .... 14
- Figure 2.9. System state when the haptic warning occurred for the initial design. .... 14
- Figure 2.10. System device setup for the second design..... 16
- Figure 2.11. Green zone for the second design. .... 16
- Figure 2.12. Yellow zone for the second design. .... 17
- Figure 2.13. Red zone for the second design..... 17
- Figure 2.14. Rear left, rear right, and strobe mounted cameras..... 27
- Figure 2.15. Rear-under bed mounted cameras..... 28
- Figure 2.16. Strobe mounted (left) and rear passenger’s (right) camera video interface..... 28
- Figure 2.17. Backup assist interface display mockup design examples (*see Appendix C for additional examples*)..... 29
- Figure 2.18. Mean rankings for system preference..... 31
- Figure 2.19. Mockup of rear view overlay design..... 33
- Figure 2.20. Schematic of LED guidance system..... 36
- Figure 2.21. LED and Laser combination indicating correct lane position. .... 37
- Figure 2.22. LED and Laser combination feedback at the 3ft rightwards lane position. .... 38

Figure 2.23. Simulator plowing route: US14 from Dakota to US61 Winona, MN.....	40
Figure 2.24. Operator perspective of the simulated route without snow cover. ....	41
Figure 2.25. Operator perspective during the simulator plowing exercise using the LED guidance system with the road covered by snow. ....	41
Figure 2.26. Overall Interface Preference Scores. ....	43
Figure 2.27. Interface Satisfaction calculated by operators’ SUS scoring.....	44
Figure 2.28. Operators’ Perceived Mental Effort calculated by RSME scores.....	45
Figure 2.29. Mean Lane Deviation by lane boundary interface guidance system type.....	47
Figure 2.30. Heat map analysis of the eye tracking data - Laser systems based HMI. ....	48
Figure 2.31. Heat map analysis of eye tracking data - LED strip systems based HMI.....	49
Figure 2.32. Mock-up of potential bird’s eye display in conjunction with the LED guidance strip system.....	50
Figure 3.1. In-vehicle system for evaluating OBU performance per vehicle .....	53
Figure 3.2. Installation of RTK & Arada GPS antennas on the rooftop of a passenger vehicle .....	56
Figure 3.3. Installation of Arada & Savari GPS antennas on the rooftop of a passenger vehicle .....	56
Figure 3.4. Installation of Savari GPS antennas on the rooftop of a passenger vehicle .....	57
Figure 3.5. Savari GPS antennas installed in front-back configuration on the rooftop of a passenger vehicle. ....	57
Figure 3.6. Savari GPS antennas installed in left-right configuration on the rooftop of a passenger vehicle. ....	57
Figure 3.7. First Pair of RTK and Savari GPS antennas installed on the rooftop of a passenger vehicle (Impala).....	58
Figure 3.8. Second Pair of RTK and Savari GPS antennas installed on the rooftop of a passenger vehicle (Corolla).....	58
Figure 3.9. Estimated and Actual Locations of 2 GNSS Antennas.....	59
Figure 3.10. Images of three GNSS position test sites (Background image from Google map). ....	62
Figure 3.11. System components of a portable RTK GNSS and DSRC OBU system. ....	65

Figure 3.12. A portable RTK GNSS and DSRC OBU system.....	66
Figure 3.13. Position error of OBU vs. RTK based on vehicle trajectory (traveling SB on Radio Dr near Lake Rd).....	69
Figure 3.14. Position error of OBU vs. RTK based on vehicle trajectory (traveling SB on Radio Dr near Valley Creek Rd). .....	69
Figure 3.15. Schematic diagrams illustrating the difference in relative position error when using and not using RTK as a reference. ....	73
Figure 4.1 A radar based backup assistance system on a pickup truck. ....	74
Figure 4.2 Radar ranging specifications. ....	75
Figure 4.3 System diagram of the backup assist system. ....	76
Figure 4.4 Extended rear view camera for better field of view. ....	76
Figure 4.5 Raspberry Pi 3 computer and speaker. ....	76
Figure 4.6 Backup Assist System Installed on Plow Truck #212570.....	77
Figure 4.7 Location of the Power Switch to Turn on the Backup Assist System.....	77
Figure 4.8 Illustration of a Video Source Select Button. ....	78
Figure 4.9 Test scenarios of the backup assist system at Oakdale station parking lot.....	78
Figure 4.10 T Backup Assist System Installed on Plow Truck #212570 with plow equipment mounted. ...	81
Figure 4.11 Test Backup Assist System at Crossovers on US-169 (10/27/2017). ....	81
Figure 5.1 System diagram of the lane boundary guidance system. ....	84
Figure 5.2 Packaged Lane Boundary Guidance System. ....	84
Figure 5.3 Mapping path for protected right turn lanes.....	86
Figure 5.4 Example of a segment of MN-25 digital map. ....	89
Figure 5.5 States of LED display. ....	89
Figure 5.6 LED display to indicate lateral position correction needed .....	90
Figure 5.7 GNSS antennas installed on plow truck #203560. ....	90
Figure 5.8 Illustration of RTK GNSS and cell modem antennas mounted on the plow, view 1. ....	91

Figure 5.9 Illustration of RTK GNSS and cell modem antennas mounted on the plow, view 2.....	91
Figure 5.10 GNSS antenna mounting configuration on plow truck #203560 (10/13/2017). ....	92
Figure 5.11 LED indication of the lateral position of the plow truck (10/13/2017). ....	93
Figure 5.12 Plow mounted in front of truck #203560 (11/7/2017).....	93
Figure 5.13 Test plow truck on MN-25 (11/7/2017).....	94
Figure 6.1. Image of the lane boundary guidance system mounted in a MnDOT snow plow truck. ....	95
Figure 6.2. Map of the route researchers went on with MnDOT plow operators. ....	96
Figure 6.3 Image of system when plow edge is one foot left of the center line. ....	97
Figure 6.4 Example of possible curve indicator integrated into LED design.....	99

## LIST OF TABLES

Table 2.1. SUS Descriptive Statistics for System Design and Configuration .....	18
Table 2.2. RSME Descriptive Statistics for System Design and Configuration .....	19
Table 2.3. Overall System Preferences .....	19
Table 2.4. Name and Descriptions of Simulation Measures .....	21
Table 2.5. Design 1 Simulation Descriptive Statistics .....	22
Table 2.6. Design 2 Simulation Descriptive Statistics .....	23
Table 2.7. System Usability Scale Mean Scores and Variance. ....	45
Table 2.8. Rating Scale of Mental Effort Mean Scores and Variance.....	45
Table 3.1 List of Experiments Conducted to Evaluate Positioning Performance of DSRC OBUs .....	54
Table 3.2 Results of a Position Error Calculation .....	60
Table 3.3 Relative Position Error from Experiment Conducted on 8/10/2016.....	63
Table 3.4 Relative Position Error from North-South Runs Collected on 9/20/2016.....	63
Table 3.5 Relative Position Error from East-West Runs Collected on 9/20/2016.....	64

Table 3.6 Relative Position Error in Rural Areas Collected on 10/18/2016 .....	64
Table 3.7 Car following configuration of two-vehicle experiments.....	66
Table 3.8 Absolute position error of OBU A on a passenger vehicle (vehicle A - Impala).....	67
Table 3.9 Absolute position error of OBU B on a passenger vehicle (vehicle B - Corolla).....	68
Table 3.10 Relative position error between OBU A and B on two vehicles.....	70
Table 3.11 Absolute position error for each OBU on a separate stationary passenger vehicle.....	71
Table 3.12 Absolute position error of both OBU's on a stationary passenger vehicle (vehicle A - Impala). .....	72
Table 4.1 Test results from scenario #1 .....	79
Table 4.2 Test results from scenario #2 .....	79
Table 4.3 Test results from scenario #3 .....	79
Table 4.4 Test results from scenario #4.....	80
Table 4.5 Test results from scenario #5 .....	80
Table 5.1 RTK GNSS positional solution key.....	85

## LIST OF ABBREVIATIONS

ASD:	Aftermarket Safety Devices
BSM:	Basic Safety Message
CAMP:	Crash Avoidance Metrics Partnership
CORS:	Continuously Operating Reference Station
DAS:	Driver Assist System
DSRC:	Dedicated Short Range Communications
FCC:	Federal Communications Commission
FOV:	Field of View
ft.:	Feet
GNSS:	Global Navigation Satellite System
HMI:	Human-Machine Interface
Lidar:	Light Detection and Ranging
MDSS:	Maintenance Decision Support System
OBE:	Onboard Equipment
OBU:	On-Board Unit
Radar:	Radio Detection and Ranging
RSME:	Rating Scale of Mental Effort
RTK:	Real Time Kinematic
SAE:	Society of Automotive Engineers
SUS:	System Usability Scale
V2I:	Vehicle to Infrastructure
V2V:	Vehicle to Vehicle
VSC:	Vehicle Safety Communications
WAVE:	Wireless Access in Vehicular Environments

## EXECUTIVE SUMMARY

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. Driver assist systems were considered for 3 applications: gang plowing, back-up assist, and lane boundary guidance. The goal of the DAS is to support plow operators in making better decisions and performing their jobs safely and effectively in poor visibility.

Maintaining relative position between and among many vehicles is an important feature of gang plowing operations, in which one truck (or plow) must follow another at a specified position offset. Maintaining relative position (both lateral and longitudinal) is critical. The operator of the “follower” vehicle must receive appropriate and reliable feedback so that correct spacing and relative speed is maintained.

Following a series of interviews with snow operators, a human-machine interface (HMI) design for gang plow operations, backup assist, and lane boundary guidance applications was developed and tested using a driving simulator.

For gang plowing, we evaluated the system performance and position accuracy of Onboard Units (OBU) commercially available in 2015-16 used in a Vehicle-to-Vehicle (V2V) application for coordinated and cooperative operations of vehicles in close proximity, typical of many maintenance activities. Our test results indicated that the positioning solution from the OBUs was insufficient for providing the plow operator with adequate information needed to maintain the spacing between two vehicles.

As we were completing the tests of the V2V system, we learned from the Metro District maintenance staff that they were interested in plow operators being informed of the position of the edge line of a road boundary while performing the snow removal task, particularly when visibility is limited. In an additional request, the maintenance staff wanted the plow operator to be able to detect a vehicle behind the truck during backup. As a result, the scope of our study was modified to include developing methodologies to address the needs of lane boundary guidance and backup assistance for a snowplow.

Two driver assist systems (DAS), a backup assist system and a lane boundary guidance system, were then developed to support snowplow operations. Human factors studies were conducted to better understand the needs prior to designing an appropriate HMI for plow operations. Several HMI designs were tested using the driving simulator for both applications.

A radar-based backup assist system was initially tested on a pickup truck. It was then installed on a snowplow (#212570) that operates on Highway 169. The backup assist system provides an audio warning to the operator to look at the display from a rear-view camera when an object is detected. The system uses a 1-Hz audio feedback to alert the operator when the plow truck is backing up to an object within less than 10 m of range (which is programmable). The frequency of the alerting tone increases to 2-Hz when an object is less than 5 m behind the truck.

The backup assist system includes a switch located in the cab to allow the operator to turn the system on/off because operators were worried that the radar might trigger false alarms and the alerting tone would become annoying. Based on the feedback from the operators, we increased the radar detection range from 10 m to 20 m for the 1-Hz warning and from 5 m to 10 m for the 2-Hz alerting tone. The test results indicate that the units met their technical specifications but the sand/salt spinner partially blocks the field of view (FOV) of the radar sensor. The plow operators felt that their ability to handle crossover operations was met by extending the rear-view camera without the use of a rear-facing radar.

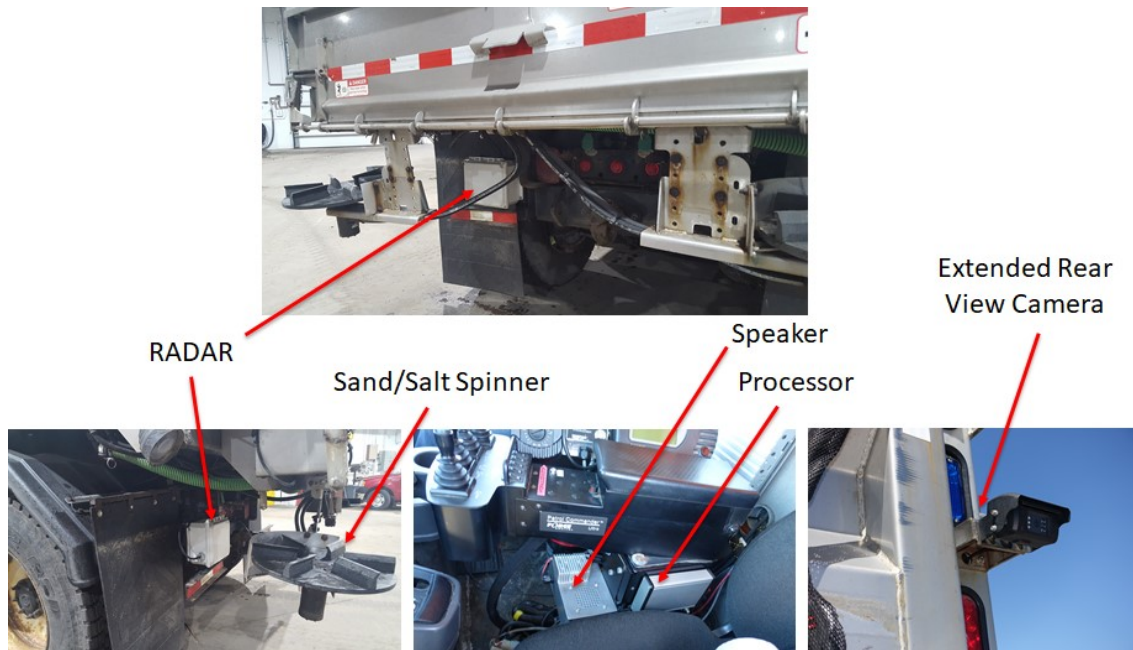


Figure ES.1 Backup assist system

A Global Navigation Satellite System (GNSS)-based lane boundary guidance system was developed to assist plow operations when visibility is poor and lane boundary cues are limited. The lane boundary guidance system was installed on a passenger vehicle for testing. It was later installed on a second snowplow (#203560) operating on MN-25 running between Belle Plaine and Green Isle. The system included an RTK GNSS system, an in-vehicle LED display (Figure ES.2), a digital map, and a single board processor. The system provides lateral position information (using a programmable look-ahead distance) to advise plow operators to correct their lane position in whiteout conditions. Output from this system is displayed using an LED strip with colored icons indicating whether the driver is centered in the lane or if steering adjustments should be made. All electronic components, except the LED display and antennas, were attached to an aluminum plate so that the system could easily be mounted behind the driver's seat and could be transferred from truck to truck if needed.

We worked with maintenance operators at the Shakopee truck station to conduct several tests on both plow trucks in the field to evaluate system performance and collect driver feedback on the LED design. The plow operators provided several recommendations to enhance the LED display by making the LED

indication dimmable, preferably with a dial knob to adjust brightness manually. The other recommendation was to remove the blinking red triangle on both ends used to indicate when the truck was outside the digital map coverage. The blinking red indication was removed.



**Figure ES.2 LED indication of the lane boundary guidance system**

Field observation and interviews for the lane boundary guidance system were conducted to evaluate the system performance and usefulness. Researchers rode along with operators during inclement snow conditions as well as conducted interviews with multiple operators and supervisors regarding the lane boundary guidance system. The purpose of the ride-along was to gather user feedback on the features of the interface and its functions while driving. Operators felt that they were more efficient with the lane guidance system as they were able to remove snow in one pass rather than having to come back and take care of missed snow. Based on the field observations of snowplow operators using the lane guidance system, the research team made several recommendations for modification and further testing of the system.

- Design a dimmable option for the LED interface to minimize discomfort or difficulty in seeing the LED strip under different day and night conditions.
- Design and test modification of the LED intensity within each color to account for the Purkinje Shift.
- Integrate a simple curve-ahead notification into the design to alert drivers of curves ahead while driving in white-out conditions.

- Test alternative placement of the LED system on the dash along with other modifications. For example, programmed look ahead distances should be examined in future studies to be conducted both in a driving simulator and in the field.

## CHAPTER 1: INTRODUCTION

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. Driver assist systems were considered for 3 applications: gang plowing, back-up assist, and lane boundary guidance. The goal of the DAS is to support plow operators in making better decisions and performing their jobs safely and effectively in poor visibility.

Maintaining relative position between and among many vehicles is an important feature of gang plowing operations, in which one truck (or plow) must follow another at a specified position offset. Maintaining relative position (both lateral and longitudinal) is critical. The operator of the “follower” vehicle must receive appropriate and reliable feedback so that correct spacing and relative speed is maintained.

High speed, low latency wireless communication of vehicle position is a critical element of the Connected Vehicles program of the USDOT. Many safety, traffic and operational applications based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication using Dedicated Short Range Communication (DSRC) have been in development for some time. Vehicle Onboard Equipment (OBE), which combines DSRC communications and position sensing, was coming to market when the project started. For many of the applications to work, the system’s position accuracy must be sufficient to locate each vehicle within a lane.

For gang plowing, we evaluated the system performance and position accuracy of Onboard Units (OBU) commercially available in 2015-16 used in a Vehicle-to-Vehicle (V2V) application for coordinated and cooperative operations of vehicles in close proximity, typical of many maintenance activities.

As we were completing the tests of the V2V system, we learned from the Metro District maintenance staff that they were interested in plow operators being informed of the position of the edge line of a road boundary while performing the snow removal task, particularly when visibility is limited. In an additional request, the maintenance staff wanted the plow operator to be able to detect a vehicle behind the truck during backup. As a result, the scope of our study was modified to include developing methodologies to address the needs of lane boundary guidance and rear vehicle detection for a snowplow.

Two driver assist systems (DAS), a backup assist system and a lane boundary guidance system, were then developed to support snowplow operations. Human factors studies were conducted to better understand the needs prior to designing an appropriate Human-Machine Interface (HMI) for plow operations. Several HMI designs were tested using the driving simulator.

## 1.1 CONNECTED VEHICLES AND DSRC

The U.S. Department of Transportation's (USDOT's) Connected Vehicle program has for several years been working on technology that would enable cars, buses, trucks, trains, roads and other infrastructure and smartphones and other mobile devices to “talk” to one another. Cars on the highway, for example, would use short-range radio signals to communicate with each other so every vehicle on the road would be aware of where other nearby vehicles are located.

As part of this program, many safety and traffic operations applications based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication were developed. In particular, a band of frequencies, known as Dedicated Short Range Communication (DSRC) was dedicated for this purpose. Originally allocated by the Federal Communications Commission (FCC) in 1999, DSRC usually refers to 75MHz of spectrum surrounding 5.9GHz, i.e. 5.850-5.925GHz. Protocols to take advantage of DSRC were integrated into an established standard, known as the IEEE 802.11p (Wireless Access in Vehicular Environments – WAVE).

For many of these safety applications to work, the system's position accuracy must be sufficient to locate each vehicle within a lane. An extensive qualifications process was developed by the USDOT. Technology vendors that met these standards were “certified.” Meeting one “standard” established by one test, however, does not necessarily mean that it will meet the needs of every application and every environment.

Standards for on-board vehicle-to-vehicle (V2V) safety communications systems were developed. These systems must be capable of transmitting the Society of Automotive Engineers (SAE) J2735 defined Basic Safety Message (BSM). Commercially available vehicle onboard devices are supposed to provide the component capabilities defined as OBE in Figure 1. The more standard term used now is the On-Board Unit (OBU) rather than On-Board Equipment (OBE.) Aftermarket Safety Devices (ASD) also incorporate a Driver Vehicle Interface (DVI) to provide warnings to the driver. The in-vehicle ASD is supposed to be capable of sending and receiving the safety messages over a DSRC wireless communications link. The ASD is intended to include a driver interface, runs V2V and V2I safety applications, and issues audible or visual warnings and/or alerts to vehicle operators. The DVI can also be called the Human Machine Interface (HMI).

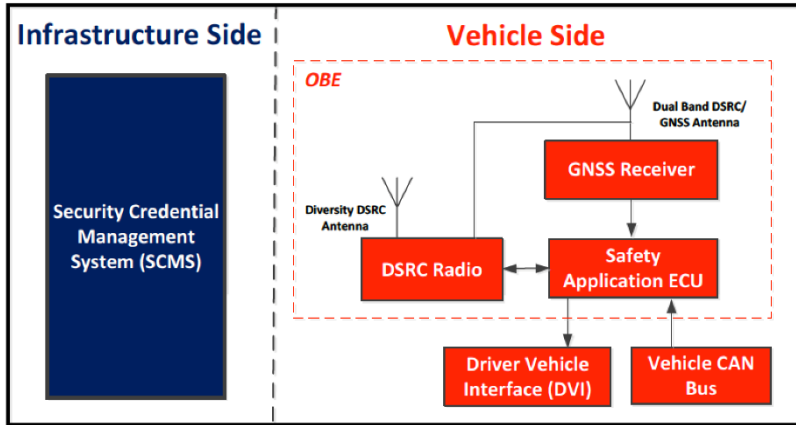


Figure 1.1 V2V subsystem components (from CAMP VSC4 consortium 2014 document)

## 1.2 DRIVER ASSIST SYSTEMS

Based on our conversations with MnDOT staff in September 2016, they agreed that a backup assist system would be very helpful when snowplow operators are clearing crossovers on Highway 169, since operators frequently need to back up without having a clear view behind them. However, these operators do not have problems with lane boundary detection on Highway 169. A lane boundary guidance system would be more helpful on Highway 25 running from Belle Plaine to Green Isle, because operators there typically experience poor visibility and get few lane boundary cues (e.g., guard rails) on this route. Highway 25 is a roadway with one lane in each direction.

We designed and developed two driver assist system (DAS) prototypes to support snowplow operations. We also developed a high-accuracy digital map of the lane boundaries for the lane boundary guidance test site (MN-25) to provide feedback to the operators. An RTK Global Navigation Satellite System (GNSS) was used on a test vehicle to determine its location, referenced to the digital map, in order to provide lane keeping guidance to the operator. For the backup assist system, we developed a radar-based system that generates an audible warning when an object is behind the plow truck. The audible alert directs the operator to look at a rear-camera display. The mount for the existing rear view camera on the snowplow was extended to provide a better field of view.

A 2012 model truck (#212570) was used on Hwy 169 to test and demonstrate the backup assistance application. Another 2003 model truck (#203560) was used on Hwy 25 for studying the lane boundary guidance application.

## 1.3 REPORT ORGANIZATION

In Chapter 2, we describe the interviews with maintenance operators regarding gang-plow operations and the design of the Human-Machine Interface (HMI) for the gang plowing, backup assist and lane boundary guidance systems. In Chapter 3, we describe the experiments used to evaluate the system

performance and position accuracy of the Global Navigation Satellite System (GNSS) used on two sets of DSRC OBUs that were commercially available from two different vendors in 2015-16. System development and testing of a radar-based backup assist system and of a lane boundary guidance system are discussed in Chapters 4 and 5, respectively. Results from field observation and interviews with plow operators are presented in Chapter 6. In Chapter 7, we summarize the results from our tests of the radar-based backup assist system and the lane boundary guidance system and make recommendations.

## CHAPTER 2: HUMAN FACTORS STUDY

### 2.1 INTRODUCTION

In this chapter, three human factors studies are described. The first examines the effectiveness of a human machine interface (HMI) given operators' input regarding how the operator controlling the following snow plow should receive information regarding the lead snow plow during gangplow operations (Chapter 2.2). The second study describes the development and user testing of possible interface display options for a backup assist system (Chapter 2.3). The third study describes a driving simulator-based assessment and usability testing of five HMI technologies to assist snow plow operators with locating and maintaining the plow edge position during white-out conditions (Chapter 2.4). The Chapter then concludes with a summary of findings and recommendations (Chapter 2.5).

#### 2.1.1 Part 1 - The HMI for the Operator of a Follower Plow during Gang Plowing

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##### 2.1.1.1 Design and Evaluation of Human-Machine Interfaces

The design and evaluation of an HMI for operators of a follower plow, included gathering user feedback via usability testing and driving simulator trials, and analyses of the results to select an HMI system for implementation in snow plows. Researchers recruited MnDOT snow plow operators to engage in simulated snow plow driving scenarios using a driving simulator at the University of Minnesota's HumanFIRST Laboratory. During the human factors assessments, plow operators performed a series of simulated low-visibility gang plowing operations using each of the six experimental HMI designs, which provided positioning feedback of the operator's location relative to a lead plow truck. Following an initial testing session with six operators, researchers redesigned the HMI systems based on operators' feedback and recruited an additional six operators to assess the refined HMI systems. In addition to examining plowing performance, researchers collected operators' feedback on best practices of where to position an HMI system and to consider various HMI design features (e.g. auditory tones, color-based notifications).

Snow plow operators reported experiencing the least amount of mental effort exertion and general ease of use using the interface which coupled color feedback and auditory messages. In addition, these interfaces were highly ranked by operators at the conclusion of the study, suggesting promising results for future efforts in implementing the system. This report describes an iterative approach to evaluating and redesign of the HMI. Participants were asked where they would place the system display in their plow. Most of the participants did not want another display screen in their truck. Consequently, most of the participants recommended that the system be integrated into the Maintenance Decision Support System (MDSS) screen ( $n = 7$ ). If the display is not integrated with the MDSS screen, participants recommended that the display should be placed at a location that can be seen using peripheral vision without moving the driver's eyes off the road ( $n = 4$ ). Some thought that the left pillar in the truck, similar to how the display was positioned during the simulation, would be a desirable position for the

display ( $n = 3$ ). Furthermore, two participants recommended that the display be placed in the center of the dashboard ( $n = 2$ ).

#### 2.1.1.2 Objectives

Research objectives for the design of the gang plowing assistive technology HMI system included maximizing operator plowing performance, designing the interface to bolster user support and usability qualities (e.g. ease of use), and reducing plow operator mental workload and stress levels during gang plow operations. A user-centered design approach was used to ensure research objectives and research goals were met.

### **2.1.2 Part 2 – Interface Display Testing for a Backup Assist System**

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#### 2.1.2.1 Interview of Maintenance Operators Regarding Backup Assist Interface Display

The second study described in this chapter details the user-centered design process and development of a rear vision system interface and radar-based positioning system for providing backup assist to plow truck operators. The purpose of the human factors backup assist interface display study was to assess operator opinions on possible features of a visual interface to provide information about objects behind the truck (e.g. other plow vehicles, approaching traffic) to bolster operators' situational awareness of the rearward roadway during backing, but also considered forward driving scenarios. This study considered possible technologies to provide the information (i.e., rear cameras and radar systems) but focused more on the end user experience rather than the system design or components. Researchers developed a total of four experimental visual interfaces that displayed rear views in order to select a candidate system based on operator feedback and usability testing. The research team interviewed MnDOT plow operators at their maintenance stations to complete the research objectives.

#### 2.1.2.2 Objectives

The research objectives for the Backup Assist Interface Display study included the design and usability testing of four candidate rear-view vision systems, and finalizing a candidate rear view interface design by conducting interviews vetted by snow plow operators. Snow plow operator feedback was solicited at truck stations across the greater Minneapolis- St. Paul metro area through a series of interviews and usability testing procedures. In addition to developing an effective HMI system, researchers were focused on collecting qualitative data from plow operators relevant to usability characteristics to ensure plow operator satisfaction using the system, while also bolstering system usefulness and efficacy during plow operations.

### **2.1.3 Part 3 – An HMI for Lane Boundary Guidance**

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#### 2.1.3.1 Lane Boundary Guidance Interface Simulation Study and Usability Test

In the third human-computer interface design study, five supplemental technologies to aid operators' performance in identifying, acquiring plow edge position, and maintaining headway on roadway lane

boundaries were studied with MNDOT plow operators. This study examined the efficacy of visual feedback systems' in mitigating plow operator effort locating lane boundaries in the context of white-out or visibility-adverse environments during plow operations. Researchers assessed snow plow operator driving performance, defined as the ability to maintain plowing position with respect to the right lane boundary of a snow-covered road in the simulator environment. Additionally, researchers quantified plow operator visual attention via eye-tracking data recording in order to characterize plow operators' visual attention patterns while using each of the lane boundary guidance interfaces. To ensure each interface design maintained high usability standards, researchers conducted usability testing exercises to determine the most appropriate interface suitable for high-stress, demanding adverse plowing environments.

#### 2.1.3.2 Objectives

The research objectives for the Lane Boundary Guidance User Interface assessment were based on three major criteria: (1) Create a realistic driving simulator environment in which snow plow operators could perform right-lane plowing operation, (2) Examine plow operators' performance in lane-keeping accuracy, average speed, eye tracking and visual attention; (3) Solicit plow operator feedback on each lane boundary guidance interface, including subjective metrics which included: reported mental workload, system usability scoring and characteristics, and qualitative interface traits to ensure candidate interfaces featured high scoring usability while also demonstrating improved lane boundary guidance to the plow operators.

## 2.2 DESIGN AND EVALUATION OF HMI FOR GANG PLOW OPERATORS

The design and evaluation of a Human-Machine Interfaces (HMI) for snow plow operators driving a truck following a lead plow truck involved designing the HMI, gathering user feedback via usability testing and driving simulator trials, and interpretative analysis of study results in order to evaluate the potential end-product HMI for implementation in trucks used for gang plowing. In this study, HumanFIRST researchers met with MnDOT snow plow operators at the University of Minnesota to evaluate plow operators' plowing performance using the HMI system, as well as to solicit their expert opinion regarding design characteristics of the system by which to improve the HMI design. To ensure that design characteristics and interface functionality were appropriate and tailored to the users, HumanFIRST researchers recruited 12 local snow plow operators from various MnDOT locations. Each driver participated in a series of simulated snow plow drives using the gang plowing system design. The first 6 drivers used the initial design of the system and provided feedback on the design, usability, and preference for information displayed (i.e., color, haptic, audio feedback).

After assessing feedback from the first 6 participants, the interface was redesigned to make it easier to understand and use and to address any issues found during initial testing. The revisions made to the original interface design included refinement of the auditory tone, visual interface feature restructuring, and color-based information for communicating distance to the lead plow truck. Then, the final 6 drivers used the new design in the simulated drives to evaluate if the issues with the original design were fixed,

and to ensure that new issues were not introduced. Snow plow operators reported experiencing the least amount of mental effort exertion and general ease of use feedback using the interface which coupled color feedback and auditory messages. In addition, these interfaces were highly ranked by operators at the conclusion of the study, suggesting promising results for future efforts in implementing the system. This report describes the iterative approach to evaluate and redesign the gang plow HMI.

## 2.2.1 Method

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### 2.2.1.1 Participants

The participants were males ( $n = 11$ ) and one female ( $n=1$ ) between the ages of 33 and 59 ( $M = 47.33$ ,  $SD = 7.64$ ) and worked for MnDOT as transportation professionals. They had between 1 and 31 years of experience ( $M = 14.54$ ,  $SD = 8.55$ ) driving a snow plow. Participants received their driver's license between 18 and 42 years ago ( $M = 29.55$ ,  $SD = 9.02$ ). Most of the participants drove over 20,000 miles in the past year ( $n = 6$ ), a few drove between 15,000 and 20,000 miles ( $n=3$ ), one drove between 10,000 and 15,000 miles ( $n = 1$ ), and some drove between 5,000 and 10,000 miles ( $n = 2$ ). Most of the participants frequently drive on highways ( $n = 12$ ), main roads ( $n = 12$ ), urban road ( $n = 10$ ), and country roads ( $n = 6$ ). None of the drivers reported being at fault for any minor or major road accidents within the last three years. Further, none of the drivers had been convicted for speeding, careless or dangerous driving, or driving under the influence within the last three years. The majority of the participants drove a pick-up truck most often ( $n = 8$ ), while some typically drove a sports utility vehicle ( $n = 3$ ), a passenger car ( $n = 2$ ), or a motorcycle ( $n = 1$ ). Participants frequently interacted with smartphones ( $n = 10$ ), Bluetooth devices ( $n = 4$ ), tablets ( $n = 2$ ), and navigation systems ( $n = 1$ ).

Color vision was tested using the Ishihara Color Vision Test. Most of the participants had normal color vision ( $n = 11$ ), while one had red-green color deficiency ( $n = 1$ ). Since the display uses color-coding to display information, it was designed so that the colors also varied in luminance (i.e., green is the lowest luminance, yellow is middle luminance, and red is the highest luminance) to add message redundancy. The color deficient participant reported that he could easily distinguish between the different colored portions of the interface and the meaning of each section of color. To assess participant well-being after the simulation, each participant filled out a Wellness Assessment Questionnaire. The Wellness Assessment Questionnaire asked the participant to circle the symptoms that were affecting them immediately after the simulation. Most of the participants reported no symptoms ( $n = 11$ ). However, one participant reported having a slight headache and fullness of the head ( $n = 1$ ).

### 2.2.1.2 Procedure

A driving simulation was designed to simulate low visibility conditions similar to what a snow plow driver might experience during a significant snow event. In the simulation, the participant drove behind the lead plow on a simulated version of US-169 between Jordan and Belle Plaine, MN. The road was completely covered with snow and atmospheric conditions were simulated to have limited visibility of 30m, created through decreased contrast sensitivity and limited particle occlusion. The lead plow

traveled at an average of 35 mph, increasing and decreasing in speed by approximately 5 mph to increase the difficulty of the task. The lead plow also traveled in a right to left sinusoidal pattern. An orange, vertical post was presented in the screen to denote the position of the end of their front plow, in lieu of other 3-dimensional distance cues.



**Figure 2.1** Picture of the simulator setup from the driver's view.

When the participant arrived in the laboratory room an experimenter described the study, obtained written consent, and began the study. First, each operator performed a practice drive to become familiar with the acceleration and braking maneuvers in the simulator. They were asked to follow the lead plow in a tight formation, following as closely but safely as possible. During the practice, the driver learned to perform an arrow task used to simulate a task that might distract them from driving, similar to managing the radio or the Maintenance Decision Support System (MDSS). The arrow task presented a three-by-three matrix of arrows. When the task begins, each arrow spins and randomly points either up, down, left, or right. The driver's task is to count the number of arrows in the surrounding matrix that match the center arrow and report the outcome on a touch pad. Then, the arrows are colored green to indicate a correct response, or red to indicate an incorrect response. Finally, the arrows re-spin to a new, random direction. The driver was given unlimited time to respond to each arrow task and told to perform the arrow task whenever they felt comfortable during the drive. See Figure 2.2 below for a picture of the arrow task.

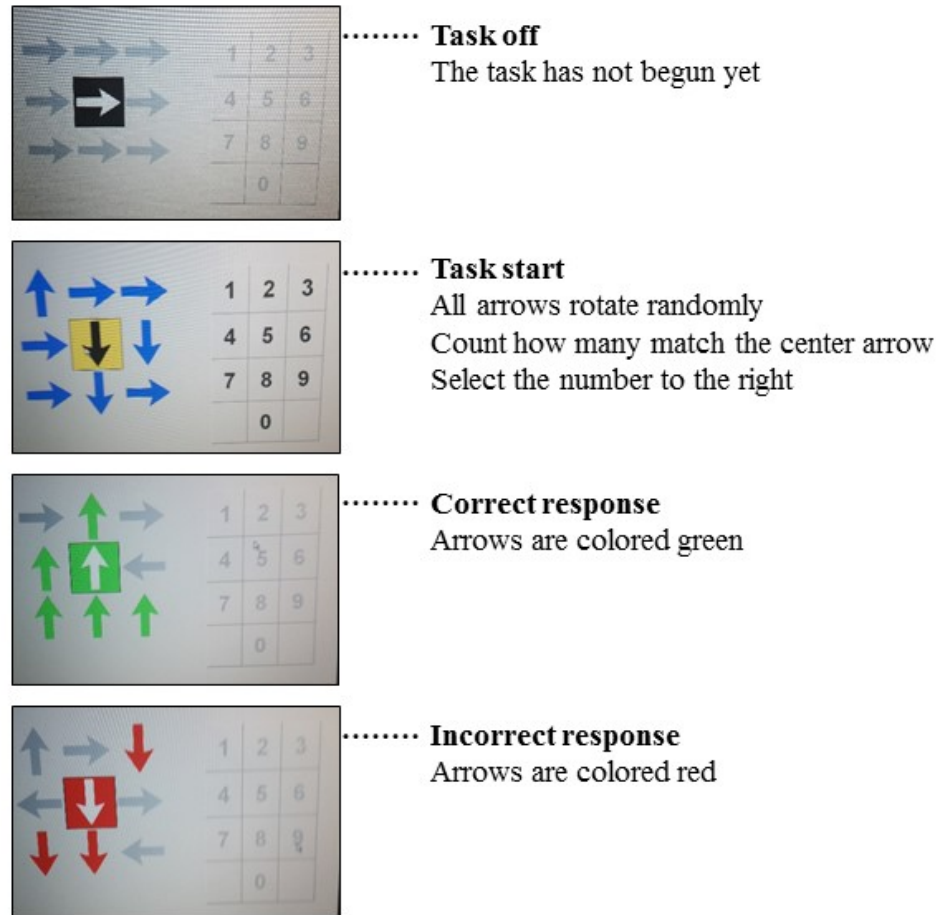


Figure 2.2 Arrow task states displayed to the user.

