Snowplow Lane Awareness System

Operator Interface Design and Evaluation

Daniel V. McGehee

Mireille Raby

Human Factors and Vehicle Safety Research Program
Public Policy Center
The University of Iowa
Iowa City, Iowa 52242

Prepared for the
3M Company
and the
Minnesota Department of Transportation

July, 2002

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the 3M Company or the Minnesota Department of Transportation. Questions or comments regarding this document should be addressed to: Daniel V. McGehee, The University of Iowa, 227 South
Several people from various organizations made this project possible and we would like to thank them for their contribution and efforts.

The 3M Company was the primary sponsor of this research and development program. We are most grateful to Gary Nourse program director, for his leadership, guidance, and efforts in coordinating across many agencies throughout the project. We also wish to thank his colleagues Steve Bartingale, Cathy Behun, Eric Larson, and Mike Roman for their technical contributions and advice.

The Minnesota Department of Transportation (Mn/DOT) has also been a major contributor to this project, not only by providing input, but also by making available human resources, vehicles, and facilities. Most specifically, we would like to thank William Gardner from the Office of Advanced Transportation Systems (OATS). We are especially thankful to John Scharffbillig, also from OATS, for his patience and the numerous nights he spent without sleep to accommodate our night-testing schedule. We would also like to thank Jack Herndon, Site Manager, and Benjamin Worel, Operations Engineer at the Mn/ROAD Project, for facilitating our use of their test facilities. Their assistance, long after normal duty hours, was much appreciated.

The authors also would like to thank Steve Bahler from the Minnesota Department of Transportation, Dennis Burkheimer from the Iowa Department of Transportation, and Steve Owen from the Arizona Department of Transportation for coordinating the distribution of surveys to their maintenance garages. We are also indebted to all supervisors and snow removal operators who participated by completing the survey and providing insightful comments. We would like to express special appreciation to Michael Volk and his dedicated crew from the Iowa Department of Transportation’s Oakdale maintenance garage, who provided us with the opportunity to ride along and interview snow removal operators during snowstorms, and who enabled us to test our procedures with his entire team of operators.
Finally, we would like to extend our thanks to our University of Iowa colleagues: Paul Debbins and James Hogsett, who spent countless hours designing, constructing, and running the sophisticated instrumentation; Professor John Lee for his thoughtful insights into our methodologies; Kirk Bateman who conducted our statistical analyses; and Teresa Lopes for editing our numerous manuscripts.
CONTENTS

ACKNOWLEDGMENTS ........................................................I
CONTENTS .............................................................III
FIGURES ...............................................................VI
TABLES ...............................................................VII
EXECUTIVE SUMMARY ...................................................VIII

SECTION 1 – INTRODUCTION ................................................. 1
  PROJECT OVERVIEW ........................................................ 1
  APPROACH .................................................................. 1
  BACKGROUND ON SNOW REMOVAL OPERATIONS ................. 2
  BACKGROUND ON LANE DEPARTURE COUNTERMEASURES ....... 3

SECTION 2 – UNDERSTANDING THE OPERATIONAL ENVIRONMENT 5
  INTRODUCTION ........................................................... 5
  RIDE-ALONG DRIVES AND INTERVIEWS ............................... 5
  OPERATOR SURVEY ...................................................... 5
    Driver demographics .................................................. 6
    Snow removal vehicle configurations ................................ 6
    Snow removal routes ................................................... 7
    Vehicle alarms and devices ......................................... 7
    Low-visibility operations .......................................... 8
  SURVEY FINDINGS ........................................................ 9
    Ride-along drives and interviews .................................... 9
    Ride-along observations ............................................ 9
    Survey respondent demographics ................................ 11
    Snow removal vehicle configuration ............................... 12
    Driver’s snow removal route ....................................... 12
    Vehicle alarms and devices ....................................... 13
    Low-visibility operations ........................................... 14
  PRELIMINARY DESIGN CONSIDERATIONS ................. 18

SECTION 3 – TASK ANALYSIS AND FUNCTION ALLOCATION .......... 21
  OPERATOR FUNCTION MODEL AND COGNITIVE TASK ANALYSIS 21

Snowplow Lane Awareness System: Operator Interface Design and
Evaluation iii
The University of Iowa
FIGURES

Figure 1. Mean Ratings of Weather Conditions for Potential to Reduce Forward Visibility .........................14
Figure 2. OFM-COG State Transition Diagram for the Function “Lane Plowing” in Snow Removal Operations ..............23
Figure 3. Directional Seat Vibration System (modified Relaxor® seat) ..................................................34
Figure 4. Peripheral Vision Lights mounted on the upper portion of the windshield (left and centered) ............36
Figure 5. Detailed View of Peripheral Vision Light (round suction cup) ................................................37
Figure 6. Control Display Unit (CDU) .................................38
Figure 7. Schematic Representation of the Control Unit with Numerical Identifiers .................................40
Figure 8. Steer Right ..................................................42
Figure 9. No Tape ....................................................43
Figure 10. Aerial photography of the Northern portion of the Minnesota Road Research Project’s Low Volume Roadway (Mn/Road) ...................................................48
Figure 11. Detail schematic of the Mn/Road, including location of roadside features and damaged areas ..........49
Figure 12. 3M™ Sensing Electronics Mounted on the Front Bumper .................................................51
Figure 13. Close-up view of the louver system located on the driver’s side headlamps (hood-mounted) ..........52
Figure 14. Drivers’ Ratings of Trust and Self-Confidence with Each Warning Combination ..............................64
Figure 15. In-Situ NASA-TLX Workload Measures (Averaged Ratings) 66
TABLES

Table 1. Summary of Some Existing Road Departure Countermeasure Systems........................................................ 4
Table 2. Response Rate by State................................................... 11
Table 3. Annoyance Levels for Visual Displays and Indicators in the Cab........................................................... 13
Table 4. Methods Most Useful in Maintaining Lane Position by Plow Use................................................... 15
Table 5. Most Frequent Method or Cue for Maintaining Lane Position by Plow Use................................................... 16
Table 6. Intentionally Crossing into Oncoming or Passing Lanes... 16
Table 7. OFM-COG Analysis for the “Estimate Distance from Centerline” Sub-function of the OFM............. 24
Table 8. Advantages and Disadvantages of Display Modalities for a Lane Awareness System ................................. 28
Table 9. Trade Study for the Modality Presentation of the Lane Awareness System............................................. 30
Table 10. Lane Deviations as a Function of Roadway and Visibility Conditions.................................................. 68
EXECUTIVE SUMMARY

This report describes the design and evaluation of a Lane Awareness System (LAS) operator interface to support 3M™’s Magnetic Tape Series 2000. The principal design team of this project was the University of Iowa—as a contractor to 3M. The LAS was designed to increase snowplow operators’ situational awareness during low-visibility snow removal operations. The UI team set out to design the LAS using a thorough human factors design process, with no ‘a priori’ assumptions. The ultimate goal was to create an intuitive and highly usable operator interface for a broad-based international winter maintenance community. Our development program was focused on developing a simple, yet fully integrated, operator interface. It was important not only that the interface would be entirely compatible with the 3M magnetic tape and sensor system, but also that it could be easily integrated into the operational environment in terms of cab installation, training and practicality. Due to the complexity of the design process and overall system goals, the project flow relied heavily on established systems engineering principles for all design decisions. The technical activities of the program were grouped into three phases:

Phase I: Understanding the operational environment
Two approaches were used to gain this understanding. First, we conducted focus group interviews and ride-along drives with active snowplow operators. These provided us with practical knowledge about the work and work environment. The drives also exposed us to the demands and constraints imposed on drivers. Using information gathered in the interviews and drives, we then developed an extensive survey that helped us quantify the fundamental operating issues in snow removal operations. The survey was sent to 1,678 State DOT snowplow operators from Minnesota and Iowa. From the ride-along drives and survey, eight design-based recommendations were carried forward:

1. The operator interface of the 3M™ Lane Awareness System should be a driver “aid.”

2. The warnings should use peripheral cues.

3. Displays should be designed to inform drivers of the distance traveled from the reference tape.
4. Display should be selectable for either centerline or shoulder-line points of reference.