Next, each driver performed a series of six drives. The six drive types were selected based on driver feedback from interviews and initial piloting of the simulation. Each drive was identical, but the system configuration presented to the driver was changed in each drive. Specifically, the interface presented for each drive included the following combinations:

- A color display only
- A color display with haptic feedback
- A color display with auditory feedback
- Haptic feedback only
- Auditory feedback only
- A control drive with no display or feedback

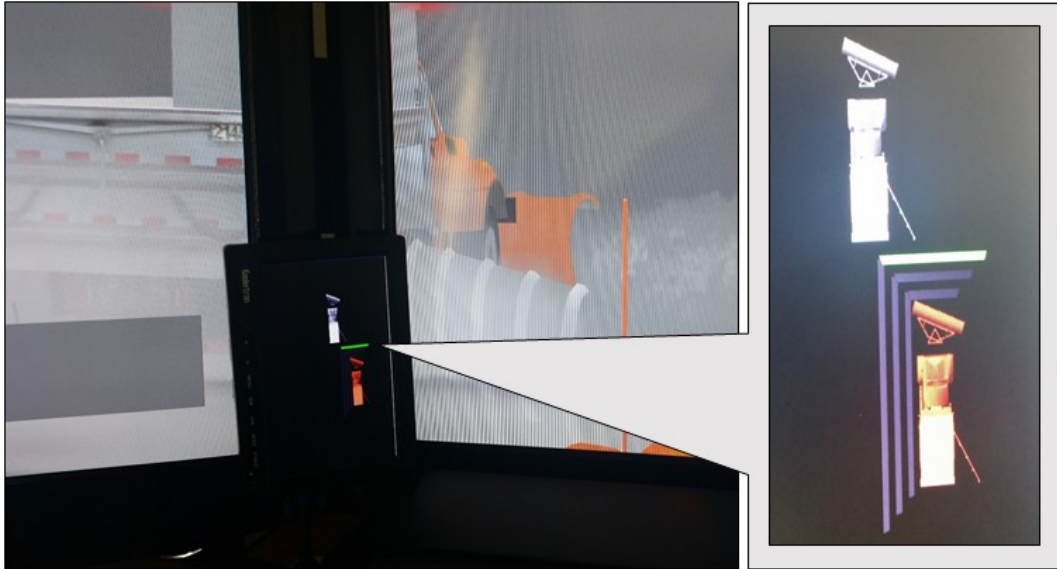
The order of the interfaces were counterbalanced using a Latin square. The color display presented an image of the driver's plow and an image of the lead plow truck. The driver's plow stayed in one location, while the lead plow truck moved onscreen in relation to the driver's plow. For example, if the lead plow was directly in front of the participant's plow, then the display would show the lead plow in front of the

driver's plow on screen. If the driver steered to the right of the lead plow, then the display would show the lead plow to the left of the participant's plow. This initial design was based on previous interview responses from MnDOT drivers and was intended to display a birds-eye view of the trucks and present information about the distance between the two vehicles. The initial design of the color display is surrounded in a yellow box in Figure 2.3 below.



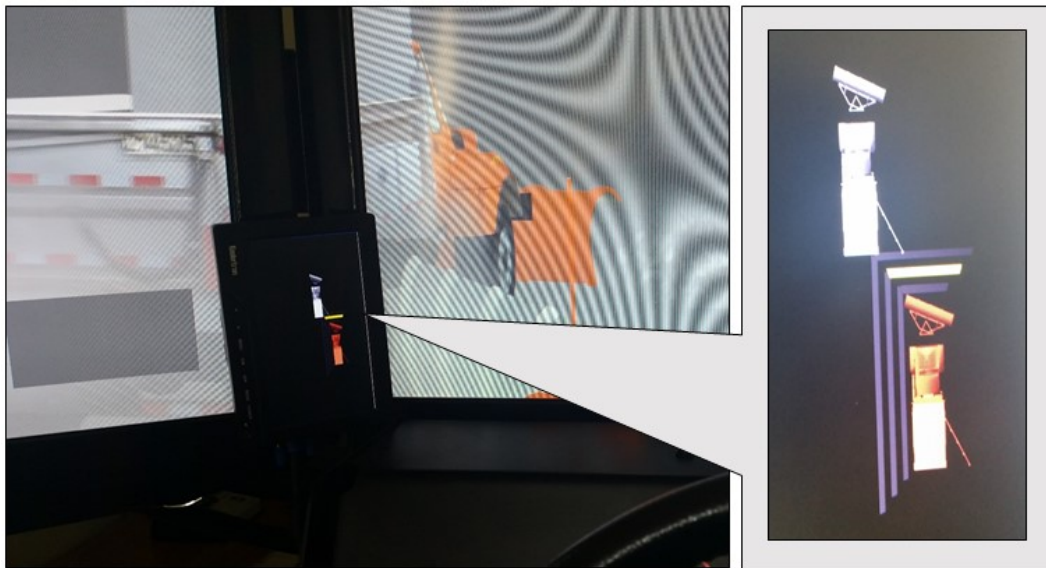
**Figure 2.3. System device setup for the initial design.**

For the color information, a set of zones was added to display feedback about how far the driver was from the lead plow. In the original design, the outermost zone changed to a green color when the trucks were between 8.1 to 12 ft. from one another to indicate a safe and optimal distance from the lead plow. See Figure 2.4 below for an example of the green zone.



**Figure 2.4. Green zone for the initial design.**

The middle zone changed to a yellow color when the trucks were between 4.1 and 8 ft. from one another to indicate that the driver should be cautious about their proximity to the lead plow. See Figure 2.5 below for an example of the yellow zone.



**Figure 2.5. Yellow zone for the initial design.**

Finally, the innermost zone changed to a red color when the trucks were between 0.1 and 4 ft. from one another to indicate that the driver is dangerously close to wing on the lead plow. See Figure 2.6 below for an example of the red zone.

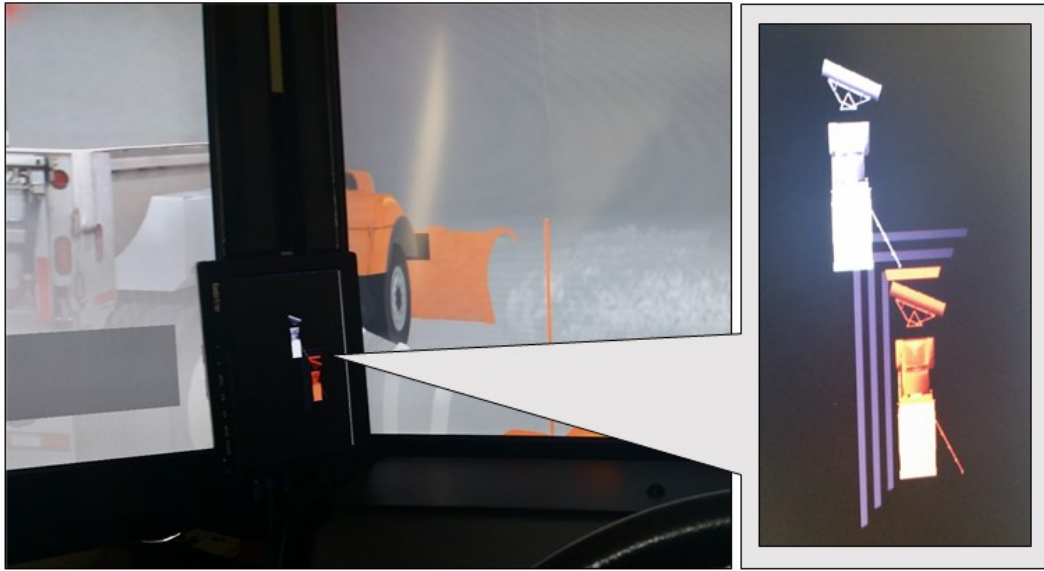


Figure 2.6. Red zone for the initial design.

If the driver's truck was too close to the lead truck on the left side, the left-side bars changed red to indicate that lateral distance was too close. See Figure 2.7 below for an example of the lateral red zone.



Figure 2.7. Lateral red zone for the initial design.

Distance between the plow trucks was calculated from the front of the driver's plow to the tip of the side wing on the lead plow. In the auditory feedback conditions, the speakers in the interface would beep 4 times to indicate that the driver was between 0.1 to 4 ft. from the lead plow. See Figure 2.8 below for an example of the system state when an auditory warning would occur.

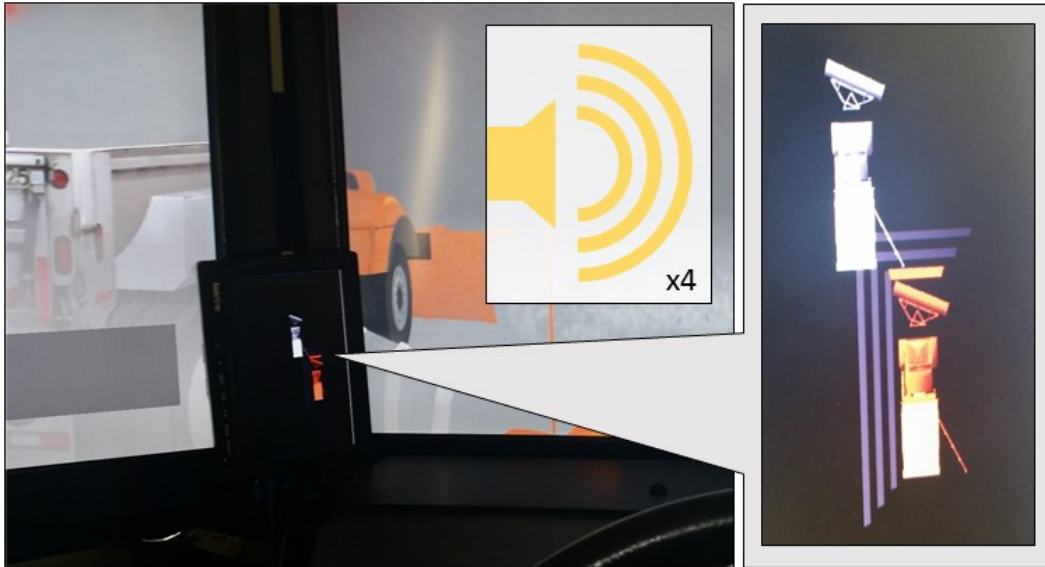


Figure 2.8. System state when the auditory warning occurred for the initial design.

In the haptic feedback conditions, the driver's seat pan would vibrate at 40 Hz for 1 second to indicate that the driver was between 0.1 to 4 ft. from the lead plow. See Figure 2.9 below for an example of the system state when a haptic warning would occur.

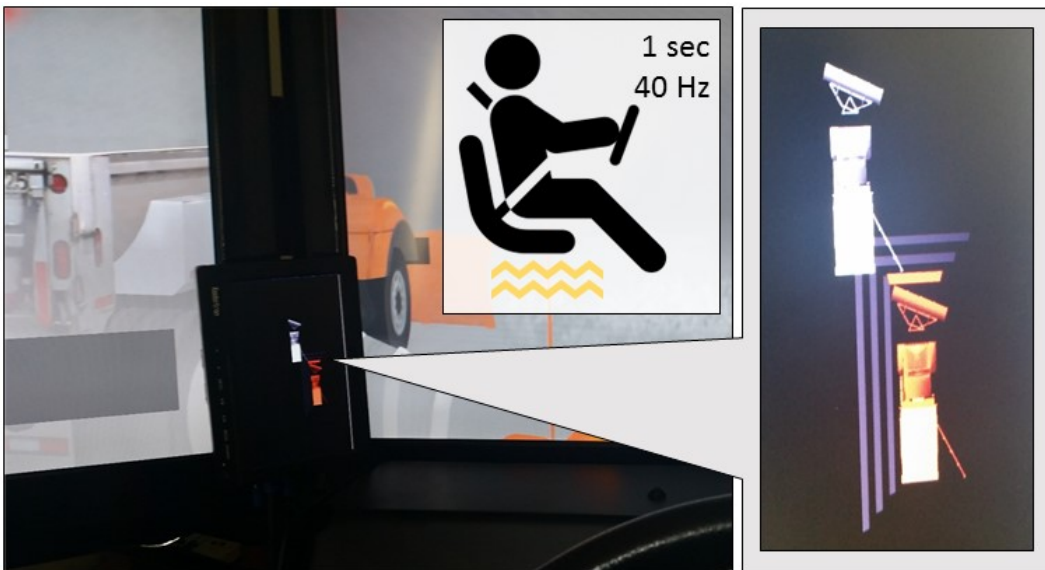


Figure 2.9. System state when the haptic warning occurred for the initial design.

During the drives with the color display and feedback, the driver would see the innermost zone turn red at the same time that they received either auditory or haptic feedback.

## 2.2.2 Results

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### 2.2.2.1 Initial Design

The following themes represent participant comments and feedback about the initial design of the system during the initial six participants.

1. Participants thought the tone would be confusable with other tones in the truck. Tones will compete for many other noises (e.g., wind, engine, dicky john, MDSS noise, radio).
  - *Recommendation:* If a tone is used, it needs to be unique compared to the other tones in the vehicle.
2. Participants requested larger green, yellow, and red zones.
  - *Recommendation:* enlarge the zones and zoom in the display.
3. Participants noted that the display seemed cluttered and contained irrelevant information.
  - *Recommendation:* Change some features to make it less cluttered and easier to understand at a glance (e.g., remove gray bars on left side, remove arrow for off-screen lead plow).
4. Participants wanted to know the distances for the red, yellow, green zones.
  - *Recommendation:* Train users or give distance information on screen.

### 2.2.2.2 System Redesign

After the initial study, the interface was redesigned to account for the design and usability issues identified from the driver feedback. First, the scale of the display was increased to make it easier for the driver to see the color information without having to constantly watch the screen. Then, the color information on the left side of the driver's truck was removed because it was widely regarded as irrelevant and seemed to unnecessarily clutter the display. The second design of the color display is highlighted in a yellow box in the Figure 2.10 below.

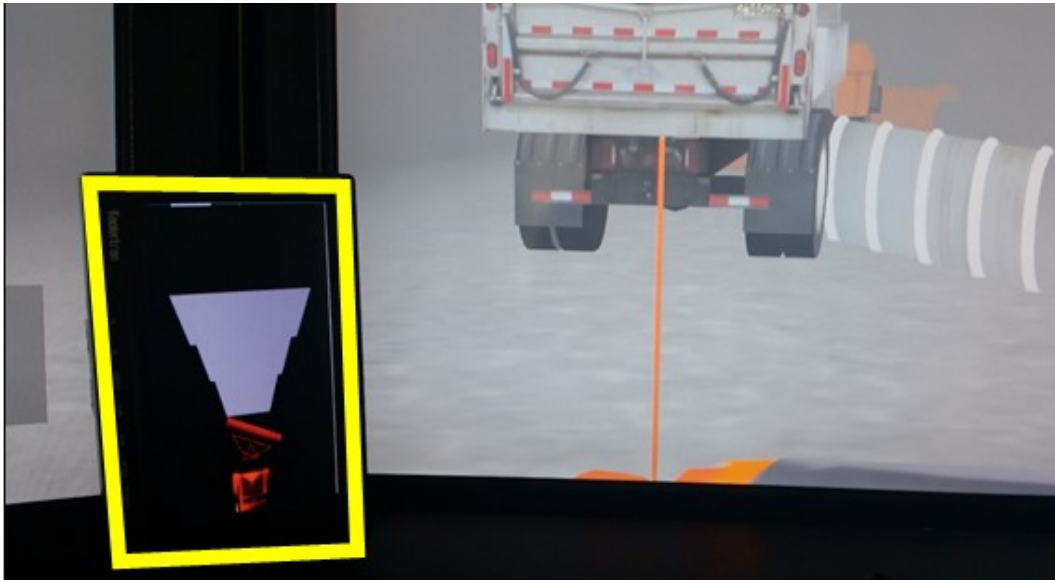


Figure 2.10. System device setup for the second design.

After removing clutter, the zone distances were changed based on user feedback. The green zone was changed to 12.1 to 20 ft. (previously 8.1 to 12 ft.) to indicate a safe distance from the lead plow. This larger zone was hypothesized to not only be easier to perceive with peripheral vision, but would be easier to maintain a position within. See Figure 2.11 below for an example of the green zone.

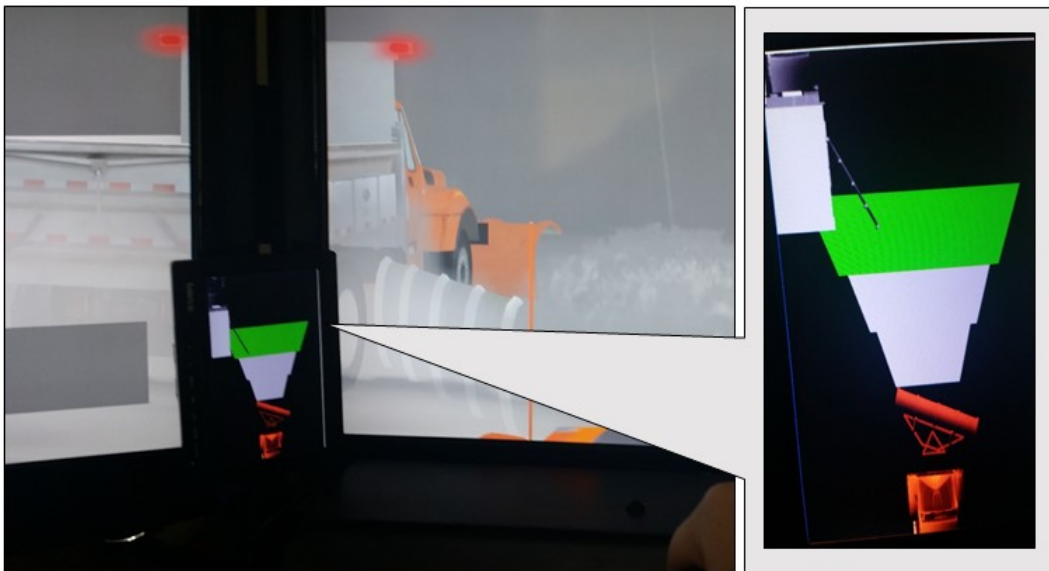


Figure 2.11. Green zone for the second design.

The yellow zone was changed to turn a yellow color when the lead plow was within 6.1 and 12 ft. (previously 4.1 to 8 ft.) from the driver's plow to indicate that the driver should be cautious about their proximity to the lead plow. See Figure 2.12 below for an example of the yellow zone.

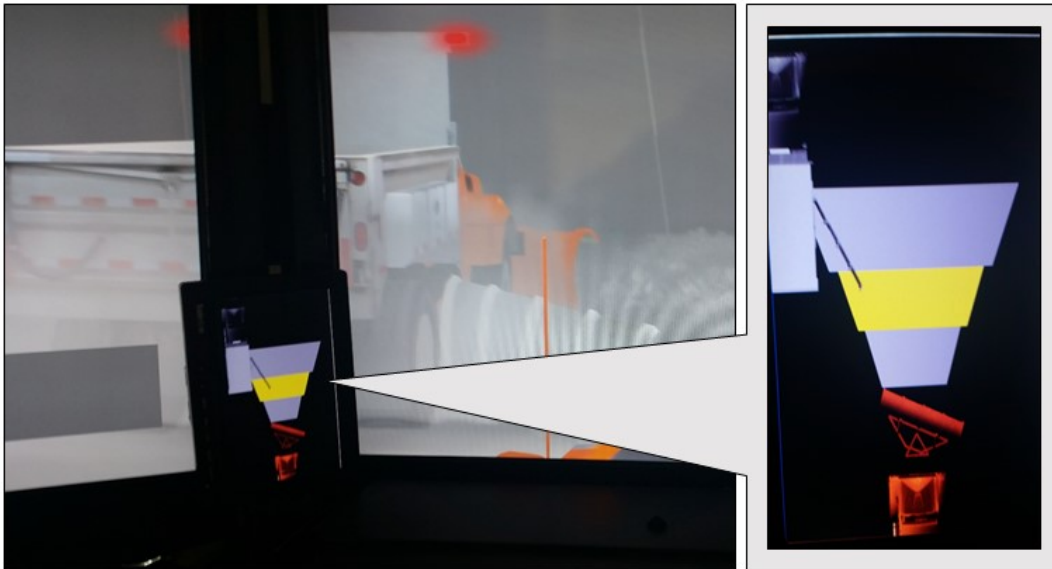


Figure 2.12. Yellow zone for the second design.

The red zone was changed to turn a red color when the lead plow was within 0.1 and 6 ft. from (previously 0.1 to 4 ft.) the driver's plow to indicate that the driver is dangerously close to wing on the lead plow. See Figure 2.13 below for an example of the red zone.

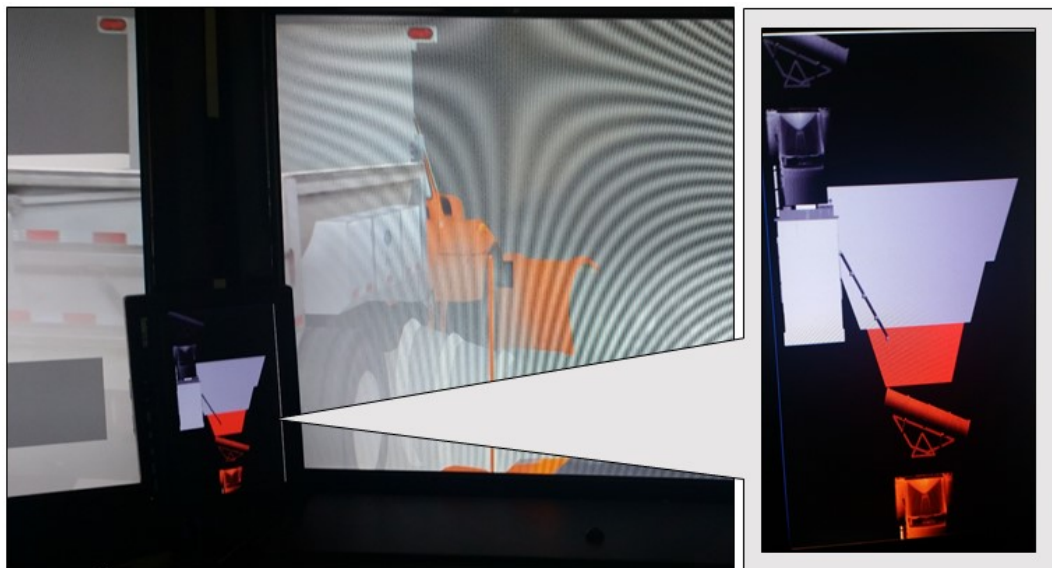


Figure 2.13. Red zone for the second design.

The design of the auditory and haptic warnings was not changed. However, the red zone size was expanded so that the auditory and haptic feedback alerted the driver that they were within 6 ft. of the lead plow’s wing instead of the 4 ft. from the initial design.

### 2.2.2.3 Testing the Redesigned System

The redesigned system was tested with an additional six participants. The following are the overall themes about the system, system preferences, usability ratings, and mental effort ratings.

### 2.2.2.4 Usability Ratings

The System Usability Scale (SUS) was used to quantify the usability of the systems. In general, usability ratings were relatively high for all system configurations and both designs. A 2x5 Mixed ANOVA was performed to assess the main effects of the system configuration (5 levels, within-subjects) and system design changes (2 levels, between-subjects) for the usability ratings. While the SUS scores are slightly lower on average for Design 2, there was no significant difference in SUS ratings between the system configurations or system designs.

**Table 2.1. SUS Descriptive Statistics for System Design and Configuration**

System Configuration	Design 1		Design 2	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Auditory only	72.50	19.87	67.50	20.49
Color	71.25	20.05	67.08	15.84
Color+Auditory	73.75	15.63	60.42	19.07
Color+Haptic	70.42	19.96	67.92	17.92
Haptic only	80.42	14.95	71.67	19.73

### 2.2.2.5 Mental Effort Ratings

The Rating Scale Mental Effort (RSME) was used to quantify the perceived mental workload of the participants. The scale ranged from 0 (i.e., no mental effort) to 150 (i.e., highest mental effort). In general, ratings of mental workload were relatively low across all system configurations and system designs. A 2x5 Mixed ANOVA was performed to assess the main effects of the system configuration (5 levels, within-subjects) and system design changes (2 levels, between-subjects) for the mental effort ratings. Mental effort ranged from “Some Effort” (approximately scored at 30) to “Considerable Effort” (approximately scored at a 70). Again, while the RSME scores are slightly higher on average for Design 2, there were no significant differences in RSME scores between the system configurations or system designs.

**Table 2.2. RSME Descriptive Statistics for System Design and Configuration**

System Configuration	Design 1		Design 2	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Auditory only	38.00	14.70	60.83	34.70
Color	43.83	23.58	79.17	41.04
Color+Auditory	37.17	19.90	60.00	32.86
Color+Haptic	45.00	17.61	72.50	36.30
Haptic only	34.67	20.41	65.00	35.07
Control	33.83	16.38	66.67	47.61

2.2.2.6 System Preferences

Most participants preferred haptic warnings over auditory warning, since auditory warnings could be confusable with other in vehicle tones. The color indicators seemed useful for new drivers, or during very low visibility conditions. See Table 2.3 below for the most and least favorite system configurations.

**Table 2.3. Overall System Preferences**

System Configuration	Most Favorite (n)	Least Favorite (N)
<b>HAPTIC ONLY</b>	5	2
<b>COLOR+HAPTIC</b>	4	2
<b>COLOR+AUDITORY</b>	2	0
<b>COLOR</b>	1	2
<b>AUDITORY ONLY</b>	0	3
<b>NO SYSTEM</b>	0	3

2.2.2.7 Driving Simulator Data

Driving simulator data was collected during the participant drives to evaluate the differences between system configuration and system designs. The main intent of the study was to ascertain the usability and satisfaction with the gang plow follower HMI design options; however, the research team collected driving performance metrics to determine if any differences could be measured in the operators’ abilities to maintain a consistent position behind the lead plow based on interface type. Out of consideration for the operators’ time, the simulation drive was not designed to allow for prolonged performance metrics measurements. Instead, the simulation routes were structured to capture first impressions of the system, so the results are not conclusive to the interfaces efficacy as an assistive tool. The names and descriptions of all simulation measures evaluated are listed in Table 2.4.

A 2x6 Mixed ANOVA was performed to assess the main effects of the system configuration (6 levels, within-subjects) and system design changes (2 levels, between-subjects) for each of the simulation variables measured.

- There were no significant differences between the initial and second designs for any of the simulation variables.

- Median time headway was significantly different between the system configurations,  $F(2.95,26.58) = 3.08$ ,  $p = .045$ , partial eta-squared = .255. Specifically, the median time headway in the Color display configuration was greater than the Haptic only warnings ( $p = .001$ ).
- The percent of single red warnings given during the drives was significantly different between the system configurations,  $F(2.17,19.52) = 4.21$ ,  $p = .028$ , partial eta-squared = .319. However, there were no significant differences between the system configurations after using a Bonferroni adjustment for multiple comparisons. Therefore, we cannot conclude that the percentage of single red warnings were different between system configurations. There were no other significant effects for the other simulation variables measured.

**Table 2.4. Name and Descriptions of Simulation Measures**

<b>Measure</b>	<b>Description</b>
Average lateral positioning	Average lateral distance from lead plow at 0 reference point. All values should be converted to absolute values so we do not have a wash of positive and negative distance
85% percentile lateral distance left	85 <sup>th</sup> percentile lateral distance left of lead plow at 0 reference point.
85% percentile lateral distance right	85 <sup>th</sup> percentile lateral distance right of lead plow at 0 reference point
Mode lateral positioning	Mode lateral distance (indicating positive or negative) from 0 reference point
Average longitudinal positioning	Average longitudinal distance from lead plow at 0 reference point. All values should be converted to absolute values so we do not have a wash of positive and negative distance
85% percentile longitudinal nearest distance or overlapping (positive)	85 <sup>th</sup> percentile longitudinal nearest distance or overlapping with the lead plow at .0 reference point.
85% percentile longitudinal distance lagging (negative)	85 <sup>th</sup> percentile longitudinal distance overlapping with the lead plow at 0 reference point.
Mode longitudinal positioning	Mode longitudinal distance (indicating positive or negative) from 0 reference point
Median Time headway	Median time headway in seconds
85 <sup>th</sup> percentile time headway	85 <sup>th</sup> percentile time headway in seconds
Crash Rates	Assess the frequency of collisions.
Longitudinal All Red count	Frequency of lateral All Red warning activations
Longitudinal All Red percent	Percent of miles driven in lateral All Red warning zone
Longitudinal single Red count	Frequency of lateral single red warning activations
Longitudinal single Red percent	Percent of miles driven in lateral single red warning zone
Longitudinal Yellow percent	Percent of miles driven in longitudinal Yellow warning zone
Longitudinal Green percent	Percent of miles driven in longitudinal Green zone
Longitudinal Gray percent	Percent of miles driven in longitudinal Gray zone

Descriptive statistics for all simulation measures for the initial design are displayed in Table 2.5.

**Table 2.5. Design 1 Simulation Descriptive Statistics**

Measure	Color		Color+Auditory		Color+Haptic		Auditory only		Haptic only		Control	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Average lateral positioning	0.57	0.30	0.55	0.54	0.52	0.43	0.54	0.41	0.60	0.54	0.38	0.19
85% percentile lateral distance left	-0.72	0.45	-0.80	0.66	-0.79	0.57	-0.77	0.51	-0.79	0.70	-0.57	0.28
85% percentile lateral distance right	0.38	0.75	0.30	0.12	0.43	0.23	0.27	0.21	0.39	0.13	0.18	0.60
Mode lateral positioning	-0.40	0.55	-0.38	0.74	-0.27	0.56	-0.38	0.64	-0.48	0.78	-0.20	0.37
Average longitudinal positioning	4.12	1.21	3.83	0.56	4.11	0.95	3.71	1.59	3.29	1.00	5.40	2.91
85% percentile longitudinal nearest distance or overlapping (positive)	5.60	1.80	5.30	1.46	5.78	1.79	5.21	1.81	4.52	1.30	6.71	3.74
85% percentile longitudinal distance lagging (negative)	-1.00	0.00	-0.89	0.25	-0.93	0.18	-1.08	0.30	-1.22	1.05	-0.87	0.32
Mode longitudinal positioning	3.57	1.19	2.98	0.42	3.30	1.03	3.07	1.40	2.77	0.87	4.75	2.49
Median Time headway	0.28	0.08	0.26	0.04	0.28	0.06	0.25	0.12	0.21	0.08	0.37	0.20
85 <sup>th</sup> percentile time headway	0.41	0.13	0.39	0.11	0.43	0.13	0.37	0.14	0.33	0.10	0.49	0.27
Crash Rates	0.00	0.00	0.20	0.45	0.17	0.41	0.83	1.17	0.50	0.84	0.00	0.00
Longitudinal All Red count	0.00	0.00	0.20	0.45	0.17	0.41	1.17	1.60	0.83	1.60	0.17	0.41
Longitudinal All Red percent	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.08	0.03	0.06	0.00	0.00
Longitudinal single Red count	6.00	5.93	3.80	3.63	5.50	3.56	4.67	5.92	7.83	5.71	2.67	5.20
Longitudinal single Red percent	0.05	0.09	0.04	0.04	0.05	0.07	0.17	0.27	0.20	0.21	0.01	0.02
Longitudinal Yellow percent	0.46	0.23	0.53	0.19	0.47	0.23	0.29	0.19	0.43	0.08	0.34	0.33
Longitudinal Green percent	0.36	0.11	0.33	0.13	0.32	0.14	0.38	0.27	0.27	0.21	0.38	0.27
Longitudinal Gray percent	0.13	0.17	0.10	0.09	0.15	0.12	0.11	0.10	0.07	0.06	0.27	0.36

Descriptive statistics for all simulation measures for the redesigned display are in Table 2.6.

**Table 2.6. Design 2 Simulation Descriptive Statistics**

Measure	Color		Color+Auditory		Color+Haptic		Auditory only		Haptic only		Control	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Average lateral positioning	0.73	0.44	0.74	0.79	0.68	0.62	0.76	0.75	0.99	0.68	0.76	0.57
85% percentile lateral distance left	-1.04	0.80	-1.39	1.10	-1.11	0.64	-1.12	0.94	-1.44	0.84	-1.19	0.73
85% percentile lateral distance right	0.46	0.24	0.64	0.45	0.20	0.65	0.49	0.88	-0.04	0.77	0.49	0.86
Mode lateral positioning	-0.65	0.94	-0.48	0.73	-0.55	0.72	-0.68	1.03	-0.65	0.88	-0.48	0.98
Average longitudinal positioning	5.55	1.60	4.91	1.66	5.34	2.96	5.32	2.60	4.88	2.80	6.06	1.56
85% percentile longitudinal nearest distance or overlapping (positive)	7.85	2.25	7.07	3.35	6.93	3.24	8.04	3.73	6.44	2.67	8.45	2.41
85% percentile longitudinal distance lagging (negative)	-1.04	0.30	-1.08	0.30	-0.78	0.37	-1.16	0.38	-1.07	0.45	-1.14	0.33
Mode longitudinal positioning	4.97	2.61	3.65	1.01	4.80	3.84	4.18	2.59	3.33	1.89	4.92	2.43
Median Time headway	0.37	0.13	0.31	0.09	0.35	0.21	0.37	0.21	0.27	0.13	0.38	0.12
85 <sup>th</sup> percentile time headway	0.56	0.17	0.51	0.25	0.50	0.23	0.57	0.27	0.45	0.20	0.61	0.17
Crash Rates	0.50	0.55	0.50	0.55	0.33	0.52	0.17	0.41	0.50	0.84	0.17	0.41
Longitudinal All Red count	1.17	1.94	0.67	0.82	0.33	0.52	1.17	2.86	1.33	2.80	0.83	2.04
Longitudinal All Red percent	0.02	0.03	0.01	0.01	0.00	0.00	0.03	0.09	0.06	0.13	0.01	0.03
Longitudinal single Red count	3.50	5.17	4.67	4.89	3.00	2.83	5.50	5.47	4.17	3.97	2.17	4.40
Longitudinal single Red percent	0.05	0.08	0.05	0.07	0.03	0.03	0.10	0.13	0.08	0.11	0.03	0.06
Longitudinal Yellow percent	0.18	0.15	0.35	0.26	0.38	0.26	0.27	0.22	0.35	0.31	0.15	0.18
Longitudinal Green percent	0.45	0.25	0.39	0.22	0.34	0.24	0.30	0.16	0.32	0.23	0.39	0.23
Longitudinal Gray percent	0.31	0.25	0.20	0.20	0.25	0.32	0.29	0.30	0.19	0.21	0.41	0.28

#### 2.2.2.8 Overall Themes regarding the System

The following quotes are statements made by participants that represent the key themes identified in these studies.

*“Looking at a computer a lot will be a bad distraction, but if it’s there to help you in white out conditions it’s a good distraction.”*

Overall, participants thought that the device would be helpful in low visibility conditions. However, participants expressed concern that another screen to watch would be distracting. Color feedback should be salient and understandable at a glance. Moreover, the color display screen should be designed to accommodate understanding the distance information, while not having to constantly monitor the screen. The redesigned system aimed to fix this issue by making the zones more salient (i.e., larger). As a result, participants who used the redesigned display stated that they could “get into the green zone and monitor the display out of the corner of their eye”.

*“The problem with this is that you put a system like this is the truck, now that system goes down, can the operator still operate the truck?”*

Training on the system prior to first use may alleviate user concern with having to monitor and rely on the display. A system training could describe the intent of the system (i.e., to help them maintain safe distance from the lead plow in low visibility conditions), the meaning of different zone sizes and alerts on the color display, and how to use the display (i.e., do not constantly monitor or become reliant on the display, but use it as a reference to locate and maintain safe distance from the lead plow during low visibility plowing conditions).