5. The warning thresholds should be adjustable.

6. All displays should have adjustable intensity.

7. Backgrounds on visual displays should be black.

8. Provide better defrosting capabilities.

The ride-along drives, interviews and survey, provided the initial design requirements. In Phase II we described how these design recommendations were corroborated, further refined, or eliminated through use of an analytical methodology designed to identify the system’s tasks, functions, and constraints and their influence on the design.

Phase II: Design process

The design process began with developing and operator function model and cognitive task analysis (OFM-COG). The OFM-COG helped us to identify the functions and sub-functions that snowplow operators usually perform while cleaning the roadway. It also enabled us to identify the cognitive demands associated with those tasks, and to learn how operators obtain the information necessary to accomplish a given task.

Next we performed trade studies and design rational to further narrow our interface design. Using trade studies, we consider several design factors and objectives, and then decide which objectives to compromise in favor of others. The overall goal of a trade study analysis is to maximize the design advantages. Finally we provided design rational for each of the design recommendations, which were then forwarded to the preliminary design.

The user interface we proposed has three components. Two primary cues for lane departure warnings involve peripheral displays, while a third cue is intended to act as a secondary supporting visual reference. The primary peripheral cue is a directional seat vibration. The other peripheral lane departure warning consists of lights that use large-format LEDs mounted on the windshield. The final cue, the control unit, provides detailed
information to the operator on exact lane position relative to the sensor.

Phase III: System Evaluation

The LAS operator interface was evaluated using two different approaches. The first approach was a field operational evaluation in which the system was used in actual snow removal operations. The LAS and operator interface were installed in a DOT snowplow vehicle, and drivers were free to use the system in their normal snow removal operations. The field operational evaluation took place in Minnesota and Arizona, with the former occurring over a two-winter period while the latter consisted of only a few outings that were part of drivers’ initial training with the system.

The other evaluation, a closed-course usability study, was more structured—we wanted the rigor of a controlled experiment but the flexibility and operational validity of a field study. Overall, we found that drivers responded favorably to the peripheral warning strategy and interface design. Drivers learned to use the interface quickly, and understood its function as an ‘aid.’ They related well to the “seat of the pants” driving approach with the directional vibrating seat. The peripheral vision lights were considered by some to be a useful complement to the vibrating seat. The control-display unit (CDU) was also easy to understand, and operators who used the system in the field liked the adjustable warning thresholds.

Future interface designs of the LAS might consider integrating two new components into the operator interface: 1) a forward collision warning (FCW) system and 2) a navigational unit.

Our data from this project suggest that the 3M™ LAS is beneficial to drivers involved in snow removal operations. The LAS appears reliable and useful in increasing drivers’ situational awareness in low-visibility conditions—its primary function. Drivers trusted the system to provide accurate and reliable information, and felt that it had good potential to improve their overall safety and confidence in maintaining their lane position.
SECTION 1 - INTRODUCTION

Project overview

The University of Iowa (UI), together with the 3M Company and with the cooperation of the Minnesota DOT (Mn/DOT), have embarked on a comprehensive research program to develop and test a Lane Awareness System (LAS) operator interface to support 3M’s Magnetic Tape Series 2000. The UI team set out to design an operator interface from the ground up, with no a priori assumptions. The LAS was designed to increase snowplow operators’ situational awareness during low-visibility snow removal operations. Our overall goal was to design the LAS using a thorough human factors design process. We used a systems-based approach to ensure that the resulting LAS would have a practical interface for use internationally. The ultimate goal was to create an intuitive and highly usable operator interface for a broad-based winter maintenance community.

Approach

Our program was highly focused on developing a simple, yet fully integrated, operator interface. It was important not only that the interface would fit well with the 3M™ magnetic tape and sensor system, but also that it could be easily integrated into the operational environment in terms of cab installation, training and practicality. Due to the complexity of the design process and overall system goals, the project flow relied heavily on established systems engineering principles for all design decisions. The technical activities of the program were grouped into three phases:

Phase I: Understanding the operational environment
   - Ride-along drives to experience the operational environment
   - Development and distribution of a survey to gather objective and operational information

Phase II: Design process
   - Cognitive task analysis and function analysis
   - Trade studies and design rational
   - Preliminary design

Phase III: System Evaluation

Snowplow Lane Awareness System: Operator Interface Design and Evaluation
The University of Iowa
These phases comprise the systems-based approach used for the design, test and evaluation of the LAS. The systems-based approach involves a series of well-defined development stages carried out sequentially and in a manner consistent with the principles of systems engineering design (Bailey, 1982). The sequence of these steps and their complexity vary depending on the nature of the system under design. Applied here, it ensured that the resulting interface conforms to the operational requirements (e.g., local government resources and vehicle infrastructure) and operators’ attentional limits, while incorporating the most practical technological solutions.