*“I was looking down when I was in the red, [the vibration] was handy to know I was in the red zone.”*

Participants liked having the alerts to tell them if they were too close to the lead plow. Several were concerned that the auditory alert (i.e., four beeps) would be annoying and confusable with other sounds in the plow truck. For this reason, many of the participants preferred haptic feedback (i.e., seat vibration at 40 Hz for 1 second). Some felt that the vibrating seat was distracting, but performed a useful function. That is, participants felt the seat vibrate and immediately understood that their plow was too close to the lead plow and let off the accelerator to get to a safer distance from the lead plow. However, some noted that the vibrations might be confusable with the vibration of the plow as it drives over rumble strips in the road. Whichever alert is chosen should be modified and tested to ensure that it is not confusable with other sounds or vibrations felt while plowing.

*“It would help [newer drivers] get a sense of the right distance...If you're me, I wouldn't need that, but new people, they might need it. Someone that is new might utilize the green [zone] until they're used to the system.”*

Finally, several of the drivers felt that the system would be more useful for newer drivers, and less useful for the experienced drivers. However, they stated that it would be useful for plowing in low visibility weather conditions.

#### 2.2.2.9 System Placement

Participants were asked where they would place the system display in their plow. As noted earlier, most of the participants did not want another display screen in their truck. Consequently, most of the participants recommended that the system be integrated into the MDSS screen ( $n = 7$ ). If the display is not integrated with the MDSS screen, participants recommended that the display should be placed somewhere that can be seen from peripheral vision without moving the driver's eyes off the road ( $n = 4$ ). Some thought that the left pillar in the truck, similar to how the display was positioned during the simulation, would be a sufficient position for the display ( $n = 3$ ). Further a couple participants recommended that the display is placed in the center of the dashboard ( $n = 2$ ).

#### 2.2.2.10 Desired Features

Participant made several comments about features that they would like to use in the final version of the system. Several participants discussed the idea of being able to adjust the zone sizes for which the warnings trigger. For example, one participant noted that when driving in the city during the day that the plow formation tended to be closer than when plowing at night or outside of the city. Another suggestion was to allow the driver to dim the brightness of the screen when using the system at night to reduce eye fatigue due to lights.

### 2.2.3 Conclusions and Recommendations

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The iterative design of the human machine interface allowed the research team to gather information based on user impressions of the initial system and implement changes to best accommodate their preferences. Based on subjective reports of users, the spatially expanded and visually enlarged zones appeared to be successful in allowing users to be better able to monitor and maintain their following position in the green zone with fewer direct fixations on the screen. The generalizability of the driving performance from the simulation is limited since the visual information of the distance to the lead plow was collapsed into a 2-dimensional representation. Operators struggled to rectify their perceived following distance based on the simulation monitors and the reported distance from the HMI display. It is hypothesized that drivers will increase their satisfaction and reduce their mental effort in interacting with the display once it is easier to rectify and match their following distances between the display and the 3-dimensional distance cues from which they benefit on a real road.

- Operators preferred the Haptic only and Color+Haptic interfaces
  - Combining Haptic and color feedback best practice for optimal following distances
  - Effective at communicating when the operator is too close to lead plow
  - Cons: Haptics are expensive, potentially confusing with other road vibrations
- Color+Auditory interface popular with all operators
  - Combining visual and auditory modalities promising
  - Operators reported satisfaction with this system with an appropriate tone

Operators most frequently reported that the Haptic only feedback was the most preferred interface, followed closely by the Color+Haptic feedback. Understandably, operators reported a hesitancy to use a system that may visually distract them from the task of driving. While the haptic only system would free their visual attention, there is some evidence from the simulation data that they would be more likely to follow too closely with this system since they would only receive feedback when they were too close and not when they reached an “optimal” zone. Pairing the haptic feedback with the color display is most likely to add the proper redundancy needed to illicit more optimal following distances and to warn drivers when they are approaching the lead plow too closely.

Implementing a haptic, vibratory system into the truck’s driver’s seat, however, is a more expensive option than the auditory feedback option. Drivers were doubtful of their ability to clearly discern a beep from the HMI among the many other beeps and sounds already present in the cab. There is potential, however, that there may also be some confusion between the haptic feedback and with other types of vibrations the operators may experience in the plow (e.g., rumble strips, etc.). While the Color+Haptic system is the recommended system based on the results of this investigation, there is an opportunity to create a Color+Auditory system which would likely generate high user satisfaction as long as the tone was carefully selected to be unique and easily distinguishable from other competing sounds. While only two of the operators selected the Color+Auditory system as their favorite option, it was the only system that was not selected by any operators as their least favorite system. This may suggest that operators could bolster their preference for this system with some minor changes to the auditory signal.

### 2.3 INTERVIEW OF TRUCK OPERATORS REGARDING BACKUP ASSIST INTERFACE DISPLAY

HumanFIRST researchers visited five of Minnesota Department of Transportation truck stations. All truck stations were located in the Metropolitan area around Minneapolis, MN. The truck stations included Chaska, Lakeville, Maryland Avenue, Maple Grove, and Shakopee. Nine operators provided input during the interview sessions across the five truck stations. The goal of each visit was to observe a demonstration of current technology used for rear detection (e.g., back up cameras) and interview maintenance operators to evaluate the placement, efficacy, and usability of the technology.

During interviews and evaluation of current technology, researchers presented operators with several potential designs of a backup assist interface display. Feedback from operators was used to make final modifications to the designs. Designs were evaluated by five operators located across three truck

stations (i.e., Shakopee, Chaska, Maple Grove) to identify which designs were preferred by the user. This report describes the process and results of interviews in order to determine the final interface design recommendations for a backup assist interface display.

### 2.3.1 Participants

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Participants included nine maintenance operators during the initial backup assist interface display demonstration visits, and 5 maintenance operators during the subsequent design feedback interviews. All participants were currently employed at MnDOT truck stations in the Metropolitan area of Minneapolis, MN. Operators were from five different truck stations, including Chaska, Lakeville, Maryland Avenue, Maple Grove, and Shakopee. We did not collect any other demographic information because this study was intended to assess the system and not the users.

#### 2.3.1.1 Procedure

Maintenance operators were contacted to identify which truck stations had used a snow plow truck with rear vision technology. Truck stations that had used rear vision technology were contacted to schedule a visit to observe a demonstration of the technology and interview any available operators that had experience using the rear vision system. During rear vision system demonstrations, HumanFIRST researchers assessed the placement of the cameras and rear vision interface, efficacy of the system, and usability for operators by observing the system in use and asking semi-structured interview questions to the operators. Each visit lasted approximately 60 minutes. See Appendix C for a list of questions that were used to guide the discussion. Placement of the current rear vision systems were inconsistent between the truck stations that were visited. For example, trucks with backup cameras featured different mounting positions including: on the rear driver's side, rear passenger's side, strobe-mounted on the passenger's side, and rear-under the truck tailgate (see Figures 2.14 and 2.15).



Figure 2.14. Rear left, rear right, and strobe mounted cameras.



Figure 2.15. Rear-under bed mounted cameras.

The interface used for the rear view camera was a camera feed display integrated into the MDSS with no interactive functions. If the truck had two cameras, the operators were provided with a full screen image of one camera, and given the capability of switching inputs to the alternative camera feed. See Figure 2.16 below for a picture of the strobe-mounted and rear passenger's side backup camera display.

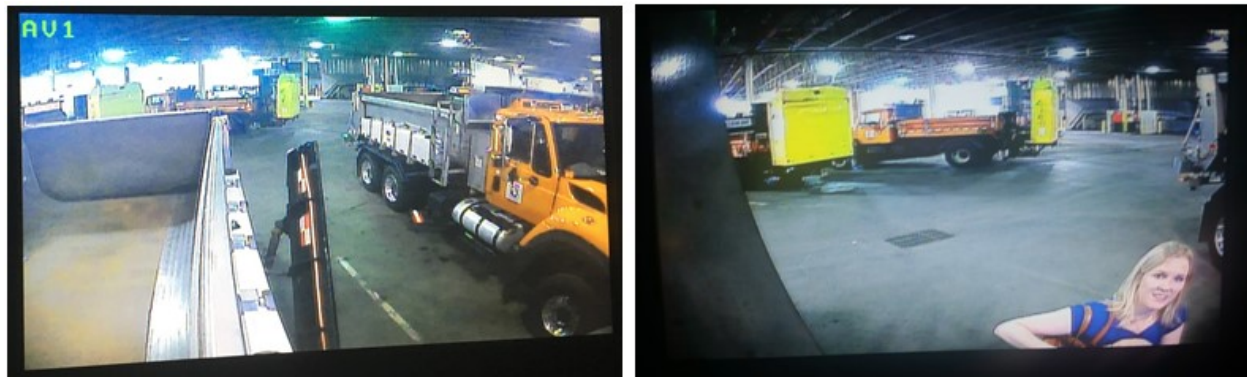


Figure 2.16. Strobe mounted (left) and rear passenger's (right) camera video interface.

Next, a set of backup assist interface display mockups were design based on the feedback gathered during MnDOT truck station visits. Figure 2.17 displays the backup assist interface display mockups.

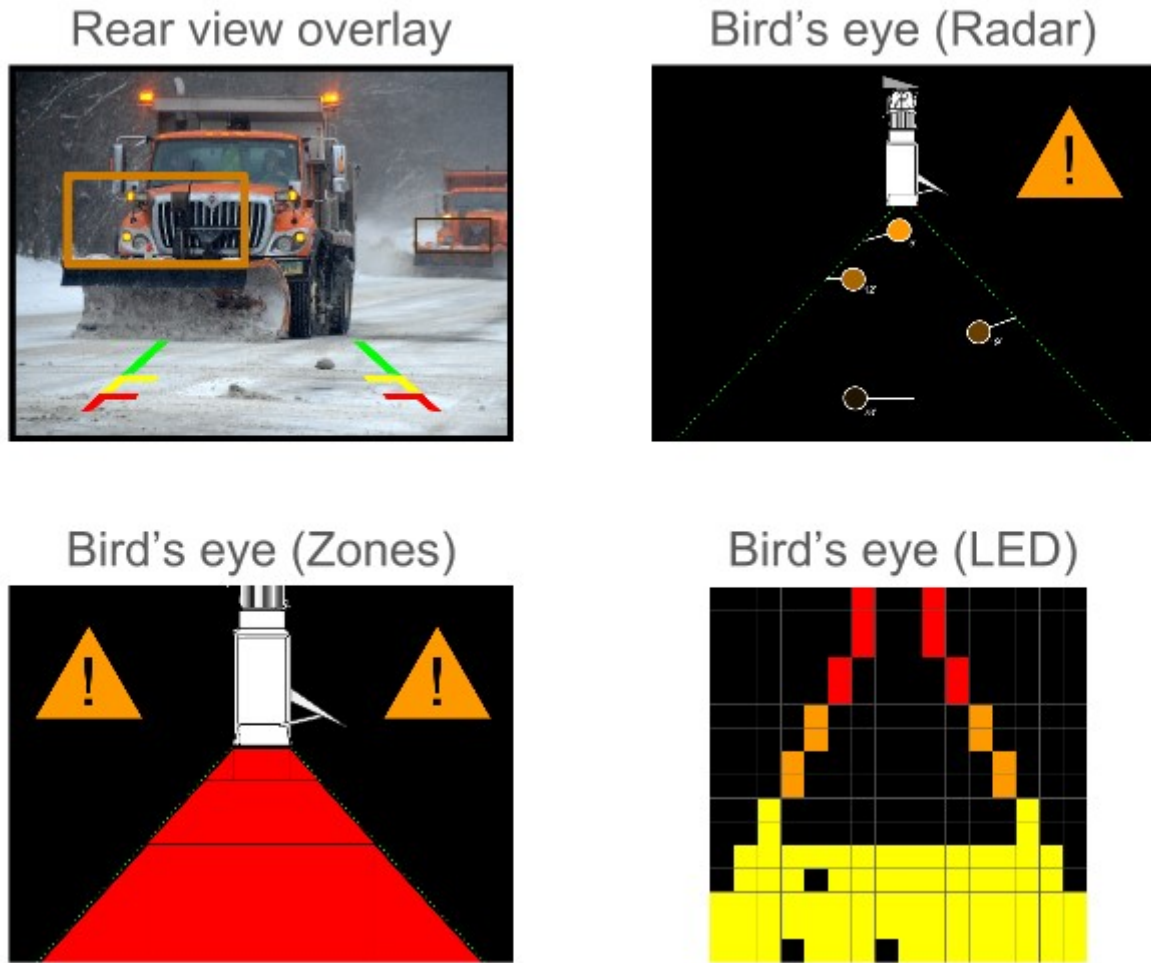


Figure 2.17. Backup assist interface display mockup design examples (see Appendix C for additional examples).

The rear view overlay option (see top left image in Figure 2.17) is an interface mockup of a backup assist system that integrates information from a radar system into a typical backup camera display. In this system, the system would overlay distance zones (e.g., red, yellow, green) and target bounding boxes. Distance zones provide information about how far away a target is from the operator's vehicle while backing. The target bounding boxes would code distance to a target by line width and color (e.g., black-body radiation). For example, a box with smaller line width and darker color indicate a target that is far away, while a box with wider lines and brighter color indicate a target that is near. Bounding boxes on screen would change width and color as the radar targets moved closer or farther from the operator's truck during backing. An auditory and visual alert would be triggered when a target is too close to the operator's vehicle while backing.

During site visits, one of the common recommendations for designing a backup assist system was to create a display with a bird's eye viewpoint. Consequently, several bird's eye perspective mockups were designed. The bird's eye radar option (see top right image in Figure 2.17) is a mockup of a rear vision

system that integrates information from a radar into a display with a top-down viewpoint. In this display, the truck would remain fixed while radar targets moved within the radar's field of view. Distance to the target is coded using color and relative positioning behind the truck icon. For example, targets that are closer become a lighter color and move toward the back of the truck icon, while targets that are further become a darker color and move away from the back of the truck icon. Further, this display coded the speed and direction of targets behind the operator's vehicle by altering a target's trailing vector. For example, slower moving targets might have shorter trailing lines, while faster moving targets might have longer trailing lines. An auditory and visual alert would be triggered when a target is too close to the operator's vehicle while backing. The visual alert could be displayed on screen, such as the exclamation symbol shown on the example in Figure 2.17.

The bird's eye warning zones option (see bottom left image in Figure 2.17) is an interface mockup of a backup assist system that integrates information from a radar system into display with a top-down viewpoint, similar to the radar mockup. However, this system does not show the operator information about precisely where the targets are located within a zone, the number targets, speed or direction. Instead, this system aims to provide a visual warning to the operator that there is at least one radar target within a set distance from the rear of the truck while backing. For example, the lowest "green" zone could illuminate if a target is between 20.1 to 30 ft. behind the truck, the middle "yellow" zone could illuminate if a target is between 10.1 to 20 ft., and the highest "red" zone could illuminate if a target is within 10 ft. from the truck. An auditory and visual alert would be triggered when a target is too close to the operator's vehicle while backing. The visual alert could be displayed on screen, such as the exclamation symbol shown on the example in Figure 2.17.

The bird's eye LED option (see bottom right image in Figure 2.17) is a mockup of a rear vision system that integrates information from a radar system into a simple 16x16 LED array with a top-down viewpoint. This system was shown to the operators to determine whether or not a low-cost and low-fidelity LED array could be used to display the same information that the other systems would present using a more expensive display. Given this goal, this mockup display was designed to display the radar zones marked in color. Each square in the grid represents a single LED in the array. In this mockup, distance warning zones were displayed. The green zone was lowest and would illuminate when a radar target is furthest from the back of the operator's truck. Then, the zones would illuminate yellow, orange, and red as the target moves closer to the truck. The display would fill all preceding zones with the color of the current zone in which the target is located. Radar targets could be shown by omitting the light within a zone to display where the target is located. The closest target would determine which zone color is filled on the display. For example, the bottom right image in Figure 2.17 shows three targets with the closest target in the yellow zone. As the operator is backing the targets would move higher on the display to indicate that an object is getting closer. If a target reached the red zone, the driver would receive a visual alert (i.e., red zone illumination) and an audible alert.

Five snow plow operators from three different MnDOT truck stations (Maple Grove, Chaska, Shakopee) were recruited to evaluate and provide feedback on the rear vision mockup designs. The operators were

provided with a PowerPoint file containing the rear vision mockups. During the interview, the intent of each design was described and demonstrated to all operators. Participants provided comments and ranked each design based on their preference. Each interview lasted approximately 45 minutes. See Appendix C for a list of questions that were used to guide the discussion.

## 2.3.2 Results

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### 2.3.2.1 System Preferences

All five participants rated the rear-view overlay design as the most preferable interface design for a backup assist system with integrated radar information. See Figure 2.18 for the mean rankings for system preference. Lower mean rank indicates a higher preference.

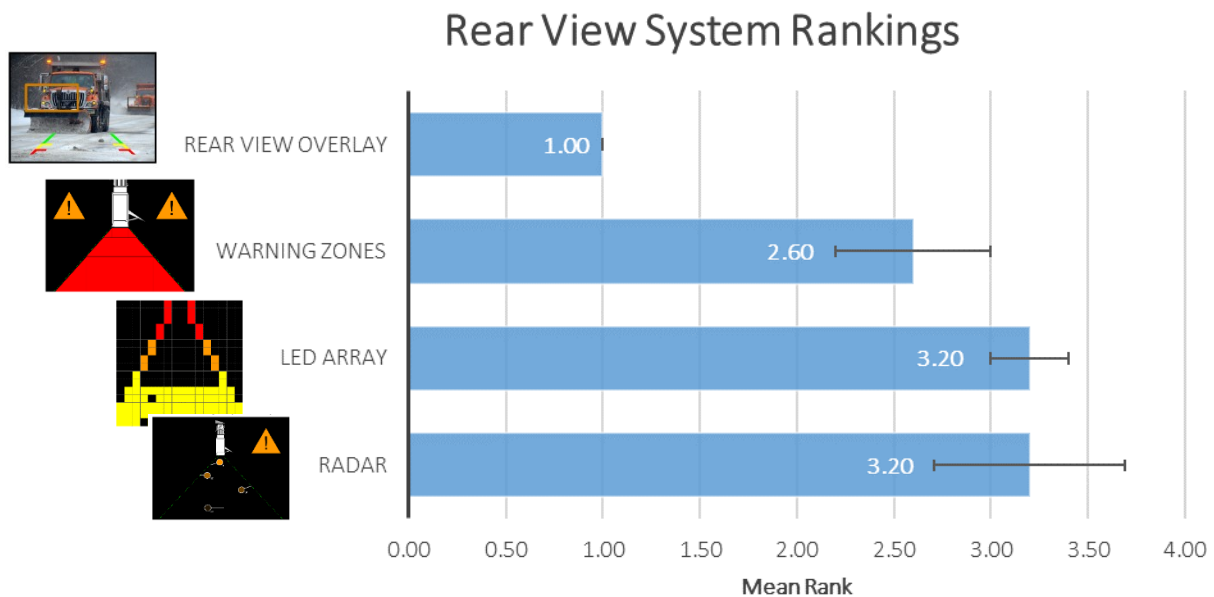


Figure 2.18. Mean rankings for system preference.

*\*note: 1 indicates highest preference and 4 indicates lowest*

## 2.3.3 Overall Themes regarding the Design Options

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### 2.3.3.1 Rear view overlay

Users stated that the rear view overlay system would be user friendly and meet the expectations of operators who had used backup cameras in the past, because this system integrates the additional radar information without drastically changing pre-existing rear-vision technology. Operators noted the importance to have the ability to visually confirm what is behind you, as you might do by looking in a rear view mirror or backup camera display. This rear view overlay system provided operators with the ability to visually confirm what is behind the truck, but also supported awareness of objects even if the

camera view was foggy or snow covered. A driver might naturally look to their backup camera display when backing, but with this system even if visibility conditions are white out, the driver can still see targets behind them. Further, this system was perceived as easy to learn, since some of the operators are already familiar with using backup camera systems.

Additionally, this design could be useful during other seasons to help with backing in the truck stations or other maintenance tasks, whereas the bird's eye designs might only be useful when it is snowing. Finally, the operators were satisfied that this interface could be integrated with a backup camera interface because it reduces the number of screens compared to the bird's eye versions, which would need to be presented on another display.

#### 2.3.3.2 Bird's eye (radar)

Participants believed that this design would require more interpretation by the operator compared to the rear view overlay system. The importance of the distance information included on the radar design was not agreed upon by the operators. For instance, several operators considered the labels for feet to the target useful for this design, while some believed that it was unnecessary because operators will have limited time to read the information while performing snow plow tasks. However, the radar system did not allow the operators to identify objects behind the truck. Object identification could be important when determining the importance of the distance to the object. For example, operators stated that they might feel more comfortable backing if they knew the object behind them was a traffic cone, as opposed to a person or another vehicle. Conversely, the rear view overlay system would allow the operator to identify objects behind the truck if necessary.

#### 2.3.3.3 Bird's eye (warning zones)

In general, operators stated that the warning zone system is simpler than the radar design, but that the radar provided more useful information. One operator stated that this design was not worth an extra screen.

#### 2.3.3.4 Bird's eye (16x16 LED array)

One operator liked that the LED array was simple and showed where targets were and how they were moving in relation to their vehicle. One operator thought that the LED array looked "cheesy." Finally, two operators thought that the LED array might be confusing.

#### 2.3.3.5 System Placement and Desired Features

All operators stated that they wanted to minimize the amount of displays that they have in the vehicle. To meet this needs, user stressed that the system should be integrated into the current MDSS screen. Operators expected this system to automatically turn on anytime the vehicle is shifted into reverse. Further, the operators expected an audible alarm to sound to cycle with increasing frequency as they approach an object. The system should provide the option to toggle the audible alarm on or off.

### 2.3.4 Conclusions

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Based on feedback from interviews and analysis of current rear view technologies, we conclude that the rear view overlay design integrated into the MDSS with an audible alarm would be the most preferred design (Figure 2.19). This system would best match operator expectations and requests for system realism and integration.

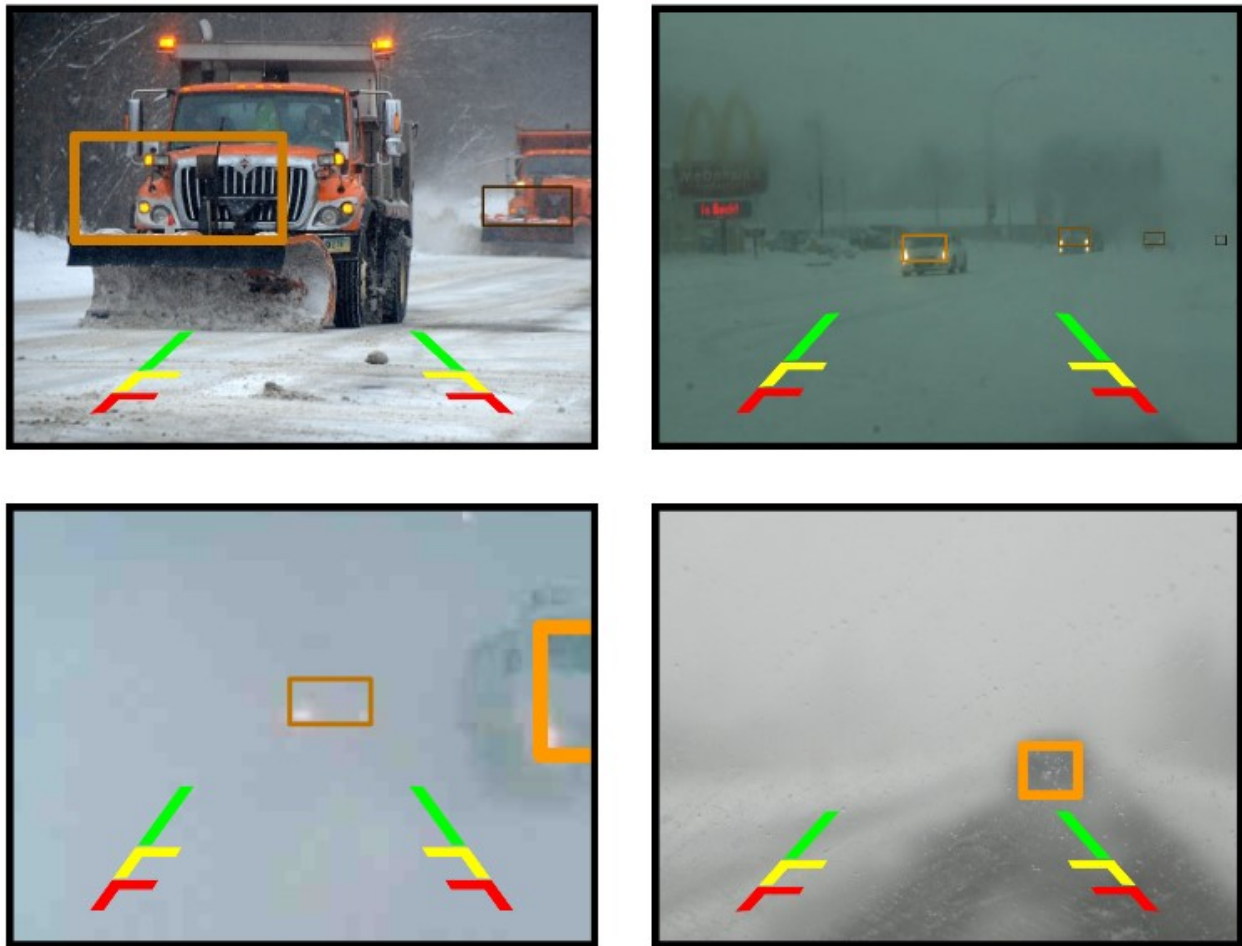


Figure 2.19. Mockup of rear view overlay design.

*\*note: images depict visual angle directly behind truck, regardless of the angle of the roadway*

- Fabrication of the rear overlay design would require radar and computer vision programming to capture features
  - Cost and labor intensive process
  - Pursue as an alternative research study
- Research team proposes creating a back-up camera system using auditory alert
  - Design criteria based on operator feedback

- Examine effective and safe back-up camera field of view
- Locate best positioning for camera equipment

To fulfill the requirements of the current project in the interim, we propose that we pursue reasonable steps to move toward providing a system which most reasonably matches the system most requested and preferred by operators. What is feasible within this project scope may be to only provide an auditory alert once a target is near and within the “red zone” range of nearest proximity. This will likely not be matched with a visual indicator since video integration is not yet feasible. Operators have made it clear that they do not wish to have an additional display introduced into their truck cabin. Providing the next most preferred display option (i.e., Bird’s Eye: Zone) is not seen as a beneficial use of resources since it would be in direct opposition to operators expressed wishes of an integrated system. However, it is prudent to ensure that the back-up camera placement and visibility is tested and modified to provide the clearest field of view for operators. A clear video display from the back-up camera, paired with an auditory alert indicating that the truck is approaching an obstacle provides the most feasible course of action until the radar is visually integrated into the video display.

## **2.4 SIMULATION STUDY AND USABILITY TEST OF LANE BOUNDARY GUIDANCE USER INTERFACE**

The objective of this task was to assess the efficacy and usability of proposed experimental lane boundary guidance interfaces for snow plow operators in order to understand the needs, desires, and subjective feedback of such a system for future use in the development of a lane boundary guidance interface for MnDOT operators. The purpose was to examine snow plow operator driving performance, visual attention, and subjective measures feedback during their use of five lane boundary guidance systems.

### **2.4.1 Lane Boundary Guidance Interface Simulation Study and Usability Test**

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A series of driving simulation trials were completed by MnDOT snow plow operators from the Minneapolis and St. Paul metro area in order to examine and assess each of the five experimental lane boundary guidance interfaces. This simulation study was performed by seasoned snow plow operators in order to evaluate five potential lane boundary guidance systems to help inform potential future development by MnDOT. Seven MnDOT snow plow operators were recruited for a 2-hour driving simulation study and usability exercise to assess five lane boundary guidance interface systems for use in plowing operations that reduce operators’ situational awareness and plow rig lane position under low-visibility roadway conditions. Researchers were interested in snow plow operator feedback on the usability dimensions of each lane boundary guidance system, including the degree to which the systems are understandable, realistic to real- world plowing demands (e.g. situational awareness issues in whiteouts), visually comprehensible, and their mental effort exerted to engage with the system while performing the plowing tasks. Participants were provided by various MnDOT truck stations around the

greater Minneapolis- Saint Paul Metro area, and each was skilled and familiar with plowing operations, specifically in low-visibility or whiteout roadway conditions.

The current study was broken into three primary components:

- **Simulated right-lane plowing operation in the driving simulator**  
Participants drove each of the five systems for five minutes each  
Examined lane-keeping accuracy, average speed, eye tracking and visual attention
- **Operator feedback and discussion on each interface design**  
Subjective measures of mental workload, system usability  
In-depth discussion on practicality, use case, usability dimensions of each interface
- **Interface design preference, think-aloud exercise**  
Ranking systems by safety, effectiveness, comfort, mental effort metrics  
General discussion on plow operations and the need for improving plow truck technology

#### **2.4.2 Experimental Lane Boundary Guidance System Interface Designs**

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Findings from previous tasks led the development of five experimental lane boundary guidance systems for testing in the simulation study and usability test for the task. Each system prototype fell within two design categories that provided lane position feedback either within the vehicle via an LED display, or an external visual aid that projected the predicted position of the right of the plow wing using a laser beam. The laser-based system used projections on the forward roadway in the fog line position, and the in-vehicle LED strips provided visual feedback relative to the plow truck's lane position. Furthermore, the researchers also examined operator performance and usability feedback using a combination of the two systems, the LED + Moving Laser and LED + Fixed Laser combinations, in order to observe potential benefits of complimenting each standalone design category.

##### **2.4.2.1 LED guidance system**

The experimental LED guidance strip communicated the plow truck's position within the center of the lane to be plowed. Figure 2.20 depicts the states of the LED guidance strip, with a centered green box indicating that the plow operator is oriented in the center of the lane, from the driver's perspective. As the operator deviates from the center of the lane, either to the right or to the left, the LED guidance strip provides instantaneous positioning feedback in 1ft increments. In the case that the operator has drifted outside of a 4ft window relative to the center of the lane, the red marquee begins blinking, in order to communicate the urgency of correcting their path in the appropriate direction to avoid leaving the lane. For the purpose of this simulation study and usability test, the researchers designed the LED display using the in-vehicle LCD screen mounted within the gauge cluster region of the simulator's dashboard.

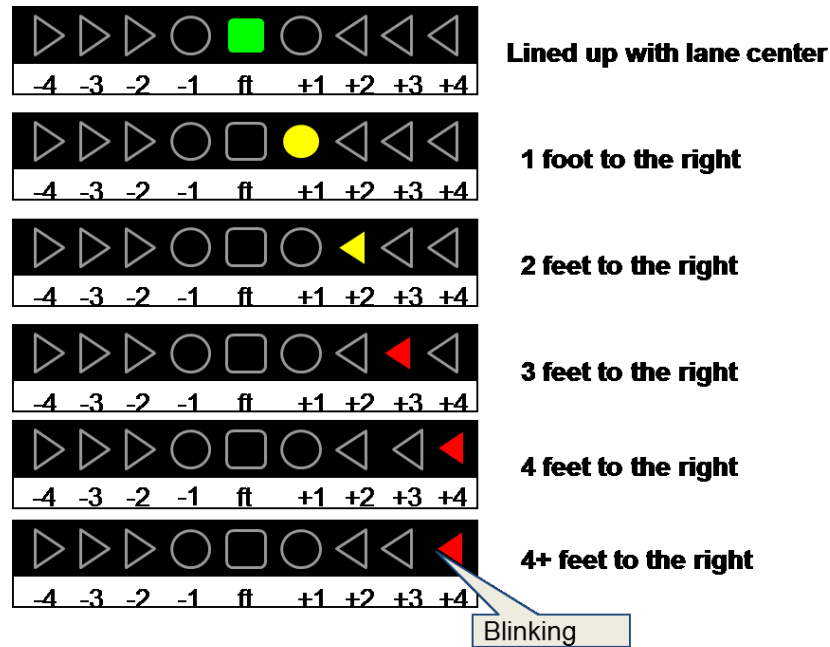


Figure 2.20. Schematic of LED guidance system.

#### 2.4.2.2 Fixed and Moving Laser forward-projecting laser design

The researchers were interested in designing a system that would provide the plow truck’s lane and wing position by means of visual feedback that appeared outside of the vehicle’s cabin. To accomplish this, two forward-projecting laser systems were developed for the purpose of this simulation study and lane plowing task. The forward-projecting lasers appeared on the fog line position of the right lane boundary, and were designed with the current tow-rig laser projections in mind. With tow-rig lasers, the positioning of the plow wing’s edge is illustrated by using a laser beam that plow operators can view on the plow trajectory in order to bolster spatial awareness of the plow truck and the truck behind it. Operators in the current study reported high levels of satisfaction and general usefulness of the system when performing plowing operations on the roadway while the tow rig laser is in use.

The forward-projecting laser guidance system visualized the position of the fog line by means of a laser directed 80ft look-ahead, roughly 60ft ahead of the driver, by means of two iterations: the Moving Laser and the Fixed Laser. The Moving Laser provided fog line position by means of a forward-projected laser that constantly kept the fog line position marked, regardless of plow truck position in the lane. The laser projection would keep a continuous fix on the fog lane position on the simulated snow-covered lane, and would rotate its orientation, thus changing the angle of the laser as it appeared, which represented the projection originating from the plow truck roof. In the event the plow truck deviated to the left of the center of the lane, the visual representation (e.g. angle observed) of the Moving Laser’s projection increased. Likewise, if the operator’s lane position with respect to the wing’s edge on the fog line was near or on the fog line, the Moving Laser’s visual feedback consisted of a shallow angle appearing vertically oriented. The purpose of the Moving Laser was to provide a dynamic visual feedback modality that represented lane, or fog line, position exterior to the cabin.

The Fixed Laser design incorporated the 80ft look-ahead projection, similar to the Moving Laser, however; the Fixed Laser differed from the Moving Laser in that it only produced a laser beam projection at a fixed angle, and did not provide continuous fog line tracking. Instead, the Fixed Laser provided a constant forward laser projection that indicated the plowing trajectory of the wing's edge, without additional cues on the fog line or lane position in the roadway. This laser design was similar to that of the familiar tow wing laser system equipped on select MnDOT plow trucks, but differed in that it projected from the roof of the vehicle, and could be used independently of the tow wing.

#### 2.4.2.3 LED guidance strip and forward-projecting laser combination systems

The research team elected to further test the effectiveness and usability of the lane boundary guidance system prototypes by combining the forward-projecting laser guidance system with the LED guidance strip interface. In principle, each system operated as it would in standalone configuration, however; both the laser and LED systems operated simultaneously to provide the plow truck's immediate lane position and the right fog line location. Researchers anticipated increased participant usability and ability to perform the plowing task with these systems coupled and operating in unison, due to the redundancy of lane position information in the simulated roadway.

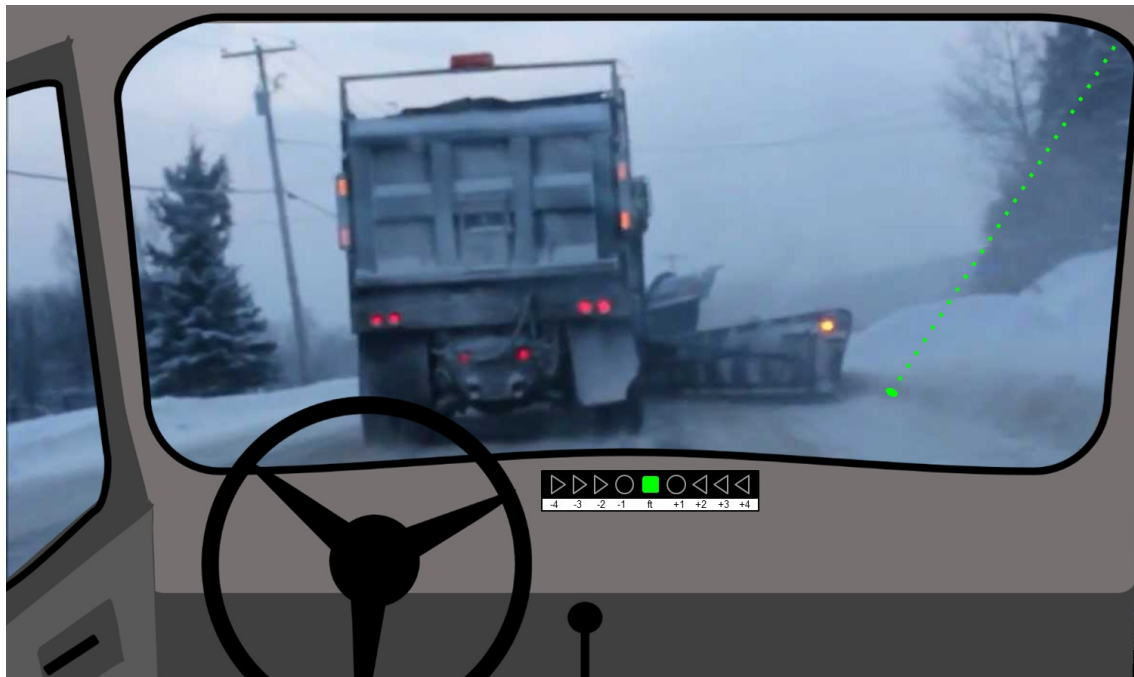


Figure 2.21. LED and Laser combination indicating correct lane position.

The LED Moving Laser and LED Fixed Laser were developed with the potential roadway information needs of the plow operators in mind under the circumstances of whiteout conditions. During low visibility and decreased situational awareness in whiteouts, the combination systems would provide reliable in-vehicle lane position feedback on the dashboard at all times, with the laser component

providing the projection of the fog line position 80ft ahead of the plow truck. Figure 2.21 depicts the combination system feedback when the plow truck is centered the lane and the blade accurately oriented with the right fog line, while Figure 2.22 provides an example of the plow truck deviating rightwards 3ft.

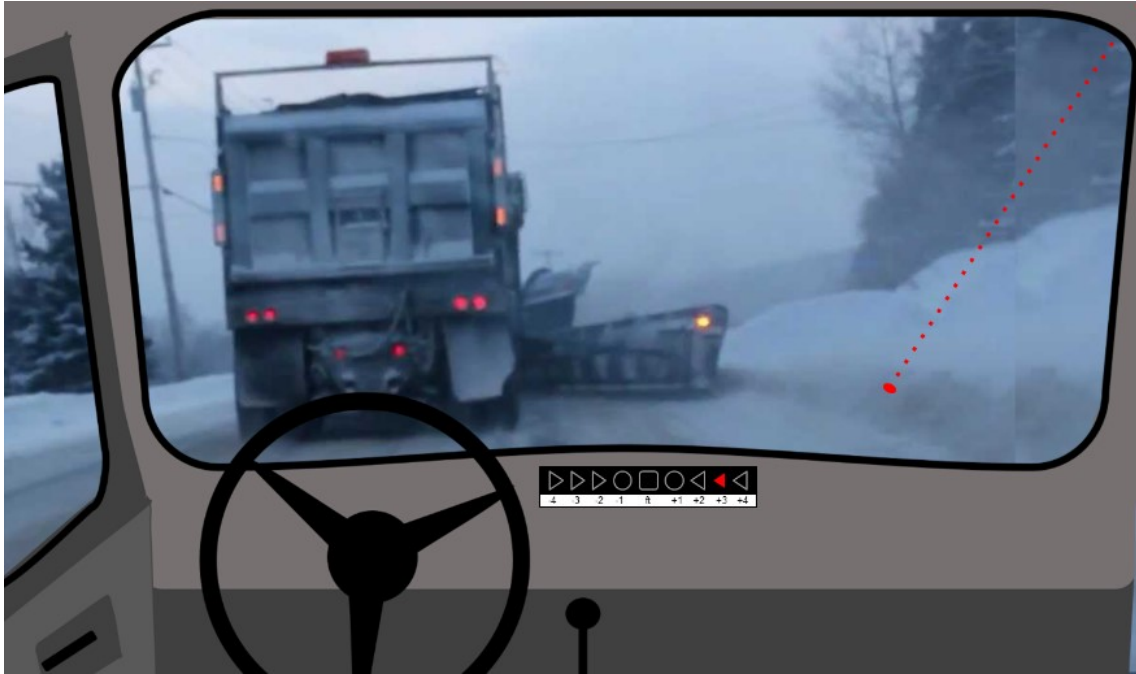


Figure 2.22. LED and Laser combination feedback at the 3ft rightwards lane position.

### 2.4.3 Method

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The experimental design of the current study included a briefing on the simulator study and the expected tasks, the execution of five simulator drives with each lane boundary guidance system, and thorough discussion on usability dimensions with each system via interviews following the conclusion of the five plowing drives.

Simulator training in the form of five-minute demonstration videos were provided to snow plow operator participants in order to establish a fundamental understanding of each lane boundary guidance system operators would assess in the simulator. Before each drive, operators viewed a video clip demonstrating the specific guidance system providing lane position feedback while in use on the simulation route. For the purpose of clarity, the video demonstration route was under sunny and dry conditions (e.g. summer day) so that road markings were visible.

Snow plow operator participants in the simulation study viewed a demo video presented on a Microsoft Surface tablet before each drive. Participants were given a five-minute video example of the interface system which they were about to use in the simulation. In addition to providing operators

with an understanding on how each guidance system worked, the demo videos also served the purpose of familiarizing the operators with the simulator.

#### 2.4.3.1 Procedure

Seven participants, each current MnDOT snow plow operators, were recruited for a two-hour driving simulation study and usability interview to evaluate five experimental lane boundary guidance systems for use in snow plow trucks. The purpose of this driving simulation and operator interview study and interview was to assess the usability of each lane boundary guidance system design, examine snow plow operator performance (e.g. ability to maintain plowing accuracy) while using each system design, and quantify operator visual attention and behavior while performing each simulator drive.

The experiment's protocol began with an informed consent process and briefing session, in which the study and experimental guidance systems were explained. The researcher then provided the participant with a five-minute demo video of the guidance system working in clear conditions, to ensure understanding of the system's mechanism before performing the simulator snow plow drive. Once the operator reported confidence in understanding the guidance system mechanism, researchers lead them to the simulator and performed calibration procedures with the SmartEye (SmartEye AB) eye tracking suite. After eye calibration, the operators completed demographic forms while the simulated drive was prepared. Operators performed a right-lane plowing exercise using the driving simulator while assisted by one of the lane boundary guidance systems for five minutes. Before concluding the operators' drive with the lane boundary guidance system, researchers verbally obtained confirmation that each operator felt confident in the length of exposure in using the system to provide evaluative feedback.

#### *Rating Scale Mental Effort (RSME)*

In order to quantify the extent to which each system taxed the operators' mental workload, the Rating Scale of Mental Effort (RSME, Appendix B) was employed after the conclusion of each plowing drive. The RSME provides the user, in this case MnDOT snow plow operators, with the opportunity to reflect on their perceived mental effort exerted when using each of the lane boundary guidance systems. The RSME appears as a vertical scale marked with numerical values ranging from 0 to 150, with 0 representing absolutely no mental effort exerted, and 150 indicating extreme mental effort exerted to engage with the system. Each operator rated their perceived mental effort exertion for each lane boundary guidance system. Researchers anticipated scores would range from 0, "absolutely no effort", to 50, above "some effort".

#### *System Usability Scale (SUS)*

The System Usability Scale captures user feedback on usability dimensions within a system. Operators completed the System Usability Scale (SUS) after the conclusion of each drive, which consisted of ten questions centered on usability aspects of the system presented in 5-point Likert scale (e.g. Strongly Disagree, Strongly Agree). Calculated scores from the SUS inventory provide researchers with an understanding of how usable (e.g. easy to use, well-integrated, organized, intuitive) operators felt each lane boundary guidance system was during the simulated plowing task. SUS scores range from 0,

suggesting an unusable system (e.g. annoying to use, unnecessarily complex, disorganized) to 100 points, indicating complete satisfaction with the system’s usability characteristics. Researchers anticipated scores would appear near the average of 68, describing a system as efficient and usable, or higher.

#### 2.4.3.2 Roadway Design and Simulator Environment

The simulated environment for the plowing task using each lane boundary guidance system was modeled on US14 in Dakota, MN northbound to Winona which turns into US61, see Figure 2.23. The roadway design was that of US14’s, including a two-lane, two-way median-divided highway. The simulated road featured the Mississippi River on the right of the roadway and hills to the left to add saliency and relative boundaries to the roadway environment, because of snow coverage that hid shoulder and median feature cues that seasoned operators would have identified. The plow route included gentle horizontal curves, subtle super-elevation at times, and subtle vertical curves.

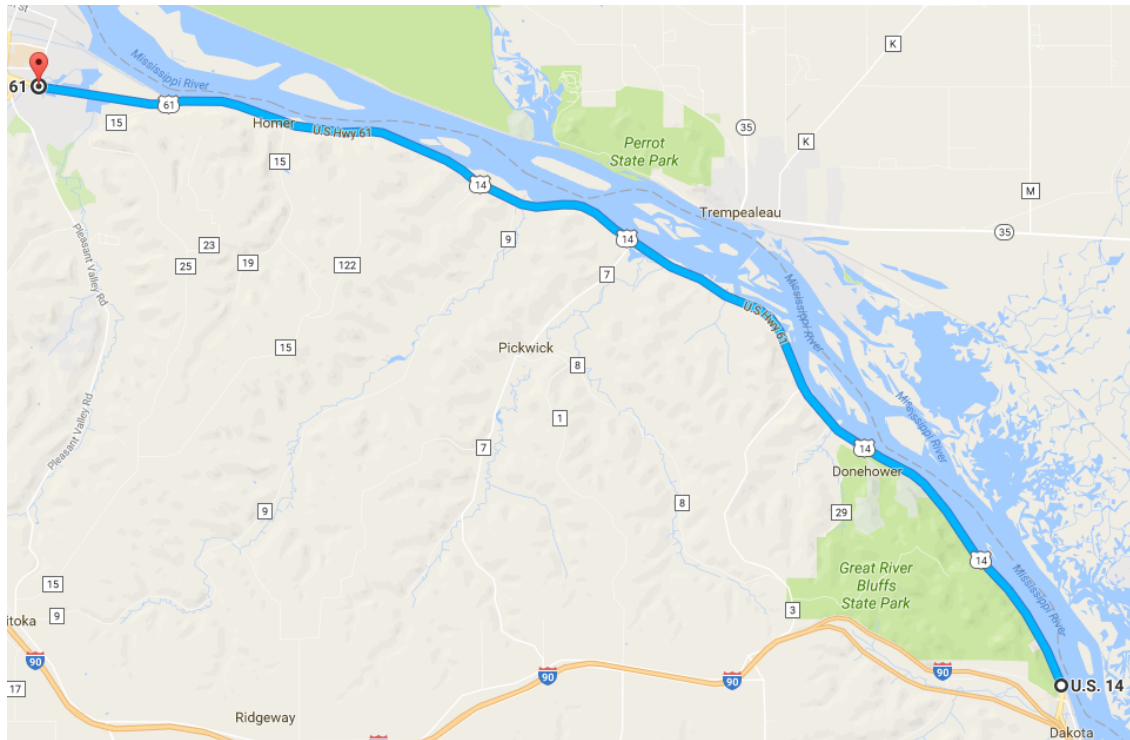


Figure 2.23. Simulator plowing route: US14 from Dakota to US61 Winona, MN.

Operators’ performed the simulated plowing task along a route under the clear visibility and overcast sky condition. The weather and lighting characteristics were chosen by the researchers to ensure that operators could clearly see the route when driving with and without snow cover. Figure 2.24 illustrates the simulated road without snow cover, and Figure 2.25 depicts the overcast sky and clear visibility condition with the road covered by snow. The vertical orange line in the field of view represents the left plow blade edge indicator. (The scenes depicted in Figures 2.24 and 2.25 do not represent the same position on the route.



Figure 2.24. Operator perspective of the simulated route without snow cover.



Figure 2.25. Operator perspective during the simulator plowing exercise using the LED guidance system with the road covered by snow.

## 2.4.4 Results

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### 2.4.4.1 Interview Components

The study's interview components occurred at the conclusion of each five-minute simulated plowing task drive, as well as a general discussion and reflection interview at the end of the fifth drive. During the interviews between drives with each lane boundary guidance interface system, researchers led operators through a series of questions that assessed various usability characteristics, real-world applicability and use case scenarios, and operator opinions on using the system while performing the simulated drive.

- What are your thoughts about using this lane boundary guidance system?
- Do you feel that the feedback (e.g., LED lights, laser) changed your ability to maintain position within the lane? How did it change?
- Can you recall any past occasions in which this system would have been useful to use? If so, please describe the situation and why this would have been helpful.
- Can you recall any past occasions in which this system would not have been useful to use? If so, please describe the situation and why this would not have been helpful
- Can you think of any issues with this design (e.g., issues that might make this design difficult to use while plowing)? If so, what would you change about this design?

Researchers also directed the discussion once operators responded to each item, in order to thoroughly explore their views on the various design and usability aspects of each lane boundary guidance system. For each round of questions, the researcher described the intent and function of the system and asked the participant to walk through each lane boundary interface system while thinking aloud. The “think-aloud” exercise provided the researchers with further detailed information, such as the self-reported cognitive or procedural processes that the operator may utilize to unpack considerations or other opinions on the system secondary to their primary feedback that may otherwise not be exposed in the interview process. Participants were encouraged to imagine that they were using the system while performing a plowing drive in their profession and to share any comments or thoughts about the designs or system functionality that came to mind. At the conclusion of the discussions, participants then ranked each lane boundary guidance system option using a 0 to 50 scale to indicate preference. The preference and ranking scale was administered physically, using a number line with bounds from 0, indicating the lowest score, to 50, representing the highest possible score. Operators placed markers with a graphical depiction of the system (e.g. dotted laser line and LED strip image) on the number line scale, verbally stating the numerical score of the system. Scores on this scale were analyzed post-hoc by researchers and converted to rank data to assess which lane boundary guidance system was preferred overall. Operators also evaluated the systems based on usability criteria, including which system required the most mental resources to use, which system felt safest to use, which system was the easiest to use during the plowing task, and which system operators would like to use overall (i.e. overall preference). A secondary researcher took notes of the participant responses to ensure the operator responses were captured in detail.

#### 2.4.4.2 Lane Boundary Guidance System Preference

Each operator was prompted to disclose their favorite lane boundary guidance system after experiencing each of the five systems. Figure 2.26 depicts the distribution of operators' preferences, where the Laser systems scored highest, followed by a system that incorporated the LED guidance strip. The researchers acknowledge the overall preference values appear to indicate higher desire for the Moving Laser and LED and Fixed Laser systems, however; these preference scores became less concrete once usability dimensions (see Figures 2.26 and 2.27), ease of use, and safety rankings were examined. Operators reported that mental workload and visual appearance of the systems led their interface preference choices.

Notable feedback relating to preference criteria included thoughts on the Fixed Laser and LED system contributed to "Eye fatigue [LED]; it's hard to see, I pay too much attention to it [Fixed Laser]." Additional operator feedback and discussion on the characteristics of their preferred system included visual traits, "Easy on the eyes [LED], easy to follow [LED], easy and off to the side [Moving Laser]." The overall preference feedback granted researchers with a general understanding of where system preference rankings stood, and led the direction of unpacking operator feedback gained in the think-aloud and system ranking questions collected during the interviews.

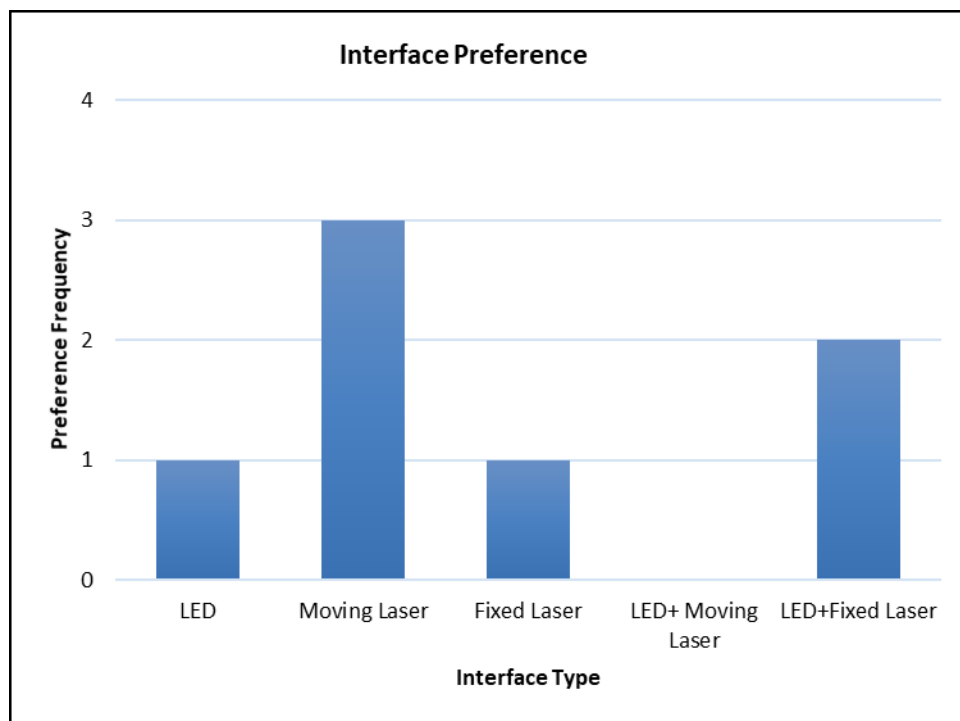


Figure 2.26. Overall Interface Preference Scores.

#### 2.4.4.3 System Usability Scale subjective measures results

After completing a drive using each guidance system, drivers were given the System Usability

Scale (SUS) satisfaction survey to measure their overall acceptance of the laser or LED system they had just used. The SUS satisfaction measure scores range from 0 to 100, with a larger number indicating a higher level of perceived satisfaction. Satisfying systems tend to produce SUS scores in the 70 – 100 range. A typical system SUS score is 68. The results of the SUS satisfaction measure for each interface are shown in Figure 2.27. The only significant difference between any of the five systems was the LED fixed laser guidance system, which was rated as being significantly worse by users, in terms of overall system satisfaction. The SUS scores for the other four systems were all relatively similar, ranging from 73.21 to 76.43 for the LED moving laser, which was the highest rated. There was, however, a relatively large amount of variation among all five system scores. While the satisfaction scores for all but the LED fixed laser system were overall acceptable, they were still not rated as being highly user-friendly or well-accepted by users. The large amount of variation within the ratings for each individual system indicates that there were disagreements between users as to which system was most preferred. Notable feedback accompanying the SUS scores for the highly scoring LED guidance strip and Moving Laser combo included “I would use the LED all the time,” and “[The] LED [is] perfect for whiteout conditions.” Conversely, the LED and Fixed Laser combination scored significantly lower in system usability metrics, and received criticism for having stress-inducing characteristics (e.g. “Stresses me out.”), in addition to increasing mental effort exertion (e.g. “[My] eyes have to fight between [the] laser and LED.”)

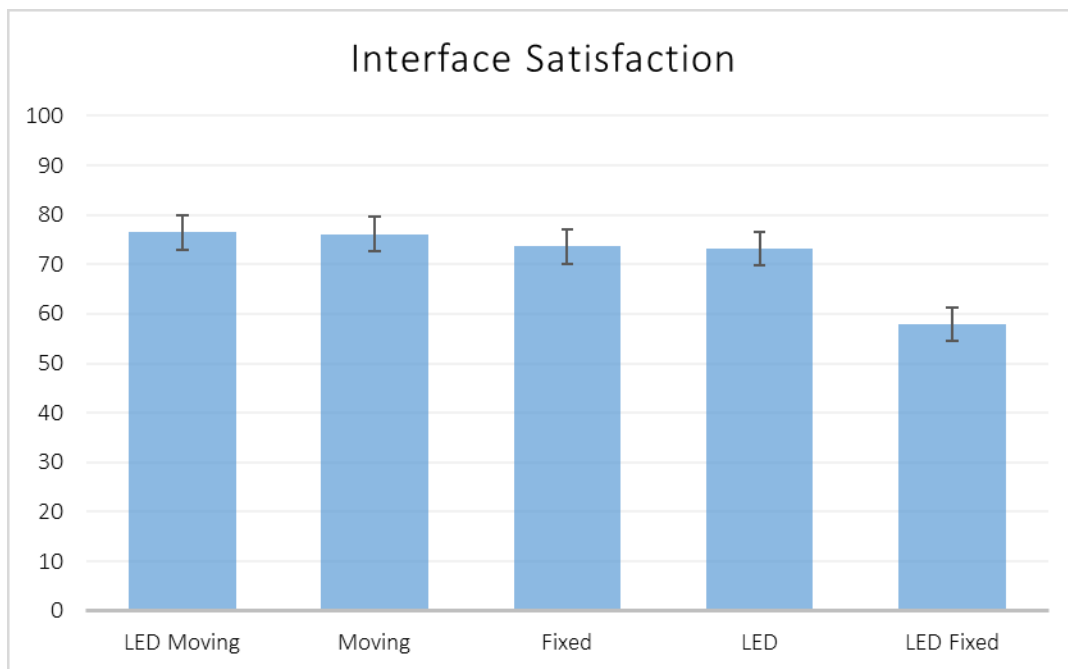


Figure 2.27. Interface Satisfaction calculated by operators’ SUS scoring.

Table 2.7. System Usability Scale Mean Scores and Variance.

	Moving Laser	Fixed Laser	LED + Moving Laser	LED	LED + Fixed Laser
<b>Average</b>	35.29	35.86	38.86	39.86	53.86
<b>Standard Deviation</b>	24.85	25.21	30.42	24.29	32.87

2.4.4.4 Rating Scale of Mental Effort subjective measures results

After completing a drive using each guidance system, drivers completed a standard mental workload rating scale (Rating Scale of Mental Effort or RSME). The purpose of this scale is for users to indicate how much mental effort they felt each of the systems required to utilize while driving, see Appendix B. The workload scale ranges from 0 (Absolutely No Effort) to 150 (Extreme Effort). Figure 2.28 shows the results of the RSME for each of the five systems tested. Only one of the five systems differed significantly in perceived mental workload, the LED and Fixed Laser system, which was rated as requiring significantly more mental effort to use when compared to the other lane boundary guidance systems. Similar to the SUS scores, the RSME scores had a large amount of variance within the ratings of workload for all five systems, see Table 2.8.

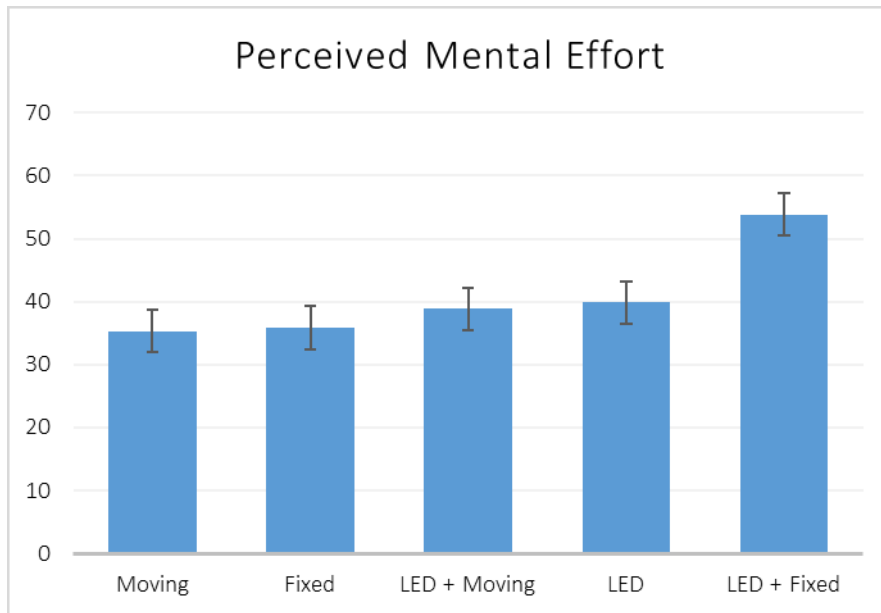


Figure 2.28. Operators' Perceived Mental Effort calculated by RSME scores.

Table 2.8. Rating Scale of Mental Effort Mean Scores and Variance.

	LED + Moving Laser	Moving Laser	Fixed Laser	LED	LED + Fixed Laser
<b>Average</b>	76.43	76.07	73.57	73.21	57.86
<b>Standard Deviation</b>	19.89	21.93	21.55	18.41	17.04

#### 2.4.4.5 In-vehicle display location preference

Operators were asked to state their preferred location and explain their choice for the hypothetical installation of the LED guidance strip component inside the plow truck cabin. Researchers were interested in operators' opinions on the most effective location for referencing the visual feedback systems, such as the MDSS display, while in plowing operations. Results were overwhelming in favor of the top dashboard location, and slightly offset to the right of the center dash stack position. When prompted to explain the reasoning of their choice, operators reported that while they typically focus their attention straight ahead when operating the plow truck, the LED guidance strip would best be suited in a right-offset position on the dashboard in order to reduce mental and visual fatigue in circumstances when they are focused on the rightmost edge of the plow blade. One operator suggested the LED guidance strip may be effective if it were located near the rear-view mirror position in the plow truck, stating that peripheral cues of the LED's color or position would be readily noticed and assist in reducing fatigue during extensive whiteout conditions.

#### 2.4.4.6 Driving performance data

Researchers analyzed the simulator's driving data to examine the influence each lane boundary guidance system demonstrated on plowing task performance while operators completed the driving simulations.

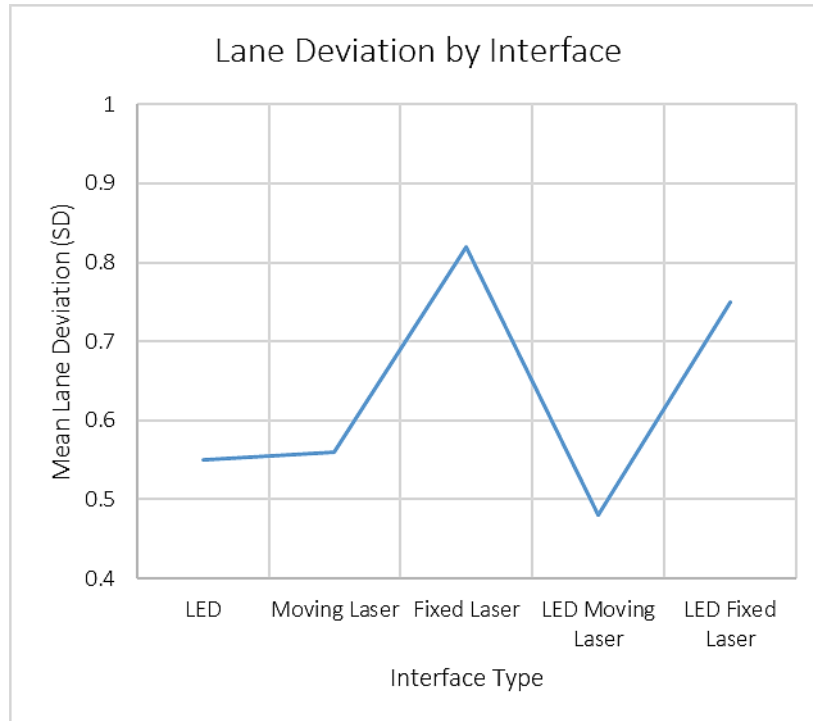
#### 2.4.4.7 Vehicle speed

No significant variances in vehicle speed or vehicle speed-keeping were observed within or across participants' driving data. This is likely due to the fact that each operator performed the simulated plowing task at a speed they felt was appropriate, or was most representative of realistic speed while plowing roadways in the real environment. Researchers attribute this lack of significant speed variation to operators' subjective opinions on which speed was most appropriate for them to complete the plowing task while maintaining speeds comparable to real world plowing operations.

#### 2.4.4.8 Vehicle Lane Deviation

The researchers were interested in evaluating the average lane position and standard lane position deviation in order to assess operators' performance in the plowing task using the lane boundary guidance systems during the simulated drives. Additionally, the measurement of lane position deviation also provides insight into the working memory load and mental effort exertion experiences that each operator experience while performing the drive. Increases in mental effort and working memory reflect in the ability for drivers to maintain consistent lane position while driving. Analysis of the simulator's vehicle lane position metrics across operators found that the presence of the Fixed Laser lane boundary guidance system, as a standalone system or coupled with the LED guidance strip, significantly impacted operators' ability to maintain continuous control over the simulator vehicle while performing the plowing task. Additionally, the standard deviation of lane position was profound, with nearly an entire lane (.83) of variance within the lane was observed while using these systems. Conversely, the LED (.55) and Moving Laser (.56) lane boundary guidance systems granted operators with lane position feedback

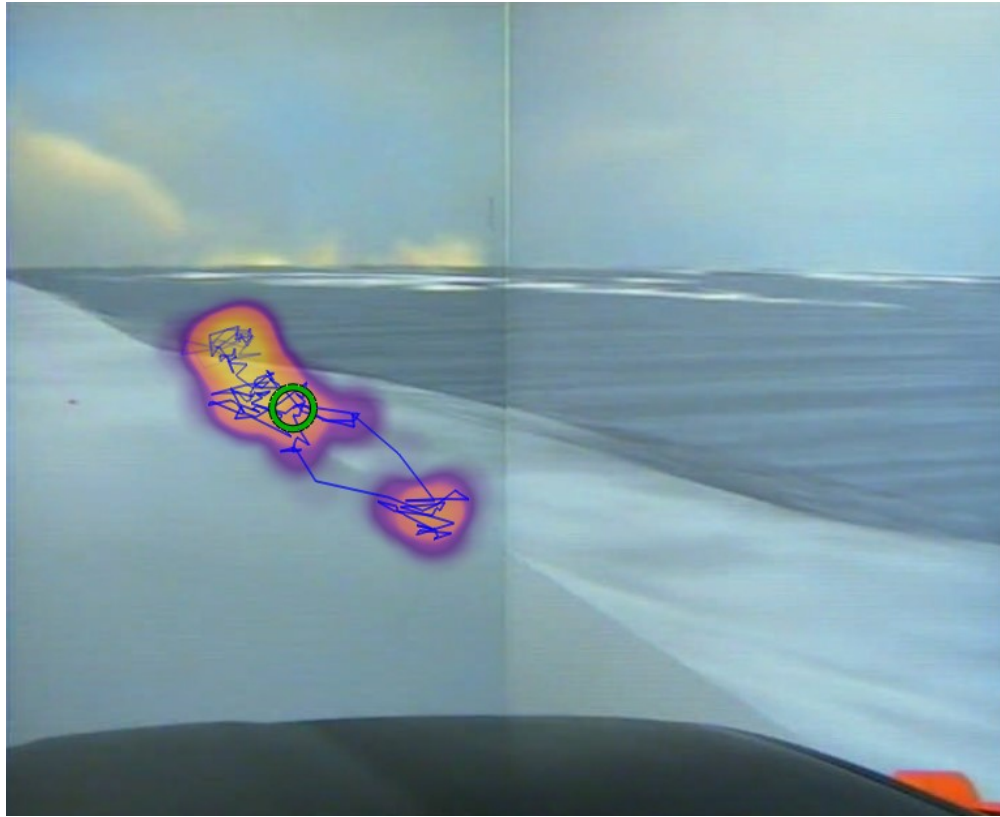
that led to more succinct lane-keeping, and therefore, more accurate performance while performing the plowing task. The best-scoring system was the LED and Moving Laser combination, which garnered an impressive .47 mean lane position standard deviation result when used by operators. Figure 2.29 depicts driver mean lane deviation by lane boundary guidance system type.



**Figure 2.29. Mean Lane Deviation by lane boundary interface guidance system type.**

#### 2.4.4.9 Visual Attention - Eye Tracking Results

Researchers analyzed eye tracking data to understand where the plow operators allocated their gaze, or visual attention, when using each of the five lane boundary guidance systems. Analysis was performed using EyesDx MAPPS software (EyesDx, IA), which allowed researchers to visualize operators' distribution of visual attention. For the purposes of this study, researchers employed the use of heat map analyses, which provided qualitative measurement of where the observer distributes, or clusters, their gaze or focus. While the heat map paradigm does not explicitly state the sequence of eye movements, or saccades, it does provide insight into the distribution of gaze location over time. The heat map analysis works well for visualizing where operators focused their visual attention during the simulated plowing drives, which provides researchers with a deeper understanding of how the operators allocate their attention among the roadway features, interior of the vehicle, and location of lane boundary guidance system information.



**Figure 2.30. Heat map analysis of the eye tracking data - Laser systems based HMI.**

Analysis of eye tracking data revealed significant differences in operators' distribution of their visual attention while performing the plowing task. Results indicate that operators using the Moving Laser or Fixed Laser lane boundary guidance systems spent significantly more time on the fog line and wing edge when compared to the LED guidance strip (see Figure 2.30). When operators performed the plowing task using the LED guidance strip visual attention was more widely distributed across the roadway, in addition to the interior of the vehicle (see Figure 2.31). Researchers interpret these results as multifaceted. Findings from the laser systems suggest that operators focus most of their visual attention directly on the location of the laser point on the roadway. While these findings demonstrate operators were attentive and utilized the laser systems to complete the plowing task as reflected in the lane deviation results, researchers acknowledge that a disproportionate amount of time was allocated to a small region of the roadway, which may be disadvantageous to general plowing operations. Conversely, results show that operators elected to distribute their visual attention more broadly when using the LED guidance strip system. In addition to looking at the LED system within the vehicle, operators' typical gaze patterns using the LED guidance strip including referencing the immediate, mid-distance, and far-ahead forward roadway. Researchers observed that operators did not reference the wing edge nearly as frequently or for extended periods of time when compared to the laser system.

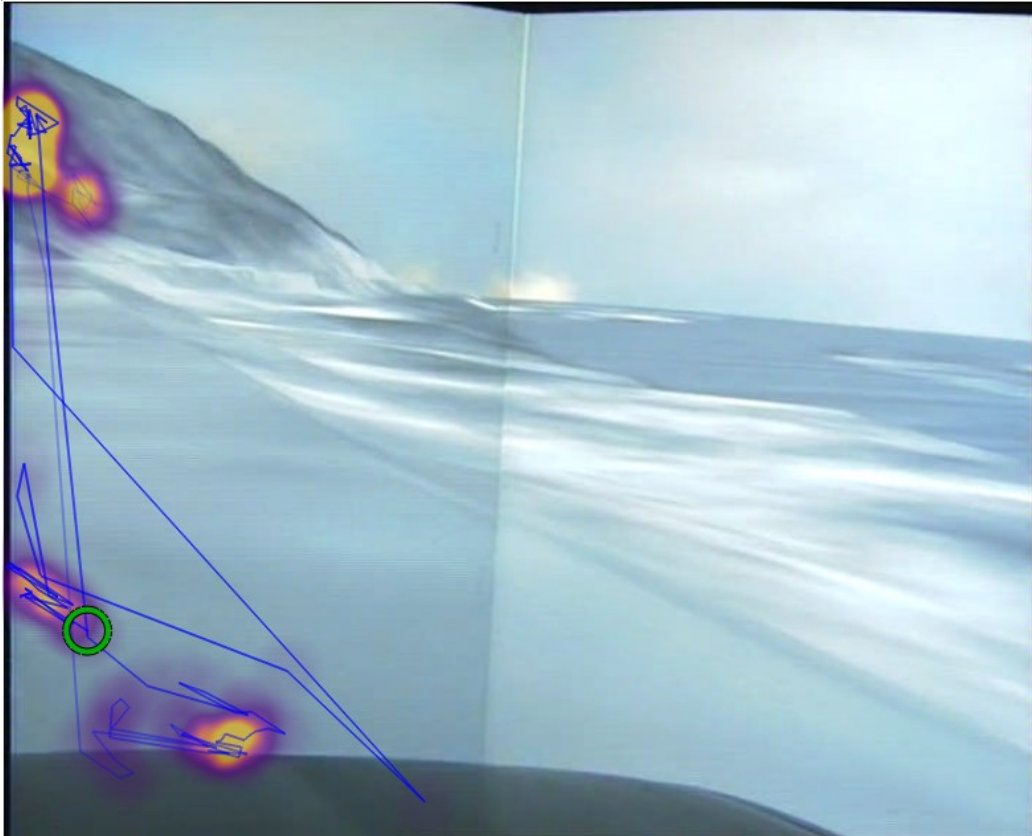


Figure 2.31. Heat map analysis of eye tracking data - LED strip systems based HMI.

## 2.4.5 Conclusions

Overall operator feedback and preference rankings suggest that the most favorable design would include the LED guidance strip component, either with or without the Moving Laser system. Further unpacking of preference and ranking results indicates that the LED guidance strip garnered more overall support. The LED guidance strip appeared at the top of ranking lists that dealt with feedback regarding ease of use, safety of use, least amount of mental resources to use, and, surprisingly, most likely to be used despite the recurrent unfavorable feedback operators provided on incorporating additional in-vehicle displays into the plow truck.

### 2.4.5.1 Recommendations

- Researchers recommend the LED guidance strip, based on operator feedback and plowing performance
  - Significantly better plow-lane keeping ability with LED strip
  - High usability ratings from operators
  - Easily customizable after field testing and further operator feedback
- Examine complimenting LED system with a bird's eye view visual display
  - Increase operators' awareness during whiteout conditions by providing map

- Add heading direction, upcoming curves and distances, or other relevant road information by incorporating bird's eye display
- Further increase operator satisfaction and performance by combining assistive measures

Based upon the findings in the current study, the researchers recommend that future development of the lane boundary guidance system contains a minimalistic in-vehicle display, namely, the experimental LED guidance strip. The LED guidance strip demonstrated its ability to assist snow plow operators with their plowing tasks in the simulation study. The impact on plowing performance was significant when considering their lane-keeping performance (i.e. plowing performance). The LED guidance strip scored highly on the subjective measures scales and received a generally warm reception during interviews. While the current iteration of the LED guidance strip system prototype could be modified to reflect the operators' wishes, such as customizable luminance and contrast sensitivity, the researchers feel confident that operators would benefit from the system during low-visibility plowing conditions. Further testing in field observation tests or continued usability test and design iterations would bolster operator support. Researchers suggest complimenting the LED guidance strip system with a bird's eye display. A rough sketch of a potential bird's eye display and the accompanying LED guidance strip is depicted in Figure 2.32. Adding the bird's eye display will bolster the operator's situational awareness and understanding of the upcoming roadway by using visual cues in the display, which would convey through visual representation, upcoming roadway curves or other features (see Figure 2.32). By adding a visual representation of the roadway, specifically under white-out or severe low-visibility conditions, an in-vehicle display system has the capacity to inform the plow operator of their position within the lane (using the LED system) and along the route (using the display), while reducing operator stress, mental workload, and visual or mental fatigue. The in-vehicle bird's eye display has the ability to further the operator's spatial awareness when coupled with the LED guidance strip, by incorporating heading direction, distance to upcoming curves, or other roadway features (e.g. superelevation, severe vertical curves).

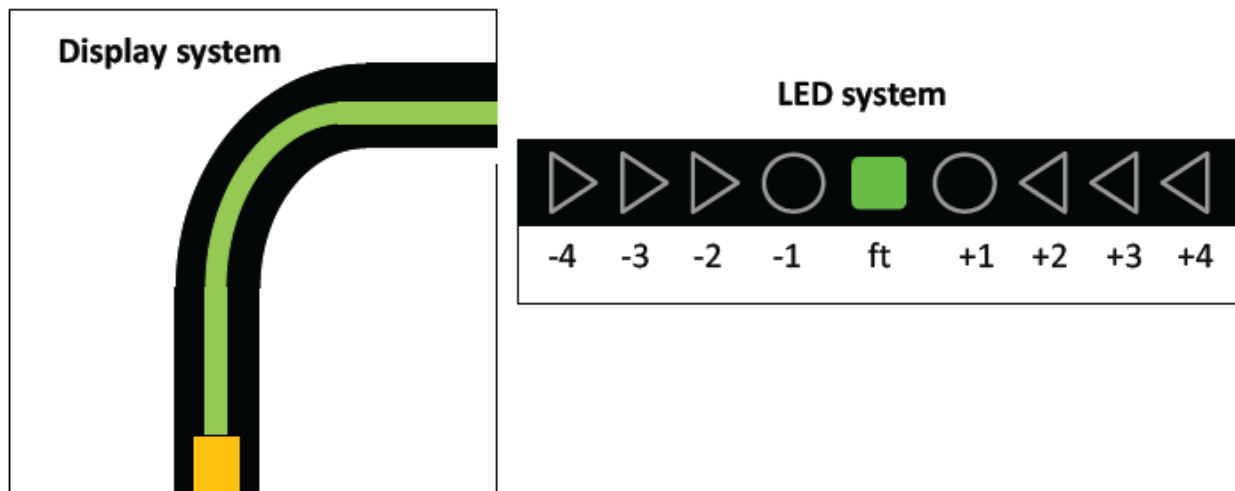


Figure 2.32. Mock-up of potential bird's eye display in conjunction with the LED guidance strip system.

## 2.5 SUMMARY OF FINDINGS AND RECOMMENDATIONS

### 2.5.1 Design and Evaluation of an HMI for the Operator of a Follower Plow in Gang Plowing

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Based on the iterative design process conducted in the driving simulator experiments, researchers were able to identify the most appropriate HMI providing feedback of lead plow truck position to implement in follower plow trucks. Results from an evaluation of operator driver performance in the simulator, in addition to qualitative feedback regarding the interface design characteristics, indicated that seat-based Haptic feedback was the most preferred interface, followed closely by a color-gradient visual display in conjunction with seat-based haptic feedback. Operators reported that while auditory alerts would be effective in providing feedback regarding lead truck position and system states, design challenges would need to be further analyzed to ensure their effectiveness given the various noise elements generated in the cabin during plow operations. Overall, the combination of a color and auditory or color and haptic HMI was highly ranked, operator efficiency and accuracy in plowing simulation drives was demonstrated, and the results were well-received by plow operators.

### 2.5.2 Backup Assist Interface Display

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Snow plow operator feedback collected through interviews and usability testing exercises provided researchers with insights on which HMI interface was best suited for the rear-view backup assist vision system. Researchers concluded that the best approach to bolster usability and maximize efficiency included combining the rear-view camera overlay interface with the ubiquitous MDSS system. Additionally, operator feedback analysis suggests an auditory alert should be added to communicate detection of objects approaching the rear field of view within the combined rear view overlay and MDSS system. Moreover, the proposed MDSS and rear-view overlay HMI system should use auditory alerts to prompt the plow operator when an object within a hazardous proximity to the rear of the plow truck is detected. Plow operators reported that the ability to visually confirm objects behind the truck was a major concern and a highly desired feature in the development of such a system, citing safety risks, driver comfort, and lowered mental workload and stressors as primary concerns.

### 2.5.3 Lane Boundary Guidance HMI

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A post-study data analysis revealed that plow operators preferred the HMI design featuring a dynamic LED display. From the operator perspective, the LED-based HMI system scored well on mental effort exertion ratings, subjective system usability scores, and preference rankings. Additionally, the LED-based feedback system positively impacted operators' abilities to maintain accurate lane boundary (or plow edge) position throughout the driving simulator study. Analysis of eyetracking data showed less demand in visual attention while performing the plow routes. Recommendations following this study suggest that the use of the LED-based HMI system, preferably configured with a bird's eye display, is best suited to serve as a candidate HMI lane boundary guidance system for use under adverse plowing conditions.

#### **2.5.4 Summary**

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Our experiments and analyses of the HMI study results suggest that each component of the HMI demonstrated its intended effectiveness at enhancing plow operators' task performance, while reducing their reported mental workload and associated cognitive effort exertion under the simulated high-stress plowing scenarios. Through human factors user-centered design methods, researchers were able to include MnDOT plow operators in the design process to bolster user feedback and satisfaction while simultaneously reaching plow operations performance goals.

## CHAPTER 3: EVALUATION OF DSRC OBU TO SUPPORT SNOWPLOW OPERATIONS

In this Chapter we describe the evaluation of the system performance and position accuracy of OBU units commercially available in 2015-16 for future coordinated and cooperative applications of vehicles in close proximity, typical of maintenance operations. Our goal is to test OBU's to verify their specifications in an operational scenario similar to that used for gang plowing or mobile work zone applications. In this application, we considered the ability of an operator to maintain the lateral and longitudinal separation of one plow following another, using the relative position measurement provided by two OBU's, one mounted on the lead vehicle and one mounted on the follower vehicle. Our focus here is on the accuracy of the measurement.

### 3.1 EVALUATION OF RELATIVE POSITION USING DSRC OBU

As illustrated in Figure 3.1, we initially proposed to equip each test vehicle with an RTK (Real Time Kinematic) GNSS receiver, a radar sensing system, an in-vehicle display, and an Onboard Unit (OBU), a cellular modem to receive Differential GNSS corrections for the RTK GNSS receiver, and a processor for data communication and acquisition. Please note that an ASD is sometimes called a Vehicle Awareness Device (VAD).

We integrated and tested the DSRC, and the RTK GNSS on a passenger vehicle for initial system verification.

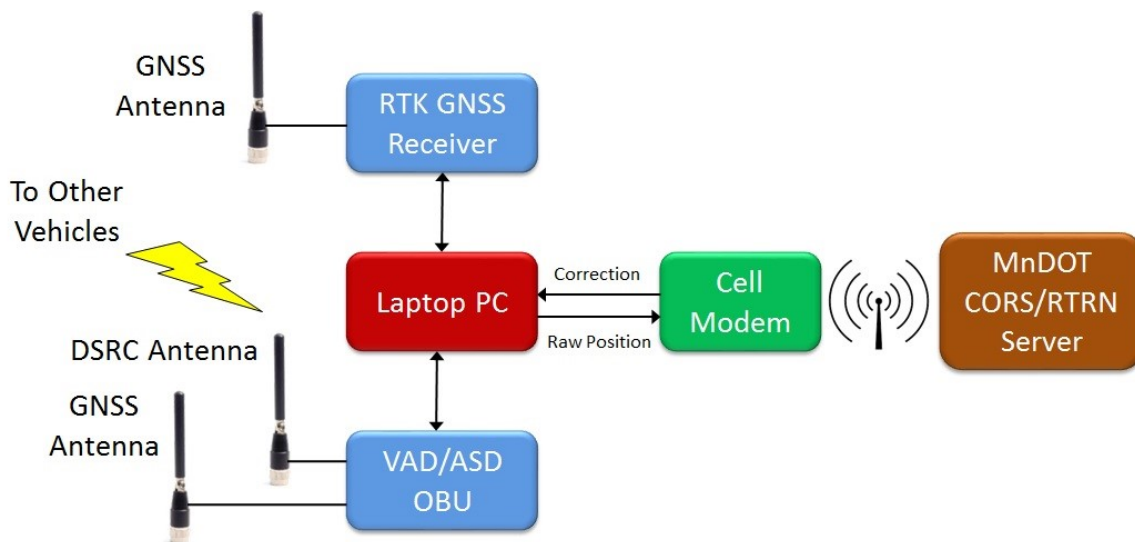


Figure 3.1. In-vehicle system for evaluating OBU performance per vehicle

We initially purchased a pair of DSRC OBUs from Arada for testing. We programmed both OBUs to collect position data to verify their positioning accuracy as compared to an RTK differential GNSS in an operational scenario using a passenger vehicle. However, the GNSS solutions from the Arada DSRC OBUs

were not satisfactory as compared to the positioning solutions from the RTK system. Based on a trip with the best GNSS performance from the Arada OBUs, the average distance error was around 2.1 meters with a standard deviation of 1.1 m. between the Arada OBU and the RTK differential GNSS. Requests to Arada regarding these results went unanswered.

In the following, we will use GNSS and GPS interchangeably; GPS is the American version of GNSS.

To further investigate the GNSS performance from another DSRC vendor, we also validated the positioning accuracy of three DSRC OBUs manufactured by Savari. These Savari DSRC units were purchased by Professor Imran Hayee’s Connected Vehicles Research Laboratory at the University of Minnesota Duluth (UMD) campus for his research. In our initial experiments on an arterial near the UMD campus, we found the “best” positioning performance measured on one of the three Savari OBUs to exhibit an average distance error of less than 0.8 meters with a standard deviation of 0.4 m between the Savari OBU and the RTK differential GNSS.

We shared our validation results with both DSRC manufacturers. Savari informed us that their current ASD uses the GPS chipset LEA-6 from U-Blox. The LEA-6 GPS solution has a specified horizontal position accuracy without aiding (i.e. without correction/augmentation) of 2.5 m Circular Error Probable (CEP) or 2.0 meters with satellite based augmentation. Savari plans to upgrade the GPS chipset on their OBUs toward the end of 2016.

We have since purchased two ASD OBUs from Savari to further our effort of GNSS performance validation for connected vehicles applications. We share the license for the SDK support libraries that Savari provided to Prof. Hayee.

The software that we used for conducting our experiments are described in Appendix D.

Several experiments under different conditions, such as antenna mounting orientation, mounting plate design, roadway type, vehicle speed, traveling direction, etc., were conducted to validate the absolute and relative positioning accuracy of the GNSS on DSRC OBUs. A summary of experiments conducted for both the Arada and Savari DSRC OBUs is listed in Table 1.

This Chapter describes the design, methodology and results from our experiments using two Savari DSRC OBUs and evaluation of the relative positioning performance of the OBUs on two moving vehicles.

**Table 3.1 List of Experiments Conducted to Evaluate Positioning Performance of DSRC OBUs**

<b>Date</b>	<b>Test Location</b>	<b>DSRC Vender</b>	<b>Notes</b>
9/10/2015	I-35W between Downtown Minneapolis and E. Diamond Lake Rd.	Arada	Speed at 50-55 MPH
9/29/2015	I-35W between Downtown Minneapolis and E. Diamond Lake Rd.	Arada	Speed at 50-55 MPH
10/2/2015	I-35W between Downtown Minneapolis and E. Diamond Lake Rd.	Arada	Speed at 50-55 MPH
10/22/2015	W. Arrowhead Rd., Duluth, MN	Arada & Savari	Speed at 35 MPH

11/9/2015	I-35W and I-94	Arada & Savari	Speed at 50-55 MPH
12/7/2015	W. Arrowhead Rd., Duluth, MN	Arada & Savari	Speed at 35 MPH
4/13/2016	State Fairground, Larpenteur, and Highway 280 between MN 36 & I-94	Savari	Stationary and speed at 35-50 MPH
4/27/2016	State Fairground Parking Lot Loops	Savari	Speed at 35 MPH
5/25/2016	Snelling/Larpenteur/Roselawn/Fairview Block	Savari	Speed at 15-45 MPH
6/13/2016	MN 65 between I-694 and US 10	Savari	No overpasses, speed at 40-50 MPH
7/7/2016	MN 65 between Blaine and Cambridge, MN	Savari	No overpasses, speed at 40-50 MPH
8/10/2016	MN 65 between Bunker Lake Blvd NE and 153rd Ave. NE	Savari	No overpasses, speed at 60-65 MPH
9/20/2016	I-94, I-694 and I-494	Savari	Speed around 60-70 MPH
10/19/2016	St. Francis, St. Cloud & Hutchinson Area	Savari	Rural area
11/8/2016	I-94 and Radio Dr. in Woodbury	Savari	Highway & arterial
12/14/2016	Stationary test in a parking lot	Savari	No vehicle movement

### 3.2 DESIGN AND SETUP OF EXPERIMENTS

We acquired 2 DSRC OBUs from Savari for the following experiments. Given the poor performance of the Arada units and no support from Arada, we no longer considered their OBU's.

We programmed the OBUs to collect GNSS position data to verify their relative positioning accuracy between OBUs in an operational scenario using a passenger vehicle. The RTK differential GNSS was not used for the following series of experiments.

For our experiments, we designed mounting fixtures and mounted GNSS antennas on a vehicle rooftop at a fixed separation while traveling on a roadway. Figure 3.2 to 3.8 shows the different configurations of mounting the DSRC OBU and RTK GNSS antennas on the rooftop of a passenger vehicle in our tests. The purpose of testing different antenna configurations is also to evaluate the impact of a vehicle's traveling direction on the GNSS positioning accuracy.

We used the default configuration in the Savari MobiWAVE-S103 units. (Details on the Mobiwave OBU product line can be found at <http://savari.net/wp-content/uploads/2016/05/Savari-OBU-DataSheet-FINALMay2016.pdf>). The Savari firmware version used for all experiments was 3.1.2.

WAAS was turned on (default setting).

We also verified results from our data collection code before the first test, and they were effectively identical to the results from the Savari API program (based on one of their examples). For most of the testing, we collected the raw NMEA output from the GPS module, since it provides more data elements such as GPS fix data and number of satellites in addition to latitude, longitude, and speed information. Our tests have shown that the GPS fix data collected with both methods is the same. (A GPS Fix means

that the receiver was able to locate a sufficient number of GPS satellites and calculated a position solution.)

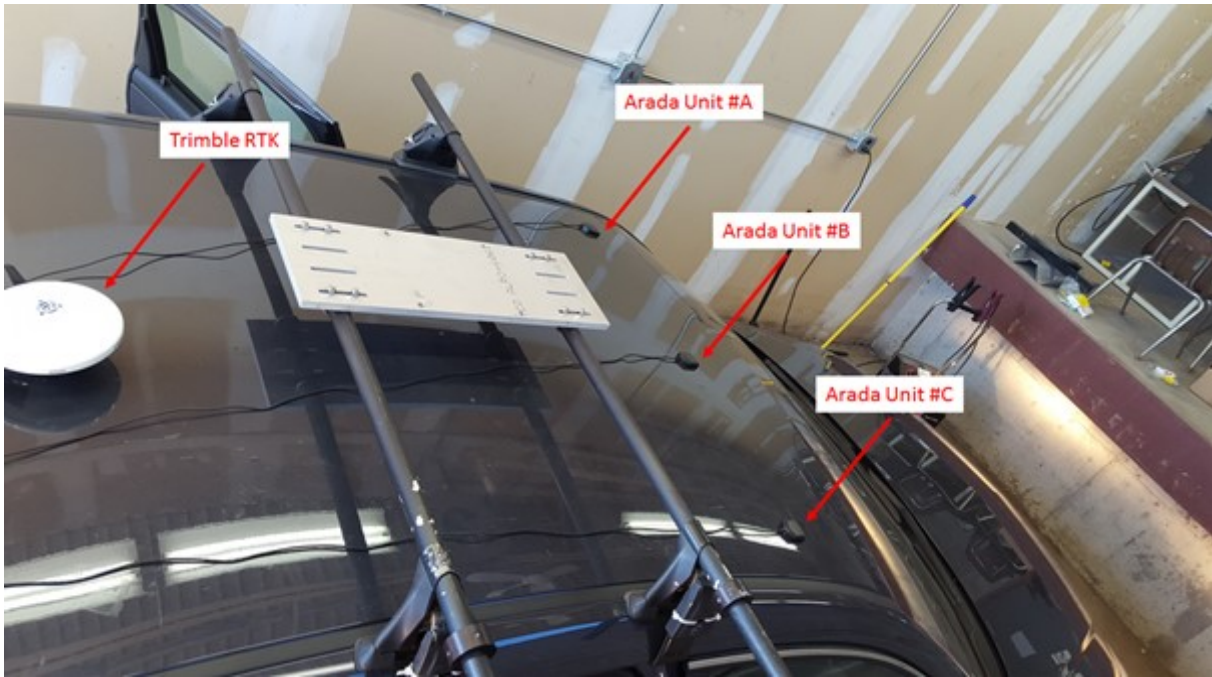


Figure 3.2. Installation of RTK & Arada GPS antennas on the rooftop of a passenger vehicle



Figure 3.3. Installation of Arada & Savari GPS antennas on the rooftop of a passenger vehicle

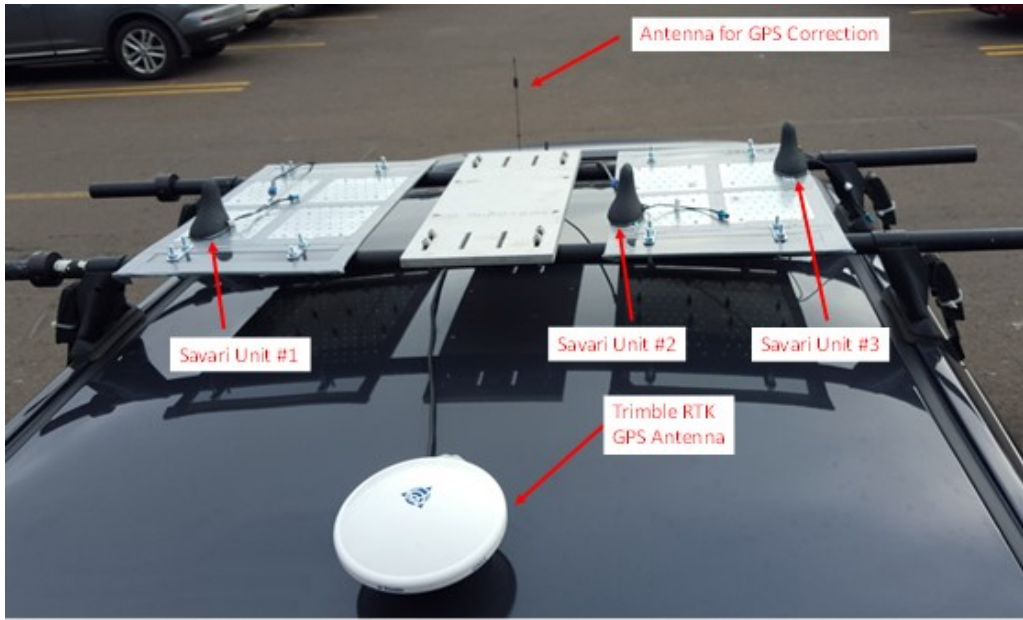


Figure 3.4. Installation of Savari GPS antennas on the rooftop of a passenger vehicle



Figure 3.5. Savari GPS antennas installed in front-back configuration on the rooftop of a passenger vehicle.



Figure 3.6. Savari GPS antennas installed in left-right configuration on the rooftop of a passenger vehicle.

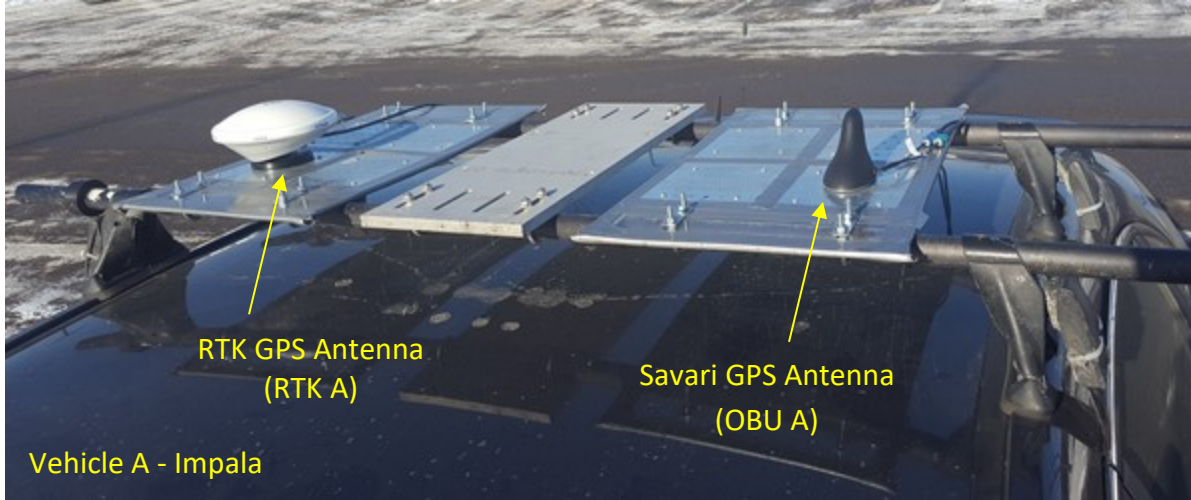


Figure 3.7. First Pair of RTK and Savari GPS antennas installed on the rooftop of a passenger vehicle (Impala).

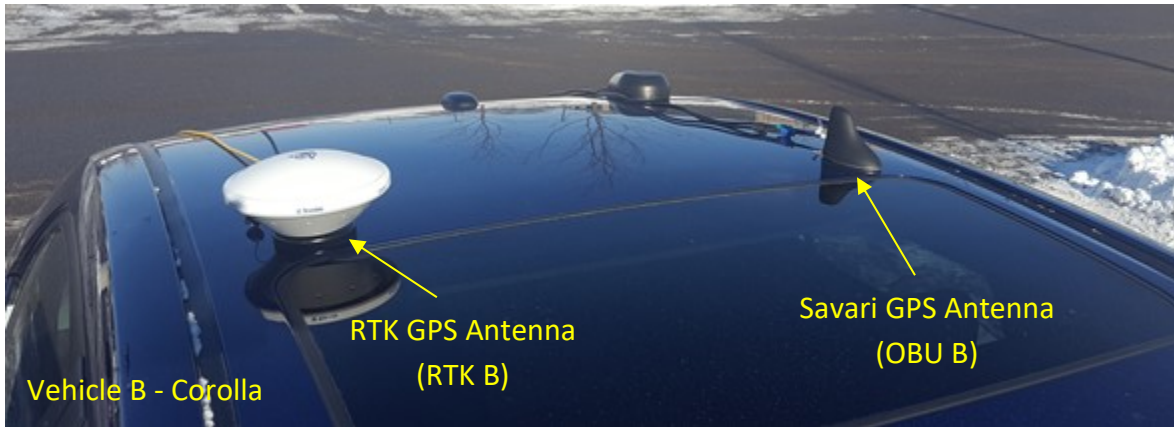


Figure 3.8. Second Pair of RTK and Savari GPS antennas installed on the rooftop of a passenger vehicle (Corolla).

### 3.3 EVALUATION METHODOLOGY

While the test vehicle was moving, we first measured the error in relative distance measurements between 2 fixed OBU antennas on a vehicle rooftop. Figure 3.9 illustrates the actual and measured locations of two GNSS antennas. The position error can be computed as,

$$E^i = \text{Relative Positioning Error at time } i = |d_{est}^i - d_{real}| \quad (\text{Eq. 1})$$

Where,

$d_{real}$  = Measured Antenna Separation in Meters,

$i$  = Seconds since last GPS Position Fix (from GPS satellites),

$A_{est}^i$  = GPS Position Estimate for Antenna A at time  $i$  (lat. & lon. in degrees),

$B_{est}^i$  = GPS Position Estimate for Antenna B at time  $i$  (lat. & lon. in degrees), and

$$d_{est}^i = \text{VincentyDistance}(A_{est}^i, B_{est}^i) \text{ (computed with } \text{geopy} \text{ module) in Meters.}$$

The *VincentyDistance* function from the Python Vincenty library calculates the geographical distance (in meters or miles) between 2 points with extreme accuracy. This library implements Vincenty's<sup>1</sup> solution to the inverse geodetic problem. It is based on the WGS 84 reference<sup>2</sup> ellipsoid and is accurate to within 1 mm or better. This formula is widely used in geographic information systems (GIS) and is much more accurate than methods for computing the great-circle distance (which assume a spherical Earth). The *geopy* is a Python geocoding tool to locate the coordinates of landmarks.

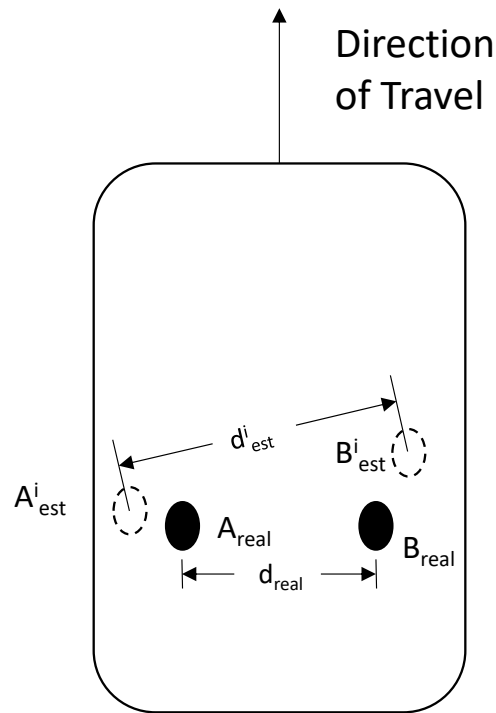


Figure 3.9. Estimated and Actual Locations of 2 GNSS Antennas.

The error over an entire run (mean and standard deviation) can be computed using equation (2) and (3), respectively.

$$E^{mean} = \frac{\sum_{i=0}^n E^i}{n} \quad (\text{Eq. 2})$$

$$E^{std} = \sqrt{\frac{\sum_{i=0}^n (E^i - E^{mean})^2}{n}} \quad (\text{Eq. 3})$$

<sup>1</sup> [https://en.wikipedia.org/wiki/Vincenty%27s\\_formulae](https://en.wikipedia.org/wiki/Vincenty%27s_formulae)

<sup>2</sup> [https://en.wikipedia.org/wiki/World\\_Geodetic\\_System](https://en.wikipedia.org/wiki/World_Geodetic_System)

Ten measurements of the relative position offsets between antennas were taken using a tape measure. These were averaged to calculate  $d_{real} = 1.1938$  meters. First, the error is calculated at each point using Eq. (1), e.g.:

$$i = 62822.0 \text{ sec.}$$

$$A_{est}^i = (44.87819867^\circ, -94.41805317^\circ)$$

$$B_{est}^i = (44.87820683^\circ, -94.41804267^\circ)$$

$$d_{est} = 1.22962 \text{ meters}$$

$$E^i = |1.22962 \text{ m} - 1.1938 \text{ m}|$$

$$E^i = 0.03582 \text{ m}$$

This calculation is repeated for all subsequent points in the run and the arithmetic mean and standard deviation are computed, yielding the results shown in Table 3.2. These simply represent an example of the computation that we used.

**Table 3.2 Results of a Position Error Calculation**

Time (sec)	A Latitude (deg)	A Longitude (deg)	B Latitude (deg)	B Longitude (deg)	$d_{est}$ (m)	$d_{real}$ (m)	$E^i$ (m)
62822.0	44.87819867	-94.41805317	44.87820683	-94.41804267	1.22962	1.1938	0.03582
62822.1	44.8781985	-94.41805317	44.87820683	-94.41804267	1.243353	1.1938	0.049553
62822.2	44.87819867	-94.41805317	44.87820683	-94.41804267	1.22962	1.1938	0.03582
62822.3	44.8781985	-94.41805317	44.87820683	-94.4180425	1.252178	1.1938	0.058378
62822.4	44.8781985	-94.41805317	44.87820683	-94.4180425	1.252178	1.1938	0.058378
62822.5	44.8781985	-94.41805317	44.87820683	-94.4180425	1.252178	1.1938	0.058378
62822.6	44.8781985	-94.41805317	44.87820683	-94.41804233	1.26108	1.1938	0.06728
62822.7	44.8781985	-94.41805317	44.87820683	-94.41804233	1.26108	1.1938	0.06728
62822.8	44.8781985	-94.41805317	44.87820683	-94.41804217	1.270055	1.1938	0.076255
62822.9	44.8781985	-94.41805317	44.87820667	-94.41804217	1.256614	1.1938	0.062814
						Mean	0.056995
						Std. Dev.	0.012547

The results of this test showed a mean relative position error between 2 fixed OBUs of 0.057 meters with a standard deviation of 0.013 meters. Note that the purpose of the data presented in Table 3.2 is only meant to show the process used. The actual results are discussed in the next section.

## 3.4 DATA COLLECTION AND ANALYSIS

This section describes the experiments we recently conducted by mounting the RTK units and Savari OBUs on two vehicles for evaluating the position accuracy. Section 6.1 includes experiment results conducted using two OBUs on the rooftop of a vehicle at three locations. Section 6.2 describes the experiments conducted by mounting the ASD OBUs on two passenger vehicles together with a RTK GNSS system on each vehicle.

### 3.4.1 Position Accuracy between Two Savari ASD OBUs

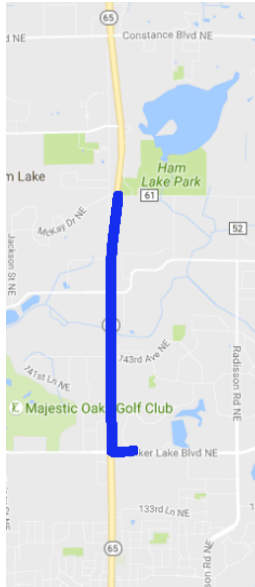
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ASD OBU antennas were mounted on a passenger vehicle as illustrated in Figure 3(d) & 3(e) to compare relative positioning accuracy between the OBUs.

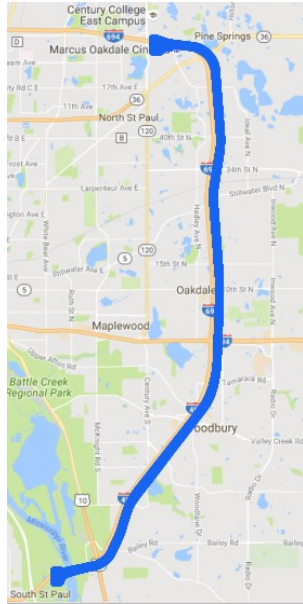
#### 3.4.1.1 Introduction

We describe two experiments conducted on 3 roadway segments, as illustrated in Figure 3.10, on 8/10/2016 and 9/20/2016, respectively, and a third experiment conducted on 10/18/2016 in the St. Francis, St. Cloud, and Hutchinson areas with less obstructions that may block satellite reception. The first experiment was conducted on a north-south segment of trunk highway MN-65 between Bunker Lake Boulevard and County Road 61 in Ham Lake (about 2 miles). The first test site is a divided highway with 2 lanes in each direction and traffic signal controls. The posted speed limit is 65 MPH. The second experiment was performed on I-694/494 (in the north-south direction) between MN-36 and US-10 in Oakdale/Woodbury (about 10 miles), and I-94 east of the I-94/494/694 interchange to the Wisconsin border (about 10 miles in the east-west direction). The second test sites are both interstate freeways. The I-694/494 test segment has a posted speed limit of 60 MPH and the I-94 east of the I-94/494/694 interchange test segment has a posted speed limit of 70 MPH.

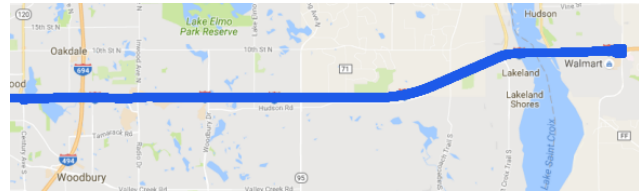
In the first experiment (conducted on 8/10/2016), we used tape to mark the antenna positions between the different tests, maintaining a 3-foot separation in all configurations. We used the corner of the roof and the edge of the moon roof in the second and third experiments (conducted on 9/20/2016 & 10/18/2016) to place the antennas, which amounted to a 3 foot offset left-right, and a 2 foot 8 inch offset front-back.



**MN-65 Test Site  
(8/10/2016)**



**I-694/494 Test Site  
(9/20/2016)**



**I-94 Test Site (9/20/2016)**

**Figure 3.10. Images of three GNSS position test sites (Background image from Google map).**

### 3.4.1.2 Test Results

We applied the methodology described in Section 5 for our data analyses. The analyses we performed accounted for the offset of the antennas and removed the turnaround points at the end of travel. We also tried to exclude GNSS data when the test vehicle went under overpasses or bridges by placing a constraint on the minimum number of satellites. (Note: Previously, we had used the GNSS fix quality of a RTK GNSS to filter out less-accurate estimates, but the RTK was not used for the relative positioning accuracy tests.)

Table 3.3 lists the relative positioning accuracy of the two DSRC OBUs from experiments conducted on MN-65 on 8/10/2016, broken down by the antenna mounting configuration. For antennas mounted in a front-back configuration, the best performance observed (scenario a.2) shows a mean error of 0.63 m with a standard deviation of 0.33 m; the 50th percentile and 95th percentile position error for that scenario are 0.54 m and 1.15 m, respectively. The maximum relative position error is 1.4 m. For antennas placed in a left-right configuration, scenario a.5 shows the best performance, with an average position error of 0.54 m and a standard deviation of 0.33 m; the 50th percentile and 95th percentile position error for that scenario are 0.51 m and 1.22 m, respectively. The maximum relative position error is 1.65 m.

Table 3.4 lists the relative positioning accuracy from experiments conducted along I-494/694 in the NB-SB directions on 9/20/2016. The results here are again broken down by antenna mounting configuration, as well as by direction of travel. For antennas installed in a left-right configuration, the best performance (scenario b.3, travelling northbound) has a mean position error of 0.92 m with a

standard deviation of 0.52 m. The 50th and 95th percentile of position error are 0.83 m and 1.91 m, respectively. The maximum relative position error is 2.3 m. When the antennas were mounted in a front-back configuration, scenario b.5 (travelling southbound) demonstrated an average position error of 0.43 m with a standard deviation of 0.35 m. The 50th and 95th percentile of position error are 0.36 m and 1.11 m, respectively. The maximum relative position error is 2.19 m.

**Table 3.3 Relative Position Error from Experiment Conducted on 8/10/2016**

Relative Position Error (m)			MN-65 North-South Runs - 8/10/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
Antennas Placed in Front-Back Configuration	a.1	Bravo Front, Alpha Back	0.97	0.52	0.69	1.89	1.96	2,485
	a.2	Alpha Front, Bravo Back (Cables Swapped)	<b>0.63</b>	<b>0.33</b>	<b>0.54</b>	<b>1.15</b>	<b>1.40</b>	<b>2,118</b>
	a.3	Alpha Front, Bravo Back (Original Cables)	0.85	0.68	0.60	1.95	2.01	2,085
Antennas Placed in Left-Right Configuration	a.4	Alpha Left, Bravo Right (Original Cables)	0.80	0.67	0.40	1.72	1.81	2,049
	a.5	Bravo Left, Alpha Right (Original Cables)	<b>0.54</b>	<b>0.33</b>	<b>0.51</b>	<b>1.22</b>	<b>1.65</b>	<b>2,929</b>

**Table 3.4 Relative Position Error from North-South Runs Collected on 9/20/2016**

Relative Position Error (m)			Scenario	I-494/696 North-South Runs - 9/20/2016 Test Results					
				Mean	SD	50th Percentile	95th Percentile	Max	N
Antenna Left-Right	All	b.1	1.02	0.59	0.92	2.15	2.85	10,914	
	SB Only	b.2	1.10	0.63	0.96	2.29	2.85	5,474	
	<b>NB Only</b>	<b>b.3</b>	<b>0.92</b>	<b>0.52</b>	<b>0.83</b>	<b>1.91</b>	<b>2.30</b>	<b>5,168</b>	
Antenna Front-Back	All	b.4	0.54	0.43	0.45	1.38	2.47	10,570	
	<b>SB Only</b>	<b>b.5</b>	<b>0.43</b>	<b>0.35</b>	<b>0.36</b>	<b>1.11</b>	<b>2.19</b>	<b>5,198</b>	
	NB Only	b.6	0.65	0.48	0.55	1.56	2.47	5,159	

Table 3.5 lists the relative positioning accuracy from experiments conducted along I-94 in the EB-WB directions on 9/20/2016. When the antennas were installed in a left-right configuration, the best performance (scenario c.3, travelling westbound) demonstrated a mean position error of 1.18 m with a standard deviation of 0.83 m. The 50th and 95th percentile of position error are 1.27 m and 2.29 m, respectively. The maximum relative position error is 3.83 m. When the antennas were placed in a front-back configuration, scenario c.5 (travelling eastbound) demonstrated an average position error of 0.95 m with a standard deviation of 0.53 m. The 50th and 95th percentile of position error are 1.04 m and 1.79 m, respectively. The maximum relative position error is 2.72 m.

On average, results from the second experiment are not as good as the results from the experiment conducted at MN-65. However, the north-south run along I-694/494 with the antennas mounted in front-back configuration shows similar results as compared to those from MN-65.

Subsequently, we conducted another experiment on 10/18/2016 using the same setup as previously described with both OBU antennas placed in the left-right configuration in the St. Francis, St. Cloud, and Hutchinson areas on roadways with less obstructions that may block satellite reception. Table 3.6 lists the relative positioning accuracy from experiments conducted in St. Francis (d.1), St. Cloud (e.1-e.2), and Hutchinson (f.1-f.3). The best performance (scenario f.1, travelling eastbound) demonstrated a mean position error of 0.5 m with a standard deviation of 0.23 m. The 50th and 95th percentile of position error are 0.54 m and 0.84 m, respectively. The maximum relative position error is 0.92 m. Scenario e.2 (travelling southbound from St. Cloud to Hutchinson) demonstrated an average position error of 1.39 m with a standard deviation of 0.28 m. The 50th and 95th percentile of position error are 1.36 m and 1.88 m, respectively. The maximum relative position error is 2.13 m. Overall, the relative position error in scenario e is about twice as large as the other two scenarios (d & f). On average, results from the experiments in the rural area (Table 3.6) are slightly better than the results from the experiment conducted from I-94 and I-494/694 (Table 3.4 & 3.5), but similar to the results from MN-65 (Table 3.3).

**Table 3.5 Relative Position Error from East-West Runs Collected on 9/20/2016**

Relative Position Error (m)		Scenario	I-94 East-West Runs - 9/20/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
Antenna Left-Right	All	c.1	1.38	0.77	1.54	2.28	5.20	9,747
	EB Only	c.2	1.60	0.65	1.64	2.24	5.20	4,728
	<b>WB Only</b>	<b>c.3</b>	<b>1.18</b>	<b>0.83</b>	<b>1.27</b>	<b>2.29</b>	<b>3.83</b>	<b>4,798</b>
Antenna Front-Back	All	c.4	1.52	0.85	1.50	3.06	5.47	9,676
	<b>EB Only</b>	<b>c.5</b>	<b>0.95</b>	<b>0.53</b>	<b>1.04</b>	<b>1.79</b>	<b>2.72</b>	<b>4,817</b>
	WB Only	c.6	2.11	0.72	1.88	3.34	5.47	4,745

**Table 3.6 Relative Position Error in Rural Areas Collected on 10/18/2016**

Relative Position Error (m)			St. Francis, St. Cloud & Hutchinson 10/19/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
Antennas Placed in Left-Right Configuration	d.1	St. Francis to St. Cloud (East to West)	0.72	0.49	0.69	1.59	1.80	6,187
	e.1	St. Cloud to Hutchinson (North to South) - Segment 1	<b>1.37</b>	<b>0.30</b>	<b>1.41</b>	<b>1.80</b>	<b>1.89</b>	<b>8,661</b>
	e.2	St. Cloud to Hutchinson (North to South) - Segment 2	<b>1.39</b>	<b>0.28</b>	<b>1.36</b>	<b>1.88</b>	<b>2.13</b>	<b>4,807</b>
	f.1	Hutchinson to Minneapolis (West to East) - Segment 1	0.50	0.23	0.54	0.84	0.92	4,550
	f.2	Hutchinson to Minneapolis (West to East) - Segment 2	0.87	0.17	0.85	1.18	1.28	1,730
	f.3	Hutchinson to Minneapolis (West to East) - Segment 3	0.72	0.39	0.66	1.44	1.69	4,529

### 3.4.2 Comparison of Position Error Using Two Vehicles

We also installed the ASD OBUs on two passenger vehicles together with a RTK GNSS<sup>3</sup> system on each vehicle, as illustrated in Figure 3.7 & 3.8. The RTK GNSS systems, which each have an absolute position accuracy of around a decimeter, was used as positioning references to compute the relative position error when two passenger vehicles are stationary or traveling near each other on a roadway.

The GPS positioning accuracy from the Savari ASD unit is insufficient for lane boundary guidance applications. Therefore, we purchased an RTK GNSS receiver and antenna to obtain decimeter positioning accuracy of a plow truck for the lane boundary following application. The RTK and other data processing and communication components, except the antennas, were packaged in an enclosure as illustrated in Figure 3.11 & 3.12. The GNSS position correction is obtained from Minnesota's Continuously Operating Reference Station Network (MnCORS<sup>4</sup>). The Savari OBU unit has an integrated antenna that is shared by both its GPS and DSRC radios. Our plan is to use the OBU processor together with the RTK GNSS to provide high accuracy lane boundary guidance (and not use the GPS packaged in the Savari OBU). This is the packaged unit which was used for 2<sup>nd</sup> evaluation of the relative position accuracy in which the RTK was used as a baseline for the analysis.

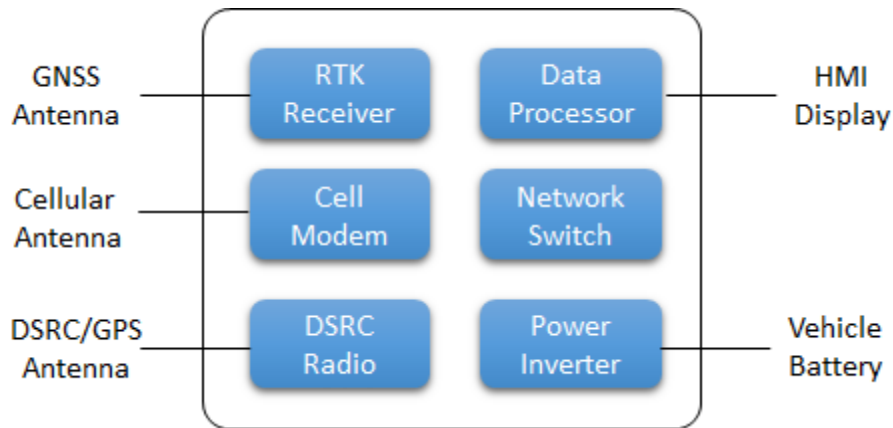


Figure 3.11. System components of a portable RTK GNSS and DSRC OBU system.

<sup>3</sup> Trimble Real Time Kinematic (RTK) GPS receiver, <http://www.trimble.com/>

<sup>4</sup> <https://www.dot.state.mn.us/surveying/cors/>



Figure 3.12. A portable RTK GNSS and DSRC OBU system.

### 3.4.2.1 Experiments

We describe two experiments conducted on 11/8/2016 and 12/14/2016, respectively. The first experiment was performed on I-94 east of the Radio Drive to Carmichael Rd. in Wisconsin (about 9 miles in the east-west direction) and on Radio Drive between 10th St. N and Lake Rd. in Woodbury (about 4 miles in the north-south direction). As shown in Table 3.7, the two vehicles were following each other in the same lane or on a different lane next to each other. The I-94 section east of the I-94/494/694 interchange test segment has a posted speed limit of 70 MPH and the posted speed limit on Radio Drive is 55 MPH. In all two-vehicle experiments, we used a tape measure to measure the antenna positions between the RTK and OBU antennas in all configurations.

Table 3.7 Car following configuration of two-vehicle experiments.

Roadway	Direction	Description
I-94	EB	Two vehicles in the same lane
	WB	Two vehicles in different lanes next to each other
Radio Dr.	NB	Two vehicles in the same lane
	SB	Two vehicles in different lanes next to each other

### 3.4.2.2 Test Results

We applied the methodology described in Section 3.3 for our data analyses. The analyses we performed accounted for the offset of the antennas and removed the turnaround points at the end of travel. We also excluded GNSS data when the test vehicle went under overpasses or bridges by placing a constraint on the minimum number of satellites. (Note: We used the GNSS fix quality of a RTK GNSS to filter out less-accurate estimates.)

Table 3.8 lists the absolute positioning accuracy of the first OBU (OBU A) with respect to a RTK from experiments along I-94 in the EB-WB directions and Radio Dr. in the NB-SB directions on 11/8/2016 on vehicle A. On I-94, the best performance (scenario g.2, travelling westbound) demonstrated a mean position error of 1.06 m with a standard deviation of 0.74 m. The 50th and 95th percentile of position error are 1.17 m and 2.31 m, respectively. The maximum relative position error is 2.45 m. On Radio Dr., scenario h.2 (travelling southbound) demonstrated an average position error of 0.24 m with a standard deviation of 0.17 m. The 50th and 95th percentile of position error are 0.23 m and 0.50 m, respectively. The maximum relative position error is 0.55 m.

**Table 3.8 Absolute position error of OBU A on a passenger vehicle (vehicle A - Impala).**

Absolute Position Error (m) Savari OBU vs. RTK			11/8/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
Vehicle A Impala	g.1	I-94 EB from I-494/694 to Carmichael Rd. WI	1.53	0.59	1.67	2.38	2.46	2,473
	g.2	I-94 WB from Carmichael Rd. WI to Radio Dr. MN	1.06	0.74	1.17	2.31	2.45	4,127
	h.1	Radio Dr. CR-13 NB	1.11	0.24	1.03	1.55	1.78	3,259
	h.2	Radio Dr. CR-13 SB	0.24	0.17	0.23	0.50	0.55	5,055

Table 3.9 lists the absolute positioning accuracy of the first OBU (OBU B) with respect to a RTK from experiments along I-94 in the EB-WB directions and Radio Dr. in the NB-SB directions on 11/8/2016 on vehicle B. On I-94, the best performance for vehicle B (scenario g.2, travelling westbound) demonstrated a mean position error of 1.71 m with a standard deviation of 0.89 m. The 50th and 95th percentile of position error are 1.92 m and 3.17 m, respectively. The maximum relative position error is 3.36 m. On Radio Dr., scenario h.2 for vehicle B (travelling southbound) demonstrated an average position error of 0.70 m with a standard deviation of 0.71 m. The 50th and 95th percentile of position error are 0.46 m and 2.56 m, respectively. The maximum relative position error is 2.67 m.

**Table 3.9 Absolute position error of OBU B on a passenger vehicle (vehicle B - Corolla).**

Absolute Position Error (m) Savari OBU vs. RTK			11/8/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
Vehicle B Corolla	g.1	I-94 EB from I-494/694 to Carmichael Rd. WI	2.98	2.21	2.25	7.17	7.32	2,618
	g.2	I-94 WB from Carmichael Rd. WI to Radio Dr. MN	1.71	0.89	1.92	3.17	3.36	4,577
	h.1	Radio Dr. CR-13 NB	2.92	0.40	3.03	3.46	3.56	3,256
	h.2	Radio Dr. CR-13 SB	0.70	0.71	0.46	2.56	2.67	5,090

We found from Tables 3.8 & 3.9 that the RTK-OBU system on vehicle B has significantly larger (about twice the) position error than the system on vehicle A. However, each vehicle has exactly the same RTK and OBU hardware, firmware, and software. We examined the RTK data on both vehicles. The RTK data quality from both units are consistent. We do not have a clear explanation on why the OBU A on vehicle A performs better than the OBU B on vehicle B.

The position errors between the OBU and RTK on each vehicle were examined based on their locations as illustrated in Figure 3.13 and 3.14. Figure 3.13 displays the position errors of both vehicles by vehicle trajectory near the Lake Rd. intersection. Similarly, Figure 3.14 shows the position errors of both vehicles by vehicle trajectory near the Valley Creek Rd. intersection. We noticed that the position errors increase when a vehicle slows down, stops near an intersection, or travels relatively slower around curves. The position error increase may be caused by satellite signal obstruction or reflections from neighboring vehicles waiting for the traffic signal or more likely due to a position estimator/predictor function built into the vendor’s software. The Savari OBU’s do not include an Inertial Measurement Unit (IMU) in their system. We observed similar patterns on both vehicles, however, vehicle B exhibited a larger position error along the entire route.

We also calculated the relative position errors between two OBUs on two traveling vehicles by subtracting the distance offset between the two RTK for each data pair. Table 3.10 lists the relative position errors between two OBUs on separate vehicles. The average position error on I-94 ranges from 2.25 to 2.99 m and the error on Radio Dr. ranges from 3.66 to 4.9 m. The 50th percentile of position error are 1.79 m and 2.44 m for I-94 and Radio Dr., respectively.

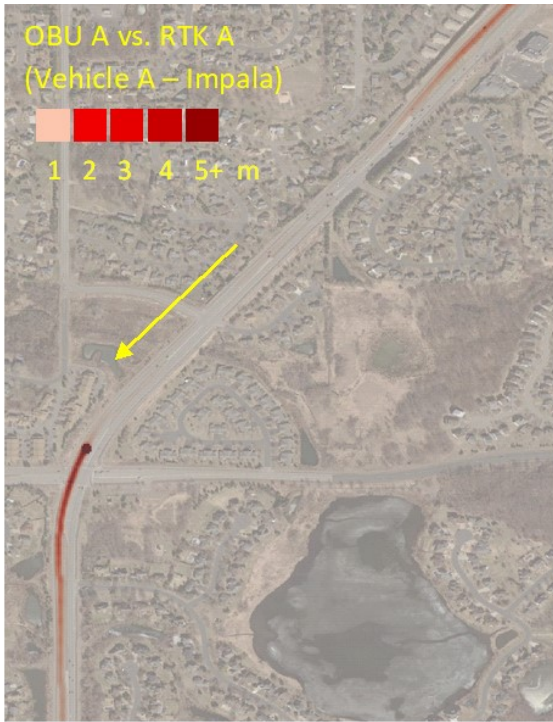


Figure 3.13. Position error of OBU vs. RTK based on vehicle trajectory (traveling SB on Radio Dr near Lake Rd).



Figure 3.14. Position error of OBU vs. RTK based on vehicle trajectory (traveling SB on Radio Dr near Valley Creek Rd).

**Table 3.10 Relative position error between OBU A and B on two vehicles.**

Relative Position Error (m) Savari OBU A vs. OBU B			11/8/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
OBU A on Impala vs. OBU B on Corolla	g.1	I-94 EB from I-494/694 to Carmichael Rd. WI	2.99	3.05	1.75	9.66	15.20	2,398
	g.2	I-94 WB from Carmichael Rd. WI to Radio Dr. MN	2.25	1.77	1.79	5.89	8.16	4,092
	h.1	Radio Dr. CR-13 NB	3.66	3.71	2.26	12.31	18.44	3,264
	h.2	Radio Dr. CR-13 SB	4.90	6.35	2.44	18.29	38.20	5,021

In addition, we also conducted experiments on the two pairs of OBU-RTK systems when both vehicles are stationary. Both vehicles were parked next to each other in a parking lot near the UMN east bank campus. Table 3.11 lists the absolute positioning accuracy for each OBU with respect to an RTK and the relative position errors between the OBUs from experiments conducted on 12/14/2016 on each vehicle.

On vehicle A, the best performance (scenario j.2) demonstrated a mean position error of 0.92 m with a standard deviation of 0.72 m. The 50th and 95th percentile of position error are 0.78 m and 2.26 m, respectively. The maximum relative position error is 3.04 m. On vehicle B, the best performance (scenario j.3) demonstrated a mean position error of 0.40 m with a standard deviation of 0.29 m. The 50th and 95th percentile of position error are 0.33 m and 1.02 m, respectively. The maximum relative position error is 1.37 m.

Scenario k computes the relative position error between the OBUs by subtracting the offset measured from tape measure. Scenario k.1 demonstrated a mean position error of 0.84 m with a standard deviation of 0.73 m. The 50th and 95th percentile of position error are 0.50 m and 2.23 m, respectively. The maximum relative position error is 2.46 m.

Scenario l computes the relative position error between the OBUs by subtracting the computed offset from the RTK units. Scenario l.1 exhibited a mean position error of 0.74 m with a standard deviation of 0.70 m. The 50th and 95th percentile of position error are 0.42 m and 2.16 m, respectively. The maximum relative position error is 2.38 m.

**Table 3.11 Absolute position error for each OBU on a separate stationary passenger vehicle.**

Absolute Position Error (m)			12/14/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
RTK A vs RTK B	i.1	Trial 1	0.02	0.00	0.02	0.02	0.03	10,228
	i.2	Trial 2	0.17	0.33	0.02	0.89	0.92	19,910
OBU vs RTK (Impala)	j.1	OBU A vs RTK A	0.98	0.81	0.68	2.51	3.31	13,365
	j.2	OBU B vs RTK A	0.92	0.72	0.78	2.26	3.04	19,585
OBU vs RTK (Corolla)	j.3	OBU A vs RTK B	0.40	0.29	0.33	1.02	1.37	16,617
	j.4	OBU B vs RTK B	0.68	0.41	0.60	1.37	1.63	10,202
OBU A vs OBU B (Use fixed offset from tape measure)	k.1	Trial 1	0.84	0.73	0.50	2.23	2.46	10,985
	k.2	Trial 2	1.24	0.92	1.18	3.15	4.21	19,404
OBU A vs OBU B (Use calculated offset from RTKs)	l.1	Trial 1	0.74	0.70	0.42	2.16	2.38	10,185
	l.2	Trial 2	1.10	0.95	0.83	3.13	4.13	15,175

Finally, we placed both OBU-RTK pairs on the Impala and repeated the experiments conducted for the stationary scenario as discussed previously. Table 3.12 lists the absolute positioning accuracy of each OBU with respect to an RTK and the relative position errors between the OBUs on the Impala vehicle.

For absolute positioning, the best performance (scenario n.3) demonstrated a mean position error of 0.34 m with a standard deviation of 0.20 m. The 50th and 95th percentile of position error are 0.32 m and 0.76 m, respectively. The maximum relative position error is 0.87 m. In the largest error scenario (n.2), the absolute position (OBU B) exhibited an average error of 3.2 m.

Scenario o computes the relative position error between the OBUs by subtracting the offset measured from tape measure. It demonstrated a mean position error of 2.62 m with a standard deviation of 1.56 m. The 50th and 95th percentile of position error are 2.40 m and 5.58 m, respectively. The maximum relative position error is 7.86 m. Scenario p computes the relative position error between the OBUs by subtracting the computed offset from the RTK units. This approach resulted in a mean position error of 3.27 m with a standard deviation of 1.85 m. The 50th and 95th percentile of position error are 3.18 m and 7.24 m, respectively. The maximum relative position error was 8.06 m.

**Table 3.12 Absolute position error of both OBU’s on a stationary passenger vehicle (vehicle A - Impala).**

Absolute Position Error (m)			12/14/2016 Test Results					
			Mean	SD	50th Percentile	95th Percentile	Max	N
RTK A vs RTK B	m	Trial 3	0.01	0.01	0.01	0.02	0.02	5,458
OBU vs RTK	n.1	OBU A vs RTK A	0.46	0.25	0.47	0.90	1.04	5,268
	n.2	OBU B vs RTK A	3.20	1.70	3.21	6.30	6.78	5,024
	n.3	OBU A vs RTK B	0.34	0.20	0.32	0.76	0.87	11,870
	n.4	OBU B vs RTK B	2.83	1.47	2.63	5.67	7.09	11,644
OBU A vs OBU B	o	Use fixed offset from tape measure	2.62	1.56	2.40	5.58	7.86	11,658
	p	Use calculated offset from RTKs	3.27	1.85	3.18	7.24	8.06	4,942

### 3.5 SUMMARY AND DISCUSSION

In a vehicular environment, the GNSS positioning accuracy can be affected by a number of external factors, such as the surrounding traffic (particularly by vehicles taller than the test vehicles) and by infrastructure elements that obscure the line of sight to GNSS satellites (i.e. overpasses and tall buildings). In our analyses we attempted to filter out less-accurate estimates because of degradation of the GNSS signal while going under overpasses. However, there is no reliable way to do this using the data output by the GNSS module alone, as the change in environment affects the position estimate but does not result in a clear change in the satellite connections or signal-to-noise ratio.

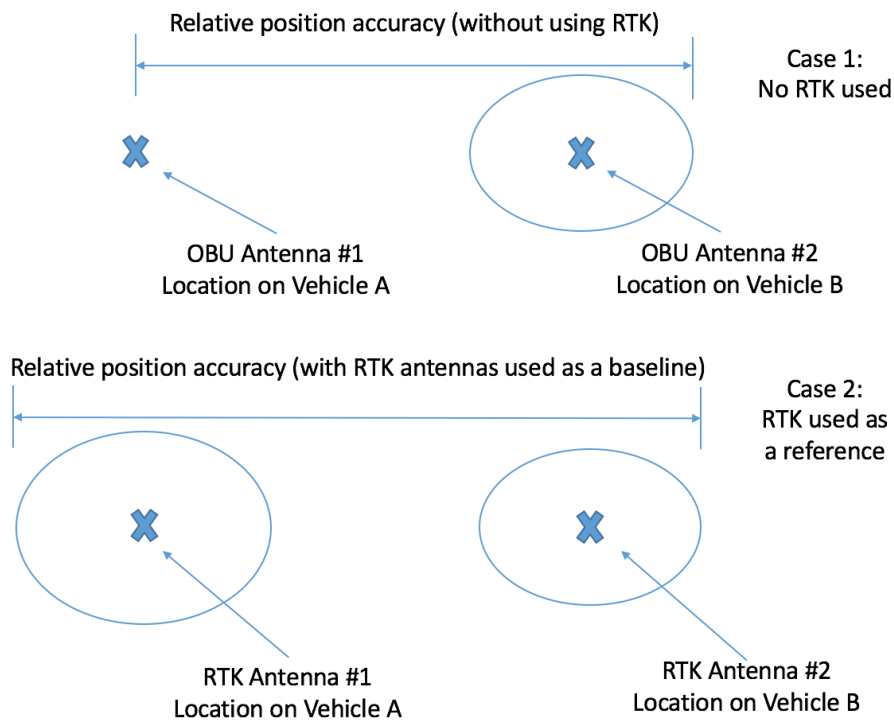
On average, the position error from the tests on the MN-65 site was 0.76 m with a standard deviation of 0.51 m. Similarly, the position error from the tests in the Hutchinson area was 0.70 m with a standard deviation of 0.26 m. At the I-494/694 test site, the position error was 0.78 m on average with a standard deviation of 0.5 m. The results from the I-94 experiment exhibited the “worst” performance (due to more overpasses on this route), with an average position error of 1.46 m and standard deviation of 0.73 m. Given the distribution of results obtained, there does not seem to be a significant pattern in the position error correlated with the positioning of the antenna on the vehicle or direction of travel. Instead, the presence and frequency of environmental factors such as overpasses and large adjacent vehicles appears to be more influential.

We also installed the ASD OBUs on two passenger vehicles together with an RTK GNSS on each vehicle to evaluate the relative OBU position accuracy between two vehicles. On average, the relative position errors between two OBUs on separate vehicles traveling on I-94 and Radio Dr. is about 3.5 m with a standard deviation of 3.7 m. The average 50th percentile error is about 2 m. When both vehicles are stationary, the average position error is about 0.98 m with a standard deviation of 0.83 m. The average 50th percentile error is about 0.73 m.

The larger relative position error when using an RTK reference can be explained by examining the schematic diagrams in Figure 3.15. The ellipses depict the cloud of position data captured from each OBU. When no RTK reference is used (Case 1), all measurements (depicted by the cloud on the right) to a second OBU antenna are referenced to the OBU antenna on the first vehicle (on the left). When an

RTK reference on each vehicle is used (Case 2), the relative position measurement will vary depending on the location of the measurement in the cloud surrounding RTK antenna #1 and the measurement in the cloud surrounding RTK antenna #2. The size of the two clouds result in a larger statistical measure of the relative position error.

Each vehicle has matching RTK and OBU hardware, firmware, and software. We also carefully examined the RTK data and the position errors between the OBU and RTK on each vehicle on a GIS map. The RTK data quality from both units was consistent. Our results did show that the RTK-OBU system on vehicle B exhibited significantly larger (about twice the) position error than the system on vehicle A. The position errors between the two OBUs increased when the vehicles traveled near an intersection or in a congested area. Why this is so, is not clear.



**Figure 3.15. Schematic diagrams illustrating the difference in relative position error when using and not using RTK as a reference.**

No matter how one analyzes the results, using ONLY V2V communication between two OBU's on two vehicles is insufficient for providing the plow operator with sufficient information to maintain spacing between two vehicles. This may change in the future if and when better GNSS modules become available.

## CHAPTER 4: RADAR-BASED BACKUP ASSIST SYSTEM

Based on our conversations with MnDOT staff in September 2016, they agreed that a backup assist system would be very helpful when snow plow operators are clearing crossovers on Highway 169, since operators frequently need to back up without having a clear view behind them. A radar-based backup assist system was initially developed and tested on a pickup truck (Figure 4.1) then later installed on a plow truck (#212570) which operates on Highway 169. The backup assist system includes a radar, a Raspberry Pi 3 computer, and an audible display. The system leverages the existing rear view camera mounted next to the tailgate of a snowplow. The audible feedback is used to direct the operator to look at the rear-camera display when an object is detected by the radar sensor.



Figure 4.1 A radar based backup assistance system on a pickup truck.

### 4.1 SYSTEM DEVELOPMENT

#### 4.1.1 Introduction

We used a high performance radar to detect objects behind a vehicle and provide audio warning to the driver as part of the backup assist system. The software that processes data from the radar has been designed to filter out targets that are more than 10 meters (which is programmable) away from the back of the truck as well as those that are closer to the truck, but are moving away from the truck. The filtering algorithm will activate an audio warning (at 1 Hz tone) when a target is detected within the 10-meter range and that warning will increase in frequency (2 Hz) if the target moves to within 5 meters of the back of the truck. The filtering algorithm runs on a small Raspberry Pi microcomputer that will take up minimal space in the cab of the truck. In order to get the program running on the smaller computer we refactored the software into two separate processes in order to spread the computational load across two of the processor cores.

### 4.1.2 Delphi ESR Radar

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The Delphi radar incorporates 2 scanners with a 50 ms update rate. As illustrated in Figure 2, the long range (LR) scan has a maximum range of 175 m and a horizontal field of view (FOV) of +/- 11 degrees. The medium range (MR) scan has a range of 60 m and a horizontal FOV of +/- 45 degrees. The outer bound for the MR scan is 60 m outside the LR FOV and 40 m inside the LR FOV. This is noted by the red line in Figure 4.2.

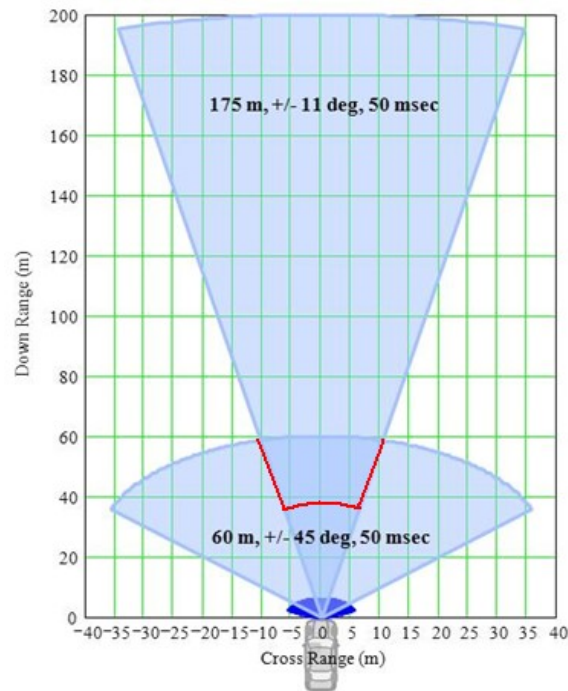


Figure 4.2 Radar ranging specifications.

### 4.1.3 System Design and Methodology

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The backup assist system consists of a radar, a microcomputer and an auditory display, as illustrated in the upper part of Figure 4.3. The objective is to alert the operator to look at the rear-camera display when an object is detected by the radar. The rear view camera mounted near the right side of the tailgate, as shown in Figure 4.4, was extended to provide a better field of view.

The Raspberry Pi computer (Figure 4.5) processes the radar data every 25 ms from both the long and medium range scans. We purposely reduced the horizontal FOV to +/- 30 degrees to remove objects outside the width of the plow truck. The total FOV (60 degrees) is then divided into 5 angular detection zones (12 degrees per zone). A clustering and noise filtering algorithm processes the data in each angular zone for object detection. When an approaching object is detected with a range between 5 and 10 m in any of the 5 detection zones, a 1-Hz alerting tone is generated. When an approaching object is detected with a range less than 5 m, a higher frequency (2-Hz) warning tone is generated through the speaker (which incorporates an amplifier), as shown in Figure 5, to alert the plow operator.

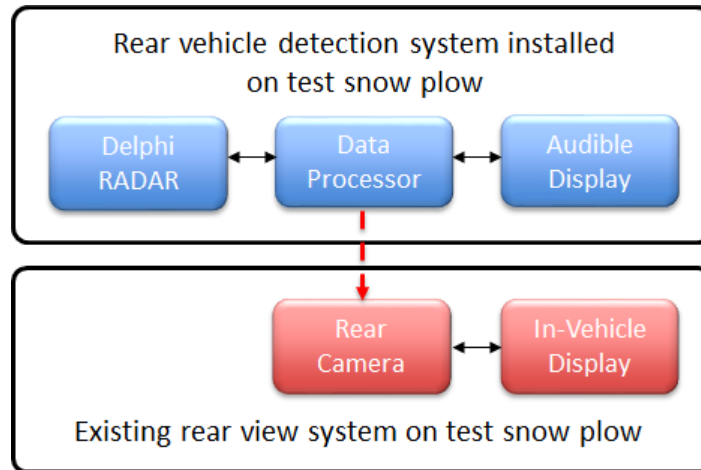


Figure 4.3 System diagram of the backup assist system.



Figure 4.4 Extended rear view camera for better field of view.

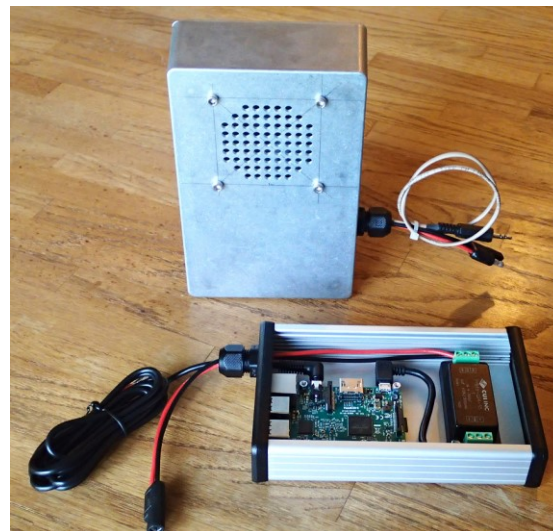


Figure 4.5 Raspberry Pi 3 computer and speaker.

## 4.2 SYSTEM INSTALLATION AND TESTING

Figure 4.6 displays the radar-based backup assist system installed on a MnDOT plow truck (#212570) which is used for calibration and testing. Figure 4.7 illustrates the location of a power switch installed near the plow operation joysticks to turn on the backup assist system. Video from the rear view camera can be displayed on the Maintenance Decision Support System (MDSS) display by toggling the button in the upper right corner of the MDSS display, as shown in Figure 4.8.



Figure 4.6 Backup Assist System Installed on Plow Truck #212570.

Switch to turn on the backup assist system



Figure 4.7 Location of the Power Switch to Turn on the Backup Assist System.

Button to select video display from MDSS or rear view camera



Figure 4.8 Illustration of a Video Source Select Button.

With the support of Bruce Thompson and his staff (Al, Mike, and Justin) at the Shakopee truck station, we were able to test the backup assist system on the first plow truck (#212570) along US-169 in Jordan. The system leverages the existing rear view camera mounted next to the tailgate of the snowplow. The audible feedback is used to direct the operator to look at the rear-camera display when an object is detected by the radar sensor.

A preliminary test of the backup assist system was conducted at the Oakdale station parking lot to evaluate the performance of the radar. A pickup truck from 6 different approaches (as illustrated in Figure 4.9) were tested to evaluate the detection zone and distance of the radar.

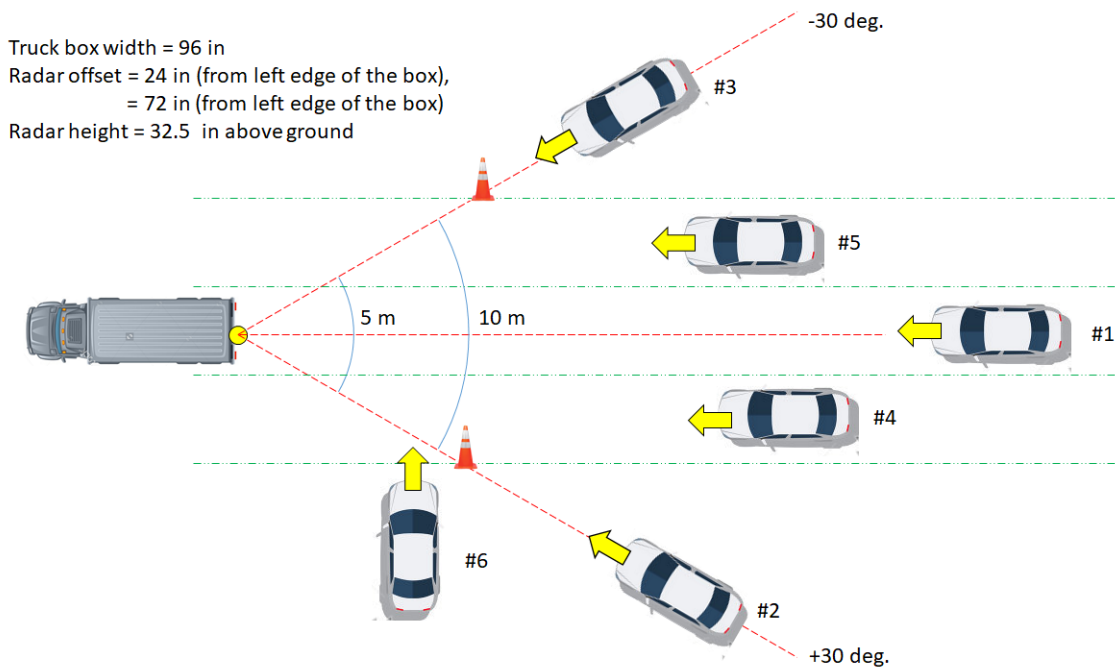


Figure 4.9 Test scenarios of the backup assist system at Oakdale station parking lot.

#### 4.2.1 Scenario #1

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A pickup truck approaches the plow truck at 10 MPH from behind (0 degree). On average, the radar detects the pickup truck approaching from behind at 8.2 meters and the 2-Hz tone is triggered when the vehicle is about 3.4 meters away as listed in Table 4.1.

Table 4.1 Test results from scenario #1

Scenario #1	1 Hz warning		2 Hz warning		1 Hz warning	2 Hz warning
	ft	in	ft	in	m	m
Trial 1	23	8	11	2	7.2	3.4
Trial 2	28	6	11	10	8.7	3.6
Trial 3	29	0	10	4	8.8	3.1
<b>Average Distance (m)</b>					<b>8.2</b>	<b>3.4</b>

#### 4.2.2 Scenario #2

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A pickup truck approaches the plow truck at 10 MPH from the left at a 30-degree angle as illustrated in Figure 1. On average, the radar detects the pickup truck approaching from behind at 8.0 meters and the 2-Hz tone is triggered when the vehicle is about 2.9 meters away as listed in Table 4.2.

Table 4.2 Test results from scenario #2

Scenario #2	1 Hz warning		2 Hz warning		1 Hz warning	2 Hz warning
	ft	in	ft	in	m	m
Trial 1	27	0	9	5	8.2	2.9
Trial 2	25	3	9	3	7.7	2.8
Trial 3	26	5	10	2	8.1	3.1
<b>Average Distance (m)</b>					<b>8.0</b>	<b>2.9</b>

#### 4.2.3 Scenario #3

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A pickup truck approaches the plow truck at 10 MPH from the right at a 30-degree angle as illustrated in Figure 1. On average, the radar detects the pickup truck approaching from behind at 5.6 meters and the 2-Hz tone is triggered when the vehicle is about 3.0 meters away as listed in Table 4.3.

Table 4.3 Test results from scenario #3

Scenario #3	1 Hz warning		2 Hz warning		1 Hz warning	2 Hz warning
	ft	in	ft	in	m	m
Trial 1	20	4	9	1	6.2	2.8
Trial 2	19	10	9	5	6.0	2.9
Trial 3	14	10	11	0	4.5	3.4
<b>Average Distance (m)</b>					<b>5.6</b>	<b>3.0</b>

#### 4.2.4 Scenario #4

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A pickup truck approaches the plow truck at 10 MPH from the passing lane on the driver’s side as illustrated in Figure 1. On average, the radar detects the pickup truck approaching from behind at 6.7 meters and the 2-Hz tone is triggered when the vehicle is about 5.9 meters away as listed in Table 4.4.

**Table 4.4 Test results from scenario #4**

Scenario #4	1 Hz warning		2 Hz warning		1 Hz warning	2 Hz warning
	ft	in	ft	in	m	m
Trial 1	18	8	NA	NA	5.7	4.8
Trial 2	22	10	NA	NA	7.0	6.3
Trial 3	24	2	NA	NA	7.4	6.7
<b>Average Distance (m)</b>					<b>6.7</b>	<b>5.9</b>

#### 4.2.5 Scenario #5

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A pickup truck approaches the plow truck at 10 MPH from the passing lane on the passenger’s side as illustrated in Figure 1. On average, the radar detects the pickup truck approaching from behind at 7.6 meters and the 2-Hz tone is triggered when the vehicle is about 6.2 meters away as listed in Table 4.5.

**Table 4.5 Test results from scenario #5**

Scenario #5	1 Hz warning		2 Hz warning		1 Hz warning	2 Hz warning
	ft	in	ft	in	m	m
Trial 1	25	1	NA	NA	7.6	6.3
Trial 2	24	2	NA	NA	7.4	6.0
Trial 3	25	1	NA	NA	7.6	6.3
<b>Average Distance (m)</b>					<b>7.6</b>	<b>6.2</b>

#### 4.2.6 Scenario #6

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A pickup truck travels perpendicularly toward plow truck at 10 mph about 8.5 m behind the truck as illustrated in Figure 4.9. On average, the radar detects the pickup truck 1.1 meters away from the centerline of the radar’s horizontal field of view (FOV) perpendicularly.

Figure 4.10 shows the radar-based backup assist system installed on a MnDOT plow truck (#212570) after the plow equipment was mounted. The radar field of view is partially blocked by the sand/salt spinner as illustrated in the top and bottom left photos in Figure 4.10. We conducted tests with a MnDOT maintenance pickup truck following the snowplow at several crossovers on 10/27/2017 (see Figure 4.11) to test the backup assist system. The radar was able to detect the pickup truck behind as expected when the following pickup truck was approaching the plow truck in less than 30-ft on highway 169. The detection range was estimated visually by the pickup truck driver using wireless radio communication with the plow operator while traveling on the highway. The radar did not pick up any

vehicles passing the plow truck on either the left or right lane at highway speed. Although, the radar FOV was partially blocked by the sand/salt spinner, the alerting tone was triggered when the plow truck was backing up to an object (or a vehicle) at less than 25-30 feet away.

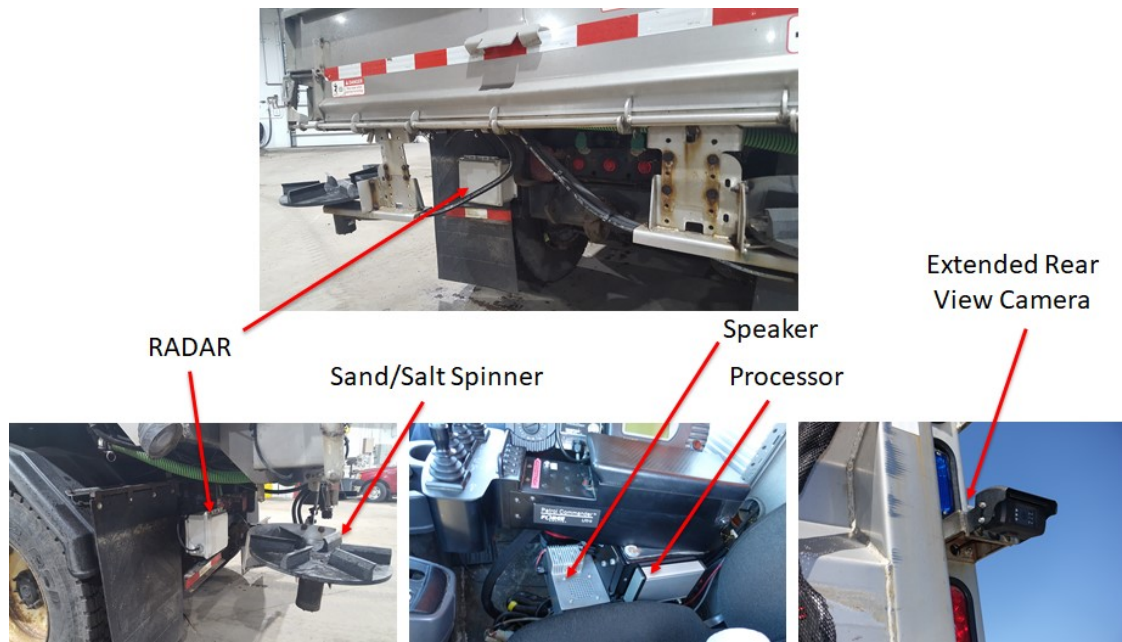


Figure 4.10 T Backup Assist System Installed on Plow Truck #212570 with plow equipment mounted.



Figure 4.11 Test Backup Assist System at Crossovers on US-169 (10/27/2017).

### 4.3 SUMMARY

A radar-based backup assist system was developed and installed on a snowplow (#212570) which is operating on Highway 169. The backup assist system provides an audio warning to the operator to look at the display from a rear-view camera when an object is detected. The backup assist system includes a switch located in the cab to allow the operator to turn the system on/off because the operators were worried that the radar will trigger false alarms and the alerting tone will become annoying. Based on the feedback from the operators, we increased the radar detection range from 10 m to 20 m for the 1-Hz warning and from 5 m to 10 m for the 2-Hz alerting tone. The test results indicate that the units meet

their technical specifications but the sand/salt spinner partially blocks the field of view (FOV) of the radar sensor. The plow operators feel it is sufficient to support their crossover operations by extending the rear-view camera without the use of a rear-facing radar.

## CHAPTER 5: LANE BOUNDARY GUIDANCE SYSTEM

In order to provide lane boundary guidance for snow plow operators under low visibility conditions, we developed a driver assistance system based on a high-accuracy Global Navigation Satellite System (GNSS). The lane boundary guidance system was installed on a snowplow operating on MN-25 running between Belle Plaine and Green Isle.

We used a high accuracy GNSS receiver (i.e. the Trimble BX982<sup>5</sup>) with corrections provided using Trimble's VRS<sup>6</sup> using a network of ground reference stations managed by MnDOT (MnCORS<sup>7</sup>) to determine a vehicle's location with respect to the lane stored in a digital map. The system predicted lateral position information (using a programmable look-ahead distance) to advise the plow operator about correcting their lane position in whiteout conditions. Output from this system is displayed using an LED strip with colored icons indicating whether the driver is centered in the lane or if steering adjustments should be made. The objective is to reduce the expected cost to facilitate wide-scale deployment.

### 5.1 SYSTEM DESIGN AND DEVELOPMENT

As illustrated in Figure 5.1, the lane boundary guidance system includes an RTK GNSS receiver, an in-vehicle display, a cellular modem to receive the differential GNSS corrections for the RTK GNSS receiver, a high-accuracy digital map, and a single board computer for data communication and data processing. All electronic components, except the LED display and antennas, were packaged onto a plate (as shown in Figure 5.2) so that the system can be easily mounted behind the driver's seat or transported to another plow truck, when needed.

The core intelligence of the lane boundary guidance system resides in a Raspberry Pi 3. It processes a vehicle's current position, heading, and speed based on input from the GNSS receiver, identifies the vehicle's current location on the associated digital map for that road, then calculates the potential lateral position error for a look-ahead distance ahead (currently based on 0.5 sec). The projected lateral position error is then displayed on a strip of LED's to assist the operator with lane keeping.

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<sup>5</sup> <http://www.trimble.com/gnss-inertial/bx982.aspx?dtID=overview>

<sup>6</sup> <http://www.trimble.com/Positioning-Services/VRS-Now.aspx>

<sup>7</sup> MnCORS GNSS Network, <http://www.dot.state.mn.us/surveying/cors/>

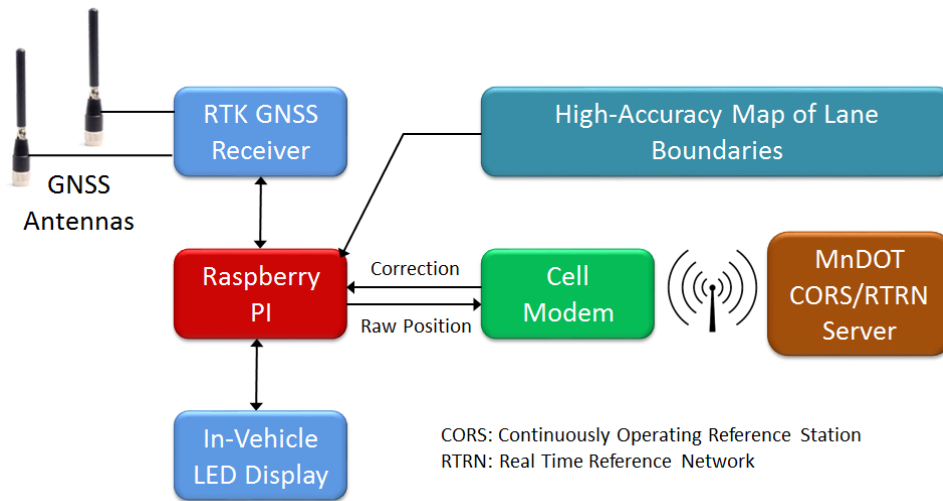


Figure 5.1 System diagram of the lane boundary guidance system.

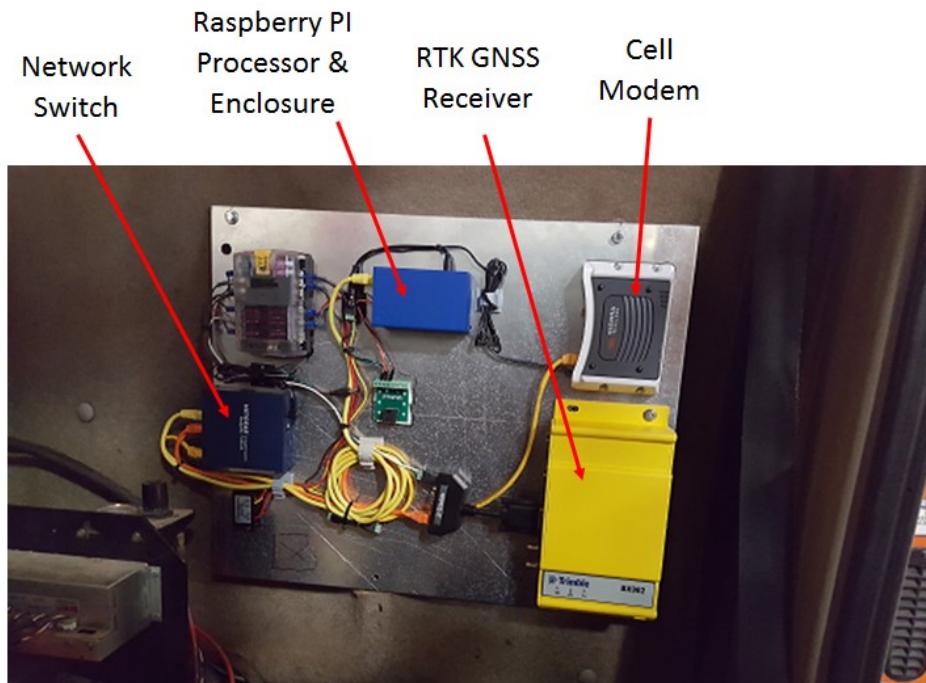


Figure 5.2 Packaged Lane Boundary Guidance System.

### 5.1.1.1 RTK GNSS System

Real Time Kinematic (RTK) processing of GNSS data is a method used to enhance the precision of position data derived from satellite-based positioning systems. The RTK GNSS receiver can provide centimeter level accuracy vehicle position (with RTK fixed as shown in Table 5.1, Solution ID=4) while traveling on a roadway. The RTK GNSS receiver we used exhibits low latency (less than 20 ms) and high update rates capabilities that provide the response time and accuracy required for precise dynamic

applications. For initial testing, we mounted both RTK GNSS antennas on the rooftop of a passenger vehicle to obtain position and heading information of the vehicle at a 10 Hz rate.

**Table 5.1 RTK GNSS positional solution key**

<b>Solution ID</b>	<b>GNSS Solution Status</b>
0	No solution
1	Autonomous (no correction)
2	DGPS (3.3 ft-level, meter-level accuracy)
3	RTK float (4 in-level, decimeter-level accuracy)
4	RTK fixed (0.4 in-level, centimeter-level accuracy)

### 5.1.2 Digital Map

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A high accuracy digital map is needed for use in a driver assist system deployed in a snow plow. Such a map would enable a GNSS- and map-based approach to lane keeping. Based on prior work with buses and snow plows, it has been determined that such a map should be accurate to approximately the 10 cm level or better.

There are many methods for creating, storing, and accessing such a map. This work only focused on the creation of a map to enable the design and evaluation of other technologies (i.e. driver assist). Because of this, methods for generating and storing the data were selected to minimize cost and time requirements. Other aspects such as scalability and storage efficiency were not major considerations as this map will be used in a limited and well defined scope.

The area mapped was a 9-mile stretch of MN 25 between Belle Plaine and Green Isle. The map digitizes the road from mile post 4 (at the top of a hill when leaving Belle Plaine) to mile post 15 (just on the edge of Green Isle).

The stretch contains only 2-lane, undivided highway. In both directions, there are occasional protected right turn lanes, and right bypass lanes. There are no protected left turn lanes. Lanes are assumed to have a standard 12-foot width.

#### 5.1.2.1 Data Collection

Data was collected in a way to minimize time and cost of both raw data collection and post-processing. This work is based on past experience collecting roadway information including breaklines and roadside features [Davis & Donath]. However, these methods require complex data collection and post-processing features so a simplified version was utilized. Data was collected by driving the corridor multiple times with a GNSS receiver and then combining the data collected in those passes to create a road centerline, lane centerlines, fog lines, and information about protected turn and bypass lanes.

Position data was collected using a high-accuracy RTK GNSS receiver capable of receiving corrections from the MnCORS system over a cellular modem. The receiver used was a Trimble BX 982 which has a

specified accuracy of 8 mm + 1 ppm (based on baseline to reference station) in the horizontal plane. This corresponds to an accuracy of approximately 2 to 3 cm. The receiver was configured to output a position at 10 Hz. The receiver's antenna was placed on the top of the vehicle, making sure it was centered right to left. The vehicle was driven through the corridor multiple times making sure to keep the vehicle as centered in the lane as possible. Data was collected on two days, roughly a month apart on September 30 and October 28. On each day, three passes were made in each direction.

Additionally, information about protected right and bypass lanes (divergent lanes) were collected on October 28. This was collected by making a single pass where every protected right and bypass lane was driven. Protected right turn lanes were traveled and then a right turn was made (exiting the mainline, turning onto the side road). Then a U-turn was made so the car would then be facing the mainline and another right turn could be made to re-join the mainline. The path is represented in Figure 5.3

Bypass lanes were traveled and the mainline was rejoined when the lane ended and merged back to the thru lane.

It is noted that by only making a single pass to capture these features, they are likely less accurate than the data collected for the thru lane features. However, these divergent lanes are included for driver context and are not intended to be as accurate as the thru lane information.

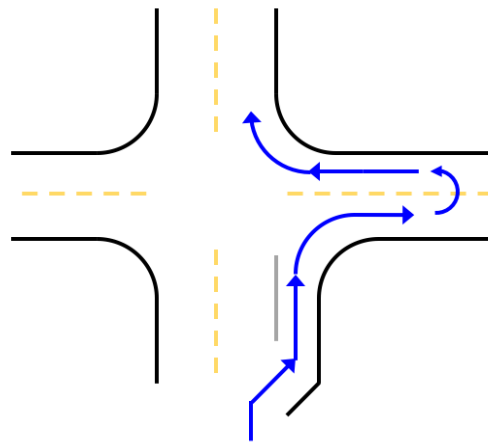


Figure 5.3 Mapping path for protected right turn lanes.

#### 5.1.2.2 Post Processing

The raw data from a single pass consists of the path traveled by the vehicle as sampled by the receiver at 10 Hz. The six passes made in a single direction were first trimmed so they would have the same start and end point (approximately at mile post 4 and mile post 15).

Next, the linestring describing the travel of the vehicle was interpolated so the resulting linestring had exactly 10,000 points describing the path of the vehicle. This number was chosen so that the points

describing the vehicle's travel would be roughly 1.75 meters apart, or half of the spacing of the position fixes reported by the receiver when traveling at 55 mph. Ultimately, this spacing is arbitrary and it's likely that a spacing exists that optimizes the trade-off between storage space (i.e. number of points) required and accurately capturing the geometry of the road.

This interpolation operation was important because it ensured that across the six passes, the nth point would be the same normalized distance along the path. This provided a simple way to combine the six passes. Here, the combined path was calculated by taking the mean position of all the points at a given index. That is to say the nth point in the combined path is the mean position of the nth point in the six passes. Before calculating the mean position however, the points were filtered so that no point with less than the most accurate position fix was considered. The result of this operation was an average traveled path for each direction.

Next, the road centerline was calculated. This was calculated by finding the midline between each of the average traveled paths. Specifically, this was calculated by iterating over all the points in the west-bound average traveled path and finding the closest point on the east-bound linestring (note that the closest point on a linestring may be in between points and is calculated by interpolating between the nearest points). Then between this pair of points (one from the west-bound and one from the east-bound lane centerlines) the midpoint was calculated. The resulting series of midpoints describes the road centerline (i.e. the midline between the lane centerlines).

To determine the location of the fog lines, it was assumed that the road's lane width is a constant 12 feet. By making this assumption, the fog line could be calculated by taking a constant 12-foot parallel offset from the road centerline. This was repeated on both sides of the road centerline in order to describe both the west-bound and east-bound fog lines.

Turn and bypass traveled paths were extracted by hand from the pass in which they were collected. As described above, these were only collected with a single pass and their geometry is less predictable so the resulting traveled path was considered to be the approximate lane centerline. It is noted that because this information is only provided for driver context, it does not need to be as accurate as the data for the thru lanes.

The centerline for a protected right turn lane begins where it diverges from that of the thru lane and continues through the turn until the vehicle fully joins the side road's thru lane. Generally, this results in roughly 20 to 25 m of centerline on the side road. There is no centerline describing the turn back to the mainline.

Bypass lanes are represented by a lane centerline that begins as the vehicle's path diverges from the center of the thru lane and continues through the bypass lane until the vehicle fully re-joins the centerline for the thru lane.

Approximate fog line locations for the turn lanes and bypass lanes are determined by calculating a 6 foot (half of one lane width) parallel offset from the turn or bypass lane centerline. It is noted however, that these lines are only approximate as turn lane and intersection geometry is not as predictable as the width of a highway lane.

Areas with diverging paths (i.e. turn and bypass lanes) are also noted in the metadata for the thru lane's average traveled path. The last point on the thru lane before a protected right turn or bypass lane centerline begins is marked with a label that identifies which feature is beginning to diverge from the thru lane. Additionally, subsequent thru lane average traveled path points are marked with a flag that identifies that a divergent path exists next to the thru lane. This marker continues until the point where the bypass lane merges back into the thru lane or the point where a vehicle would have passed the intersection.

The fog line paths for the thru lane do not contain this information about divergent lanes and continue as if there were no interruption. Displaying this geometry to the driver in a meaningful way will require that the system correlates information from a number of paths (i.e. the average traveled path, road centerline, fog line, etc.) in order to determine how best to display the information.

#### 5.1.2.3 Comparison to Aerial Photography

The generated map was compared to two aerial photography sets. The first set is 2016 aerial photography from the Metropolitan Council of the Twin Cities obtained from the Minnesota Geospatial Information Office ([www.mngeo.state.mn.us](http://www.mngeo.state.mn.us)). This set has a 1-foot pixel size. Features in the generated map generally lined up with this photography at least as well as was discernable given the resolution of the photography.

The second photography set was 2016 aerial photography from Sibley County, MN. This set has a 9-inch pixel size. Features in the generated map generally did not line up with the photography. Sometimes they coincided but generally they were around a meter off from each other. It is also noted that this photography differs from the Met Council photo set by roughly 1 to 1.5 meters. This was estimated by finding the distance between static objects visible in both image sets. Based on this information, it is possible that this photo set, although high resolution, is not accurately geo-referenced.

It is noted that this comparison only provides a cursory examination of the quality of the generated map. For a rigorous evaluation, a quantitative validation technique would need to be developed.

Figure 5.4 illustrates an example of the roadway digital map using data collected at MN-25. The yellow dots represent the road center line, green dots represent the fog lines, and the blue dots are the average travel path within each lane. The 2016 aerial photography from Sibley County, MN (9-inch pixel size) was used to validate the accuracy of the digital map.

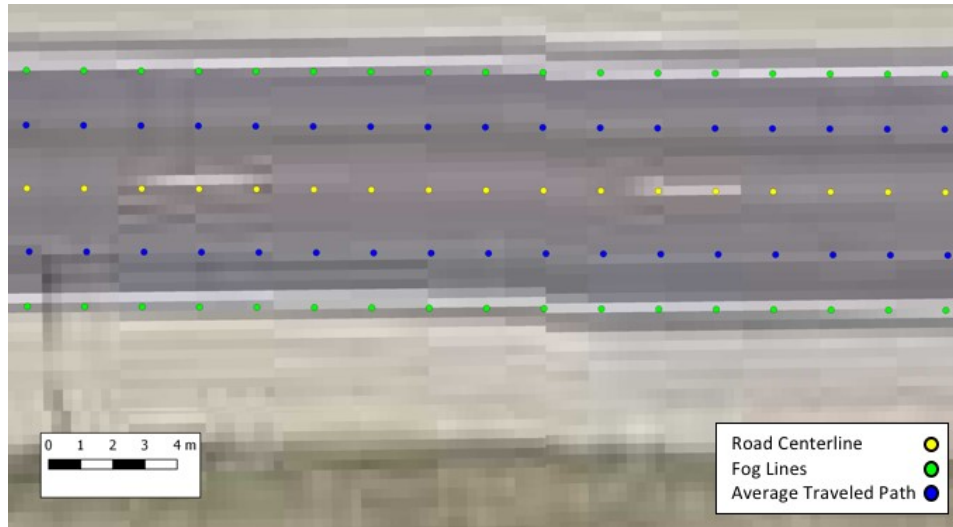


Figure 5.4 Example of a segment of MN-25 digital map.

### 5.1.3 LED Display

Figure 5.5 illustrates the design of the LED indicator. The green square LED in the middle of the strip will light up when the vehicle's look ahead lateral position is lined up with the lane center. When the vehicle drifts to the right by 1 ft, the adjacent circular yellow LED will light up. Similarly, the yellow triangle LED will be displayed if the vehicle moves over by 2 ft from the lane center. If the vehicle deviates by 3 or 4 ft from the lane center, then the 3rd or 4th triangular red LED from the middle of the indicator strip will light up. The 4th triangular LED will blink if the vehicle drifts more than 4 ft from the lane center.

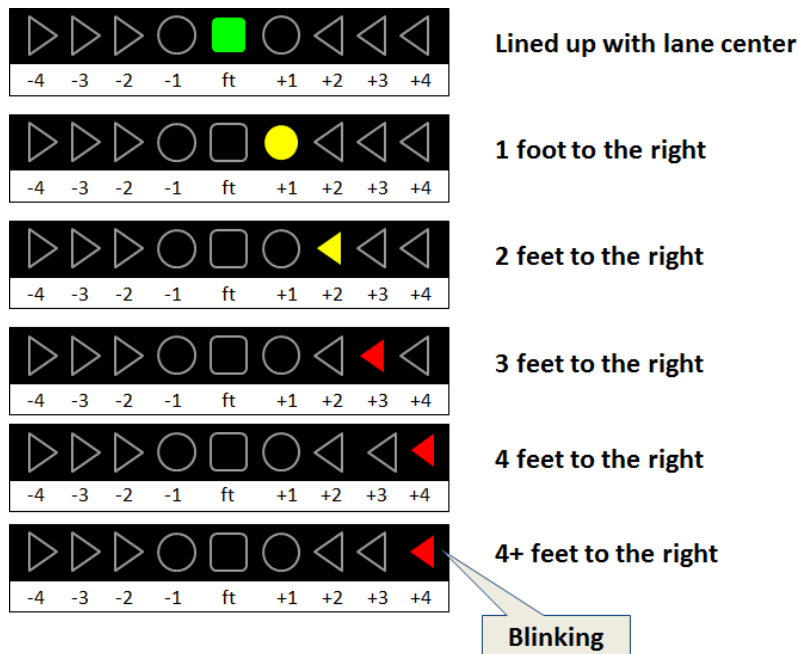


Figure 5.5 States of LED display.

Figure 5.6 shows the prototype of the LED display mounted on the dashboard of a passenger vehicle. Currently, each LED represents a 1-foot lateral position error as described in the design document and shown in Figure 5.5. The 1-foot resolution can be scaled to cover the entire lane width if necessary.

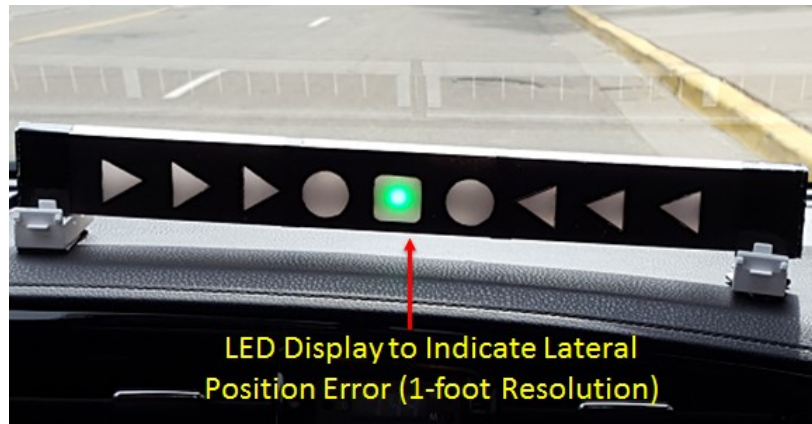


Figure 5.6 LED display to indicate lateral position correction needed

## 5.2 SYSTEM INSTALLATION AND TESTING ON A PLOW TRUCK

All electronic components for the lane boundary guidance system, except the LED display and antennas, were packaged onto a plate so that the system can be easily mounted behind the driver's seat (see Figure 5.2). The lane boundary guidance system was installed on a MnDOT plow truck (#203560). The GNSS antennas and cell modem antenna were mounted near the strobe lights on top of the plow as illustrated in Figure 5.7 – 5.9.



Figure 5.7 GNSS antennas installed on plow truck #203560.

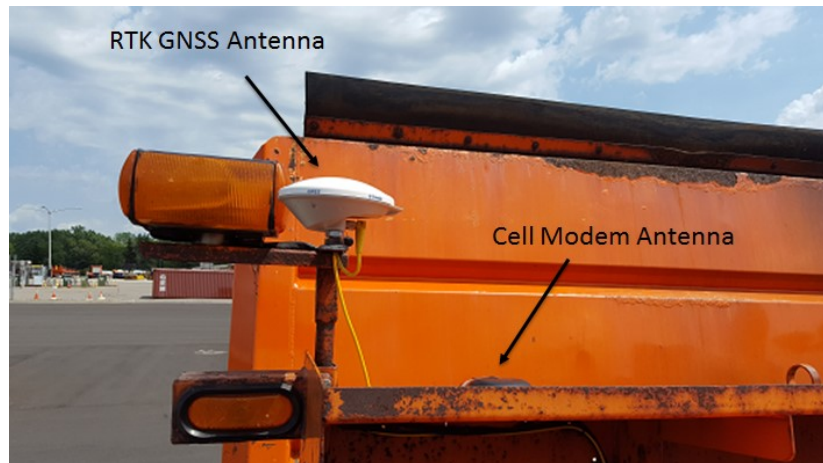


Figure 5.8 Illustration of RTK GNSS and cell modem antennas mounted on the plow, view 1.

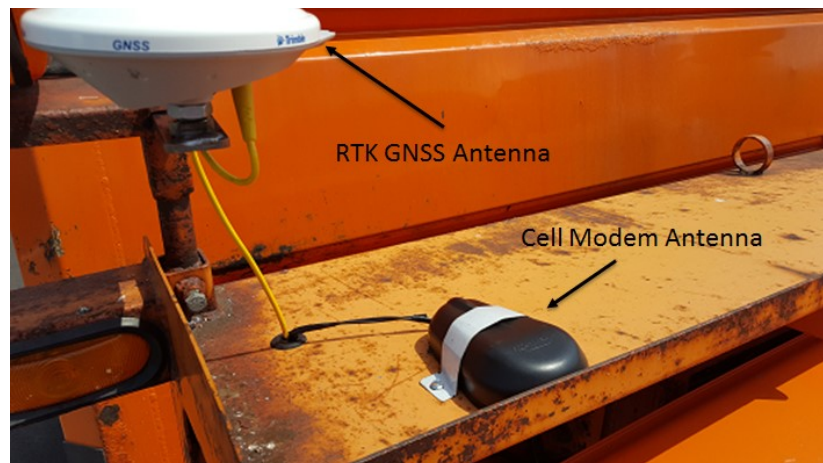


Figure 5.9 Illustration of RTK GNSS and cell modem antennas mounted on the plow, view 2.

We conducted the first test of the lane boundary guidance system on the plow truck along MN-25 on 10/13/2017. With the change of GNSS antenna configuration mounted on the plow truck (as illustrated in Figure 4), the position antenna was mounted above the box shoulder on the driver's side. The test results indicated an offset of the plow truck position with respect to the lane center from the digital map previously created. The Green LED was turned on when the left front tire is on the yellow skip stripes (See Figure 5.10 & 5.11).

We modified the program by adding a 2-ft offset to the lateral position of the GNSS position antenna and conducted another test on 11/7/2017 along MN-25 with a plow mounted in front of the truck (see Figure 5.12) to evaluate the performance of our system during a plowing operation. The system was able to identify the snowplow's location in the map and correctly select the reference lane as the truck

enters the digital map coverage. During the test, the plow operator also went over a bypass lane and let a passenger vehicle behind the truck go through. The LED initially indicated that the truck needed to move back to the left, then it indicated green as the truck was completely within the bypass lane. The LED indication seems to properly inform the plow operator of the snowplow's lateral position with respect to the lane boundary system (See Figure 5.13). With the 2-ft offset, the left edge of the plow is right on the yellow skip stripes (road center).



Figure 5.10 GNSS antenna mounting configuration on plow truck #203560 (10/13/2017).



Figure 5.11 LED indication of the lateral position of the plow truck (10/13/2017).

Right Edge  
Indicator for Plow



Figure 5.12 Plow mounted in front of truck #203560 (11/7/2017).



Figure 5.13 Test plow truck on MN-25 (11/7/2017).

### 5.3 SUMMARY

We worked with maintenance operators at the Shakopee truck station to conduct several tests on both plow trucks in the field to evaluate system performance and collect driver feedback on the LED design. The plow operators provided several recommendations to enhance the LED display by making the LED indication dimmable, preferably with a knob. The LED display becomes too bright for the operator when the environment is relative dark. The other recommendation was to remove the blinking red triangle on both ends when the truck is outside the digital map coverage. The blinking red indication was removed through the software design. We would like to modify the LED design by adding a dial knob to allow manual adjustment of brightness.

The tests performed to date indicate that the units meet their technical specifications but more significant testing with multiple operators will still be needed to gage operator response and evaluate the robustness of the system. In next Chapter, we include more information on field observation and interviews with plow operators.

## CHAPTER 6: FIELD OBSERVATION AND INTERVIEWS

The proposed user-centric design of the lane boundary guidance system was tested during on-road observations of snow plow operators using the system during whiteout snow conditions. These evaluations were conducted by researchers from the HumanFIRST Laboratory. Researchers rode along with operators during inclement snow conditions and conducted interviews with multiple operators and supervisors regarding the lane boundary guidance system. The purpose of the ride-along was to gather user feedback on the features of the interface and its functions while driving.

### 6.1 OBSERVATIONS

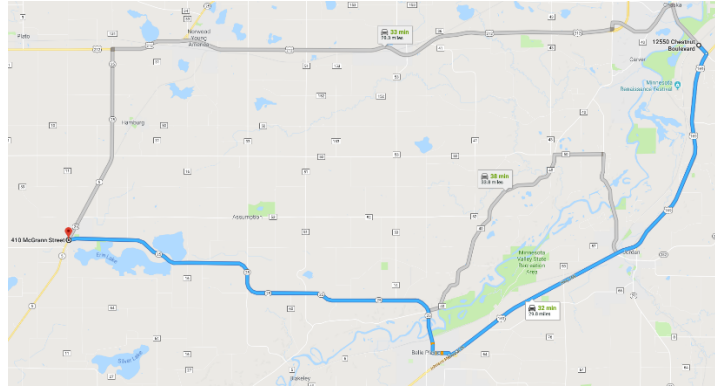
Researchers conducted three separate ride-alongs with operators from the Shakopee, MN MnDOT truck station. Each ride-along lasted several hours in which the researcher spent time observing and conversing with the operators about their interaction with the system as well as their likes and dislikes based on their use of the system. Figure 6.1 depicts the dash-mounted system in the truck that was used for the observations.



Figure 6.1. Image of the lane boundary guidance system mounted in a MnDOT snow plow truck.

#### 6.1.1 Initial Ride-along

The first ride-along occurred on the morning of December 8<sup>th</sup>, 2018 along Minnesota highway 25 (Figure 6.2). This was just a preliminary ride-along to familiarize the researcher with the route, but since the system had already been installed in the truck for several weeks, it still yielded an opportunity for researchers to interview the operator and supervisors about their thoughts on the system. The operator had a good sense for using the system and had positive feedback based on his usage with the system. The primary thing the operator liked was how useful he felt the system would be for maintain a desired roadway position during whiteout conditions. This operator had approximately 4.5 years of experience, but admitted that during heavy snow fall, with limited visibility and high winds that he still had trouble at times maintaining his desired road position. His primary dislike was that the LED lights on the system were not adjustable. During bright, daytime conditions, the lights were difficult to see. He noted that on the other hand, the lights were quite bright and overly distracting at night. Aside from this, the operator felt very happy with the possibilities the system offered drivers during inclement conditions.



**Figure 6.2. Map of the route researchers went on with MnDOT plow operators.**

During this visit to the Shakopee station, researchers were also able to talk to both shift supervisors. Both had been working for MnDOT for over twenty years and indicated how much they liked the potential of the system. Similar to the operator on the first ride-along, they both indicated that their main concern was a lack of a dimmer switch because the lights were far too bright at night and too difficult to see during the day. However, they both were overwhelmingly positive about the system in every other regard and were clear to state their excitement about being the station to get to test the system first. Each acknowledged that they wished they had had such a device back when they used to run the plows themselves and noted many occasions that they considered dangerous scenarios that they had driven in where the use of the system would have been very useful.

### **6.1.2 Second Ride-along**

The second ride-along occurred on January 22<sup>nd</sup> from approximately 1:45 pm to 8:00 pm. There was heavy snowfall for the entirety of the ride along with minimal visibility. There was about six inches of snowfall reported for the Shakopee, MN area during this ride along with temperatures around 29 degrees and high cross winds from the North. The plow operator indicated that he had nearly twenty years of experience working and driving snow plows for MnDOT. He had also been driving along the route that the system was active on (highway 25) for several months and was quite familiar with using the system when the observation occurred.

The operator was very enthusiastic about using the system during heavy snow conditions and felt that it greatly improved his awareness of where he was precisely on the roadway. Additionally, he was very vocal about how he felt the system improved his efficiency because it allowed him to maintain his desired position on the roadway without having to weave back and forth as much as he normally might. He felt this allowed him to clear the two lane road with ease in just two passes (one in each direction) without having to come back to clear off sections where he had drifted somewhat from his desired course. Having to stop and turn the truck around and make an entire pass again just to clear off a few sections of the roadway wasted a lot of the driver's time that could be spent on other roadways, which he felt was especially useful under whiteout conditions when the snowfall is heavy and constant.

When asked how he felt about the sensitivity of the system (one-foot increment indicators), the operator was quite satisfied. He indicated that he felt the sensitivity at which the system changed from one light indicator to the next was just right. He liked that it felt pretty sensitive because that gave him quick and immediate feedback if he started to deviate at all from where he was trying to be on the roadway.

The operator was also asked several questions about how useful he felt the feedback from the system was with regards to allowing him to properly maintain his desired position on the roadway. He indicated he felt the feedback was definitely helpful. The operator really liked that the system allowed him to do his first pass just to the left of the center line. His preference was, on the first pass, to keep the left edge of the plow slightly left of the center lane by keeping the left circular, yellow light on the system lit, indicating the edge of the plow was one foot to the left of the center line. Figure 6.3 depicts the system when the plow edge is one foot to the left of the center line. This allowed the driver to clear the entire lane and would allow him to see with greater ease where the center line was on the pass back in the opposite direction. He felt that aside from helping to ensure that an operator did not lose his way on the road and end up in a ditch, the best thing about the system was how it improved his efficiency. When you cannot see the lanes, he said he would often weave around the road more than normal, which in turn necessitated more passes to fully clear a section of roadway. However, when he could rely on the system instead, he could reasonably plow where he wanted and thus eliminate the need for multiple passes to clear the road of a few extra feet of snow.

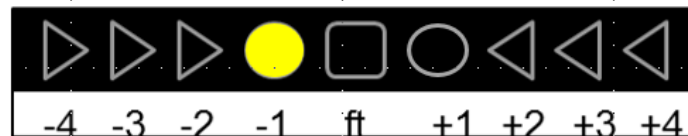


Figure 6.3 Image of system when plow edge is one foot left of the center line.

Since the system is most useful during whiteout conditions, researchers were curious as to how affective the system is in and around curves on the roadway. The operator did not find the system very useful around curves. The operator felt that he knew the roadway well enough that he knew when curves were approaching and when they began. He felt the system was not that useful for curves since it was giving immediate feedback rather than alerting you to an upcoming curve. He indicated that he felt having a navigation app or something where the driver could see an upcoming curve and how far away he was from it would be much more useful for navigating curves especially during highly inclement weather or when a driver is unfamiliar with the route.

When asked about his feelings regarding the system's physical design and location, the operator noted that he liked the location of the system on the dashboard because it was not in the way and after using it a few times he had gotten to where he could attend to it very easily out of the corner of his eye. This allowed him to keep his focus up and towards the roadway while still being able to comfortably receive the feedback from the system and adjust his lane position accordingly. He did not like that he could not adjust the brightness of the lights. During the day, the snow makes the environment very bright, which requires drivers to wear sunglasses. Between the sunlight reflecting off the snow and wearing sunglasses, the system is difficult to see during the day. The operator said his solution was to try keeping a clipboard resting over the top of the system so that it created shade so that the lights were easier to see. Additionally, at night, the LED lights, specifically the middle three lights, seemed overly bright. To counteract this, the operator indicated he would often place a thin, white cloth over the entire system to dim the lights.

Overall, the operator indicated he really like the system and found it to be very useful during heavy snowfall when visibility of the roadway and lane markings were minimal. He wanted a dimmer switch for the system's LED lights, but otherwise was very happy with the system's dash placement, sensitivity, and

that the feedback was based on the location of the plow's left edge because it allowed him to clear just to the left of the center line which allowed him to make his return pass with greater speed and efficiency on two-lane roads. The driver did not feel like the system added any real mental demand to interact with at this point in using it. He also rated the overall usability of the system and his trust in the system as very high.

### **6.1.3 Third Ride-along**

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The third ride-along occurred on March 6<sup>th</sup> from approximately 12:30 am to 4:30 am. There was heavy snowfall for the entirety of the ride along with minimal visibility. There was moderate to heavy snowfall for the entirety of the ride along with mild to moderate roadway and lane marker visibility. There was approximately 3 inches of snowfall reported for the Shakopee, MN area during this ride along with temperatures around 27 degrees with mild wind from the North. The plow operator indicated that he had been working and driving plows for MnDOT for just over two years. This was also his first time to ever interact with the system, which provided researchers a great insight into how future first-time operators may interact with the system.

Upon giving a brief explanation to the operator on how the system works, the drive began. The driver's initial feedback was that the system was very mentally demanding for him. He liked the concept of the system and felt it was definitely useful in ensuring he did not lose his way on the road and end up accidentally driving into a ditch. Even though the operator struggled to use the system with ease initially, he noted that he felt after repeated use he would likely get used to the way the system worked. When asked how he felt about the sensitivity of the system, the operator stated that he felt the sensitivity at which the system changed from one light indicator to the next was too quick in relation to how immediate the feedback was. He would have preferred a system that gave him feedback on where he needed to aim for on the roadway a little farther down the road instead of telling him where his plow was right in that moment. The operator did like the one foot increments the system used, though. The operator was also asked several questions about how useful he felt the feedback from the system was with regards to allowing him to properly maintain his desired position on the roadway. He felt the feedback was helpful in ensuring he did not drift too far off the desired roadway location, but he also felt that the system was overly demanding for him to attend to. He thought that relying on the system caused him to make too many small adjustments with the vehicle and that this resulted in him weaving left and right far more than he would have liked.

Regarding the efficacy of the system around curves, the operator did not feel the system was useful. This was not a route he typically plowed, but visibility was clear enough he could see where the major roadway curves were. He felt the system was not that useful for curves since it was giving immediate feedback rather than alerting you to an upcoming curve. He indicated that he felt having a navigation app or something similar where the driver could see an upcoming curve and how far away he was from it would be much more useful for navigating curves especially during inclement weather or when a driver, such as him, is unfamiliar with the route.

The operator had several suggestions regarding the location of the system as well as how the system worked. Firstly, he did not like how far to the right the system was mounted on the dash. He indicated he would prefer if it were over the dash cluster so he did not have to turn as much to look at the interface. He thought it was somewhat distracting to have to look so far to the right over and over. The driver thought it would be easier to drive in a straight line if the system was based on the edge of the vehicle and not the plow, but understood why some operators would prefer feedback based on the

plow edge instead. The driver liked the brightness of the system's lights, but felt they would be too dim during the day when it is especially bright with all of the snow reflecting sunlight and thought a dimmer switch would be useful to have. The operator was initially unsure of which way the system's inner, round lights (Figure 6.3) were telling him to adjust and did not understand why all of the lights, aside from the middle, square indicator, were not arrows.

Overall, the operator liked the system, but felt he had a difficult time getting used to the quick feedback. He felt like, as a more inexperienced driver, the system was one more thing for him to worry about and attend to and that in turn increased his overall mental workload quite a bit. This was made more evident by how high he rated the mental workload demand of the system. He would have preferred a screen that showed the roadway, like google maps, that had a similar light system underneath that gave the same feedback that the current system does. He felt this would help him to not deviate so much, especially on curves in the roadway.

## 6.2 RECOMMENDATIONS

Based on the field observations of snow plow operators using the lane guidance system, the research team has several recommendations for modification and further testing of the system:

- Design a dimmable option on the LED interface to ease discomfort or difficulty seeing the strip under different day and night conditions. The contrast ratio of the LED strip compared to the background lighting must be adjusted to account for day and night luminance conditions and should be between 3:1-5:1 (Ross et. al, 1996).
  - $L_{\text{foreground}} - L_{\text{background}}$  Contrast =  $L_{\text{background}}$ 
    - $L_{\text{foreground}}$  = Luminance of the foreground
    - $L_{\text{background}}$  = Luminance of the background
- Modification of the LED intensity within each color must be carefully designed and tested to account for the Purkinje Shift (Barlow, 1967). This phenomenon explains the increase in sensitivity to short wavelength (e.g., blue light) in drivers who are dark-adapted (e.g., night vision) and more sensitive to long wavelength (e.g., red light) in driver who are light-adapted (e.g., day vision). It is important to ensure that decreasing or increasing luminance of the overall LED interface during different ambient lighting conditions does not overload or make undetectable certain lighted colors along the strip.
- A simple curve notification is recommended to be integrated into the design to alert drivers of curves ahead in white-out conditions. Such a system could give a simple indicator for upcoming right or left curves (see Figure 6.4).

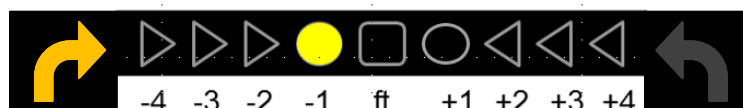


Figure 6.4 Example of possible curve indicator integrated into LED design

- Test alternative placement of the LED system on the dash along with other modifications. The programmed look ahead distances should be examined in future studies both in a driving simulator or in the field.

## CHAPTER 7: SUMMARY

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. We conducted a series of interviews with snowplow operators to engage in information gathering regarding the needs and wants of plow operators. A human-machine interface (HMI) was designed for gang plow operations, for backup assist and for lane boundary guidance applications. These were developed and tested using a driving simulator.

For gang plowing, we evaluated the system performance and position accuracy of commercially available (as of 2015-16) Onboard Units (OBU) used in a Vehicle-to-Vehicle (V2V) application for coordinated and cooperative operations of vehicles in close proximity, typical of many maintenance activities. Our test results indicated that the positioning solution from the OBUs was insufficient for providing the plow operator with adequate information needed to maintain the spacing between two plows.

By incorporating the results from human factors studies, two driver assist systems (DAS), i.e., a backup assist system and a lane boundary guidance system, were developed to support snowplow operations. Both of the DAS can support plow operators in making better decisions and performing their jobs safely and effectively in poor visibility. The radar-based backup assist system was developed and deployed on a snowplow which operates on Highway 169. The backup assist system provides an audio warning to the operator to look at the display from a rear-view camera when an object is detected. The GNSS-based lane boundary guidance system was also developed to assist plow operations when visibility is poor and lane boundary cues are limited. The lane boundary guidance system was installed on a second snowplow operating on MN-25 running between Belle Plaine and Green Isle. The two systems are summarized below.

### 7.1 BACKUP ASSIST SYSTEM

We developed a backup assist system that includes a radar, a low-cost Raspberry Pi 3 microcomputer, and an audible display. A high-performance radar was used to detect objects behind a vehicle and provide audio warning to the driver. The software that processes data from the radar was designed to filter out targets that are more than 20 meters away from the back of the truck as well as those that are closer to the truck, but are moving away from the truck. The distance for filtering targets is programmable. The filtering algorithm activates an audio warning (at 1 Hz tone) when a target is detected within the 20-meter range and that warning increases in frequency (2 Hz) if the target moves to within 10 meters of the back of the truck. The system leverages the existing rear-view camera mounted next to the tailgate of the snowplow. The rear-view camera was mounted on a post to increase its field of view (FOV). The audible feedback is used to direct the operator to look at the rear-camera display when an object is detected by the radar sensor. The radar-based backup assist system was installed and tested on a MnDOT plow truck (#212570) that operates on Highway 169.

The radar used in the backup assist system is configured to detect a vehicle or an object that is moving towards the plow truck from behind. This includes scenarios when the truck is either backing up to an obstacle, or when a tailgating vehicle is approaching the snowplow from behind at a speed faster than the plow's speed. We purposely restricted the radar detection range (from its maximum design range) in order to avoid triggering annoying audio alarms to the plow operators. If a tailgating vehicle enters the 20-m range behind the snowplow, then it will also trigger an alarm.

The backup assist system includes a switch located in the cab to allow the operator to turn the system on/off because operators were worried that the radar would trigger false alarms and the alerting tone would become annoying. However, based on our field test observations, the current radar configuration (detection range and scanning angle) generates alerts when an object is within the designed criteria. The test results indicate that the units meet their technical specifications but the salt spinner partially blocks the field of view of the radar sensor. The plow operators felt that extending the rear-view camera on a post to increase its FOV was sufficient to support their crossover operations without needing the rear-facing radar.

## 7.2 LANE BOUNDARY GUIDANCE SYSTEM

To provide lane boundary guidance for snowplow operators under low-visibility conditions, we developed a driver assistance system based on a high-accuracy Global Navigation Satellite System (GNSS). We also developed a methodology to digitize a roadway and create a digital map that contains road centerlines, lane centerlines, and fog lines. The lane boundary guidance system includes an RTK GNSS system, an in-vehicle LED display, a digital map, and a single board processor. The system provides lateral position information (using a programmable look-ahead distance) to advise plow operators about correcting their lane position in whiteout conditions. Output from this system is displayed using an LED strip with colored arrows indicating whether the driver is centered in the lane or if steering adjustments should be made. The lane boundary guidance system was installed on a second MnDOT plow truck (#203560).

We worked with maintenance operators at the Shakopee truck station to conduct several tests in the field to evaluate system performance and to collect driver feedback on the LED design. The plow operators provided several recommendations to enhance the LED display by making the LED indication dimmable, preferably with a knob. The LED display becomes too bright for the operator when the environment is relatively dark. In a future enhancement, we would propose modifying the LED design by adding a dial knob to allow manual adjustment of brightness. The other recommendation was to remove the blinking red triangle on both ends when the truck is outside the digital map coverage. The blinking red indicator was removed.

Overall, the operators liked the system and found it to be very useful during heavy snowfall when visibility of the roadway and lane markings were minimal. The indication of the location of the plow's left edge allows operators to clear just to the left of the center line, which allows operators to make their return pass with greater speed and efficiency on two-lane roads. Operators felt that they were

more efficient with the lane guidance system since they were able to remove snow in one pass rather than having to come back and take care of missed snow.

### 7.3 FUTURE OPPORTUNITIES

Researchers rode along with operators during inclement snow conditions as well as conducted interviews with multiple operators and supervisors regarding the lane boundary guidance system. The purpose of the ride-along was to gather user feedback on the features of the interface and its functions while driving. Based on the field observations of snowplow operators using the lane guidance system, the research team made several recommendations for modification and further testing of the system.

- Design a dimmable option for the LED interface to minimize discomfort or difficulty in seeing the LED strip under different day and night conditions.
- Design and test modification of the LED intensity within each color to account for the Purkinje Shift.
- Integrate a simple curve-ahead notification into the design to alert drivers of curves ahead while driving in white-out conditions.
- Test alternative placement of the LED system on the dash along with other modifications. For example, programmed look ahead distances should be examined in future studies to be conducted both in a driving simulator and in the field.

As snowplow operators in rural areas often operate in low- or no-visibility conditions, there is an opportunity to (a) incorporate a front radar for obstacle detection and (b) evaluate the effectiveness and usefulness of haptic feedback for lane departure warning. A front radar on the lane boundary guidance system could be added to detect objects in front of the plow truck. An appropriate HMI can be designed to display upcoming roadway geometry and allow visualization of detected obstacles by the radar system. In addition, a haptic interface on the driver's seat using a commercially-off-the-shelf (COTS) product can be integrated into the system to alert operators when they are drifting outside the reference line.

In 2016-17, MnDOT contracted with Continental Mapping to create a Lidar-based digital database of state highway road features. Another opportunity is to develop an interface to convert the statewide Lidar-based database (or other available high-accuracy maps) and adapt it to work across the state for the lane boundary guidance system.

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**APPENDIX A: SYSTEM USABILITY SURVEY (SUS)**

# System Usability Survey SUS

For each of the following questions, place an “X” through the one number to indicate your response. “1” for strongly disagree, “3” for neutral- neither agree nor disagree, “5” for strongly agree.

1. I think that I would like to use this system frequently.

Strongly Disagree		Neutral		Strongly Agree
①	②	③	④	⑤

2. I found the system unnecessarily complex.

①	②	③	④	⑤
---	---	---	---	---

3. I thought the system was easy to use.

①	②	③	④	⑤
---	---	---	---	---

4. I think that I would need the support of a technical person to be able to use this system.

①	②	③	④	⑤
---	---	---	---	---

5. I found the various functions in this system were well integrated.

①	②	③	④	⑤
---	---	---	---	---

6. I thought there was too much inconsistency in this system.

①	②	③	④	⑤
---	---	---	---	---

7. I would imagine that most people would learn to use this system very quickly.

①	②	③	④	⑤
---	---	---	---	---

8. I found the system very cumbersome to use.

①	②	③	④	⑤
---	---	---	---	---

9. I felt very confident using the system.

①	②	③	④	⑤
---	---	---	---	---

10. I needed to learn a lot of things before I could get going with this system.

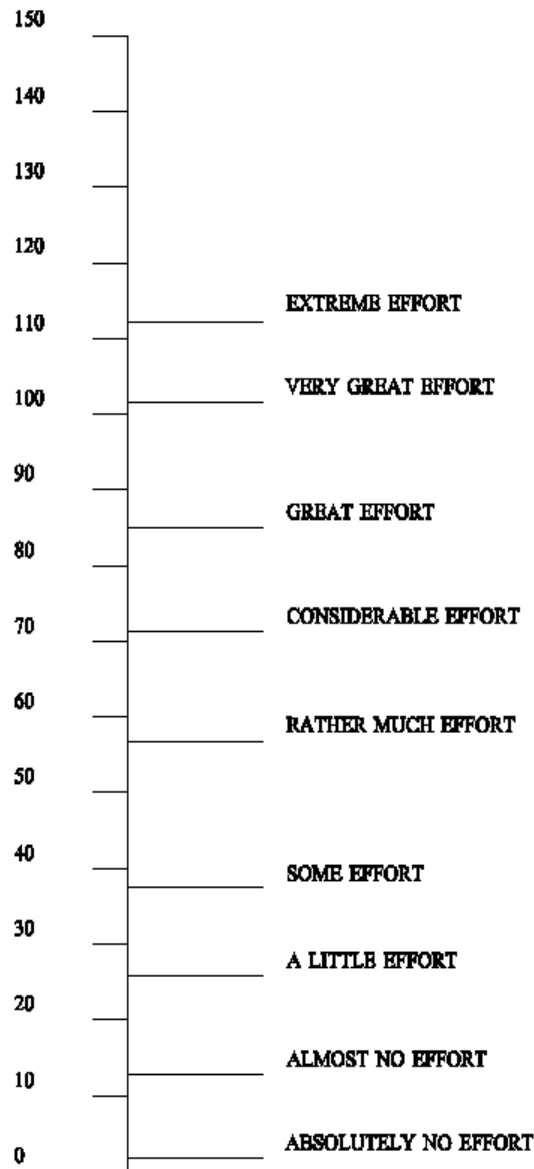
①	②	③	④	⑤
---	---	---	---	---

**APPENDIX B: RATING SCALE MENTAL EFFORT**

# Rating Scale Mental Effort

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

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**APPENDIX C: TWO SETS OF INTERVIEWS OF MAINTENANCE  
OPERATORS REGARDING BACKUP ASSISTANCE**

# Interview Maintenance Operators Regarding Backup Assistance

## Semi-Structured Interview Questions – Initial Visits

### *Current backup camera system*

- Where are the camera and interface placed? Is this the best location?
- What does the interface look like? Are there any important fns?
- Can you adjust the brightness? Does brightness matter?
- How large is the field of view? Does FOV matter?
- How effective is the camera resolution? Does resolution matter?
- Walk us through how you would use this system. What is the step-by-step procedure?
- What are your thoughts on this system?
- What are the issues with this system?
  - Is there any way to clear off or clean the camera?
  - Any usability issues with the interface?

### *Future backup assist system*

- What would a backup assist camera be useful for? What would you be able to do with it?
- How would you expect the backup assist camera system to look?
- Where would you place a backup assist camera: Interface? Camera?
- [*Show a paper prototype of the backup assist camera system*] Is this what you expected? If not, why?
- What features are missing from this system?
- What are some of the challenges to using this technology?
- How would you interact with the interface to clean off the camera lens?
- If you could change anything, what would it be?
- How likely/unlikely are you to use a virtual rearview mirror?

# Interview Maintenance Operators Regarding Backup Assist Interface Display

Semi-Structured Interview Questions – Design Evaluations

## *Purpose*

We have put together a few preliminary designs for the interfaces for the backup assist system.

## *Preface*

Keep in mind that these systems were designs based on interviews with snow plow operators to assist with low visibility conditions for backing up safely. Please think of how you might use these systems in actual plowing situations. If something about the design doesn't make sense or doesn't feel right, please point it out. Feel free to make suggestions on design options that you feel will be helpful. Further, if you don't like anything about any of the designs, please let us know. We want to design a system that will be helpful and want to hear your opinion.

## *Backup assist system*

- Rear view camera overlay
- Birds eye view, with radar interface
- Birds eye view, with zone warnings
- Bird's eye view using a simple LED array

As we walk through the systems, please try to think about actually using this display for backing.

- Will it make backing up safer?
- Anything that doesn't make sense?
- Do you think it is practical to use?
- Will this be helpful?
- Is there anything else that you need that is not in the current design?
- Which do you prefer?

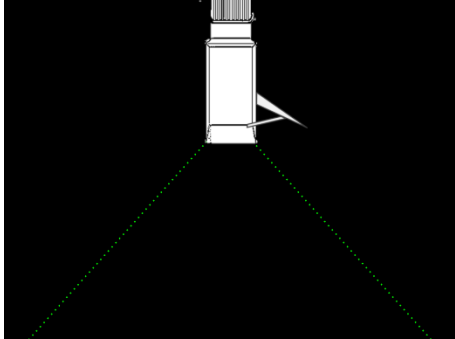
## *Overview*

- Which do you prefer?

Is there anything else that you need that is not in the current designs for rear vision?

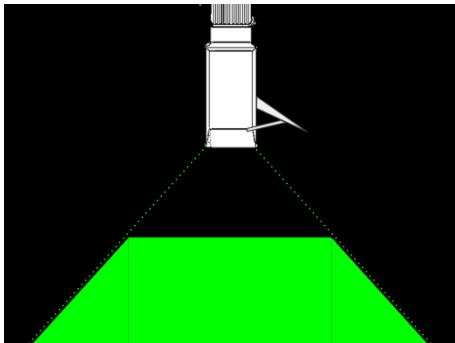
# Interview Maintenance Operators Regarding Backup Assist Interface Display

Rear Vision System Mock up Examples: Bird's Eye (Zones)



## No Zone

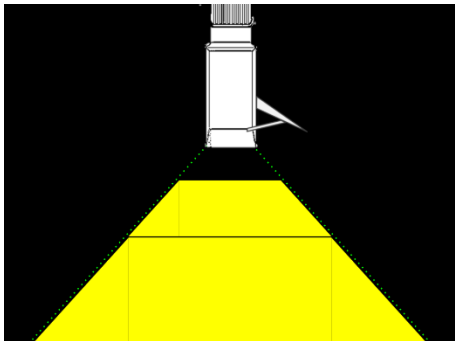
No targets detected.



## Green Zone

A target is in the green zone.

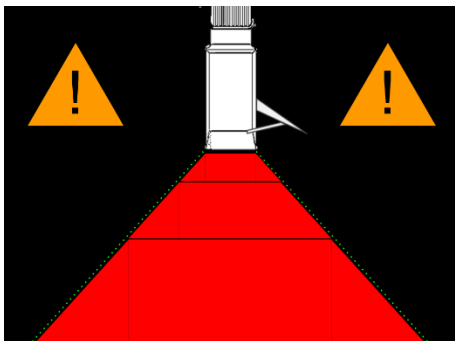
The operator should be aware of the target while backing.



## Yellow Zone

A target is in the yellow zone.

The operator should be cautious while backing.



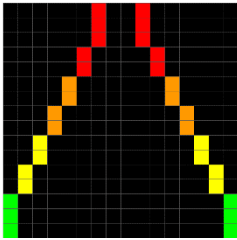
## Red Zone

A target is in the red zone.

The operator should stop immediately

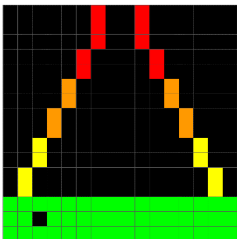
# Interview Maintenance Operators Regarding Backup Assist Interface Display

Rear Vision System Mock up Examples: Bird's Eye (LED)



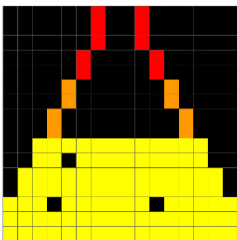
## No Zone

There are no targets detected.



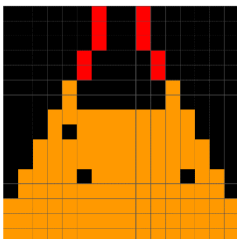
## Green Zone

1 target in the green zone.



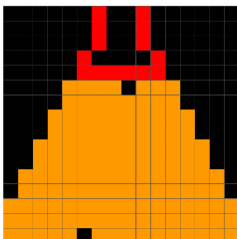
## Yellow Zone

3 target approaching in the yellow zone.



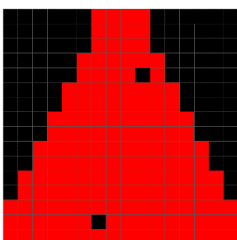
## Orange Zone

3 target in the orange zone.



## Orange Zone

2 target approaching entering the red zone.  
Previous targets have moved outside field of view.



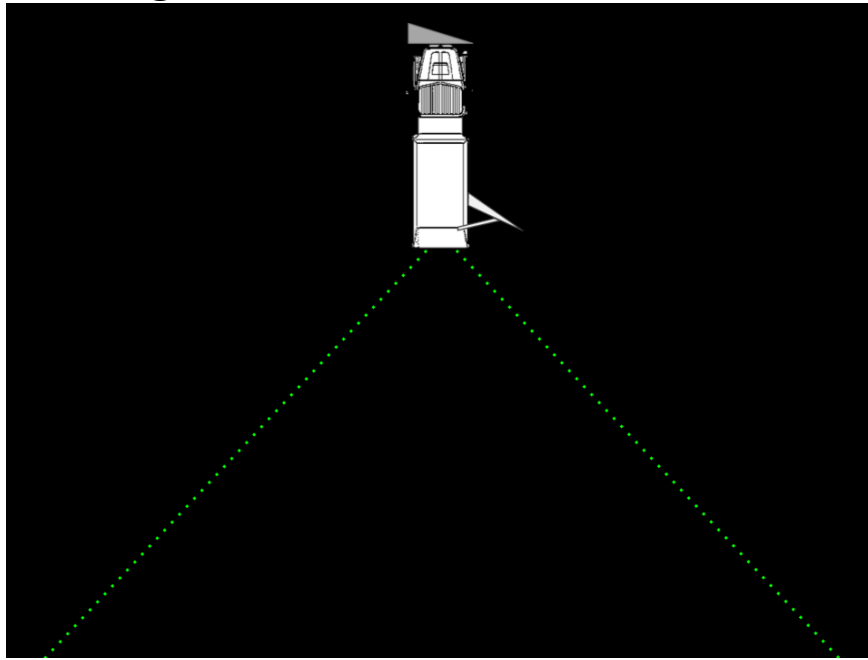
## Red Zone

2 target approaching in the red zone.  
The operator should stop.

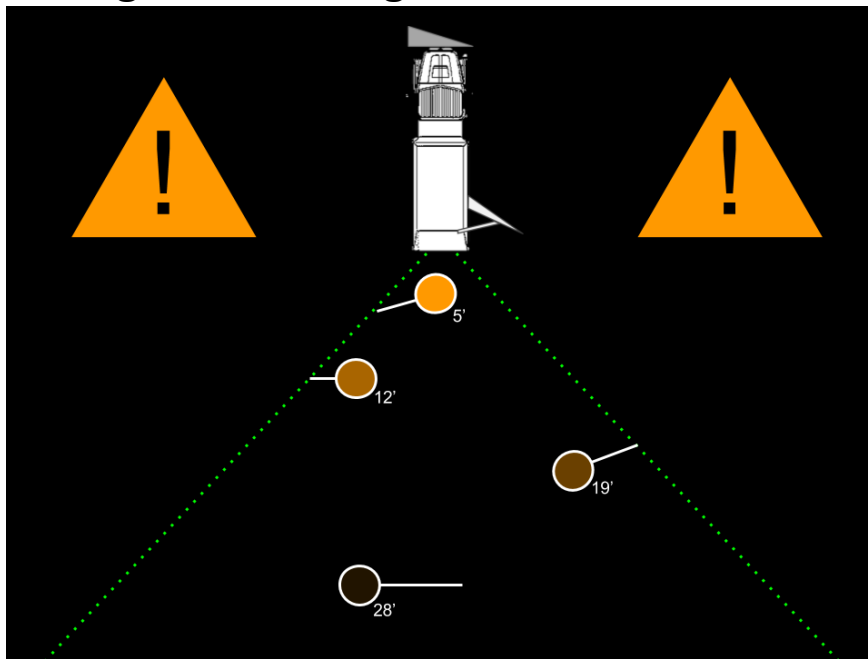
# Interview Maintenance Operators Regarding Backup Assist Interface Display

Rear Vision System Mock up Examples: Bird's Eye (Radar)

## No targets



## 4 targets + warning



Targets are located at 5', 12', 19', and 28' from the rear of the truck. A target is within 10' so the alert is displayed (i.e., the "!" symbols).

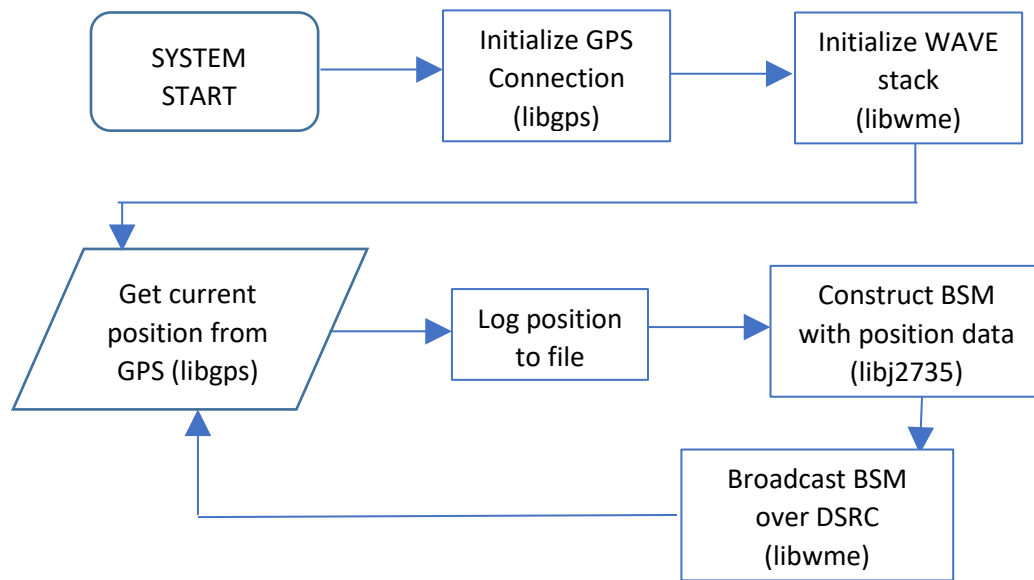
## **APPENDIX D: SOFTWARE USED FOR TESTING THE SAVARI DEVICES**

The Savari devices use a modified version of OpenWrt, an open-source, embedded operating system based on the Linux kernel that is often installed on routers. Access to the GNSS receiver is managed by GPSd, an open-source daemon that reads data from the receiver and allows multiple separate applications to access this data concurrently. The device is configured to acquire a position fix on startup which will be maintained as long as there is sufficient open sky above the antenna. This not only provides any running application with location data, but also provides the system with an accurate time source that is used to synchronize the system's internal clock.

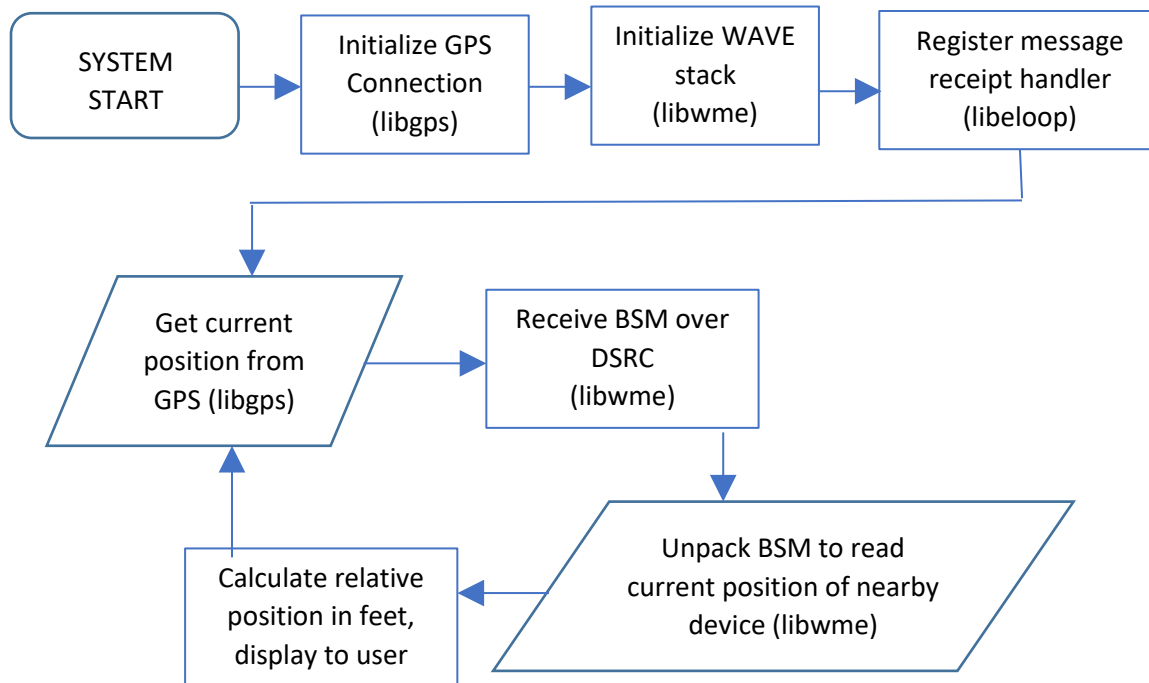
The primary software that was developed for the DSRC onboard units, logs the GNSS location data on the device and broadcasts this information via a BSM sent with each new position fix. Complementary to this, there is another program that listens for these messages over the air and, upon receiving one, calculates the distance between the local device and the position contained in the message. Position fix data includes time from GNSS satellites which is used to synchronize the data and ensure that the relative position is calculated using values from the same point in time. These applications rely on several libraries included with Savari's Software Development Kit (SDK) to handle the low-level system calls and abstract the wire protocols required by the various communication channels. These include:

- *libgps* for interfacing with GPSd and serving location data to the application
- *libj2735* for encoding and decoding BSMs according to the SAE J2735 specification
- *libwme* for communicating over the 5.9 GHz wireless connection according to the IEEE 1609.3 standard for Wireless Access in Vehicular Environments (WAVE)
- *libelooop* for handling incoming data from messages and managing synchronization of threads

These libraries make up the majority of the system's functionality, with some additional code used to interface the libraries with each other and to perform the calculations required by this particular safety application. The following figures illustrate how these pieces are assembled and how they are involved in the overall system.



**Figure D-1.** Control flow of position logging and broadcast routine.



**Figure D-2.** Control flow of relative position display routine.

Currently the application runs in an unsecure and uncertified manner. As development continues, the libp16092 library will be employed to secure messages and to certify communications originating from the equipped vehicles in accordance with the IEEE 1609.2 standard.