**Background on snow removal operations**

Maintaining an extensive network of highways during harsh winter conditions can be a challenge for states that experience frequent snowfalls. Timely snow removal and de-icing services are essential to ensure that roadways remain open to commercial traffic and the traveling public. In most storms, heavy snow and winds combine to create low-visibility conditions with short periods of whiteout. In such situations, snow removal operators may lose sight of the roadway and the surrounding area. Staying on the road while minimizing the need to stop may become a challenge. For operators, the threat of being hit from behind while stopped or traveling at low speed is a reality. During a typical winter in Minnesota, for example, Mn/DOT snowplows are involved in nearly 100 crashes (Bahler et al., 2000). Mn/DOT reports that in the vast majority of these crashes, the snowplow vehicle either ran into another vehicle, was hit from behind by another vehicle, or ran off the road and hit a sign, guardrail, or bridge abutment that was obscured from the driver’s view.

If we could provide driver assistance technology to help drivers maintain sight of the roadway, we might prevent some of these crashes and even possibly increase snow removal efficiency, thereby reducing the expenses of DOT agencies involved in snow operations. One estimate of savings associated with opening a snow covered road in Minnesota even one hour earlier predicted
commercial vehicle savings of up to $109,000 for roads impacted by adverse weather (Bahler and Bartingale, 2000).

Telematics systems that enhance drivers’ awareness of their lane position may help reduce the likelihood of run-off-road crashes. By increasing operator situational awareness, such devices may not only allow drivers to scan the environment for hazards, but also permit them to continue snow removal operations even in very low-visibility conditions.

**Background on lane departure countermeasures**

A number of technologies are currently being investigated to make snow removal operations safer and more efficient thanks to increasing capabilities and system integration. These technologies include driver warning and information systems, driver assistance technologies, and various automation systems (ITSA, 2002).

Over the last eight years, road departure technology, as it applies to passenger vehicles, has matured greatly. In 1994, the National Highway Traffic Safety Administration (NHTSA) began a series of crash countermeasures research projects that included lane drift and curve over-speed alerts. Since then, numerous research efforts have created prototypes and tested systems. Table 1 lists some of these devices. It should be noted that almost all of these roadway departure countermeasures depend on vision-based systems to capture roadway information.

There are two primary types of road departure countermeasure systems: infrastructure-based and vehicle-based. Infrastructure-based devices rely on peripheral hardware such as magnetic tape or nails installed into the roadway (e.g., 3M™ and Caltrans, respectively) and differential GPS (e.g., University of Minnesota), which requires towers to help triangulate satellite signals. Vehicle-based systems generally use optical/vision techniques that examine centerline and shoulder line lane boundaries. Such vision-based systems have difficulty in capturing lane position information during inclement weather; however, they are inexpensive for “normal” operations. Infrastructure-based systems are very expensive; however, they do work well during low-visibility conditions.
Table 1. Summary of Some Existing Road Departure Countermeasure Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Infrastructure-based</th>
<th>Vehicle-based</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerometrics</td>
<td>X</td>
<td>Vision-based</td>
<td></td>
</tr>
<tr>
<td>Assistware-Safe Track</td>
<td>X</td>
<td>Vision-based</td>
<td></td>
</tr>
<tr>
<td>AutoVue</td>
<td>X</td>
<td>Vision-based</td>
<td></td>
</tr>
<tr>
<td>CA-PATH</td>
<td>X</td>
<td>Magnetic nails</td>
<td></td>
</tr>
<tr>
<td>Cooperative Co-pilot</td>
<td>X</td>
<td>Vision-based</td>
<td></td>
</tr>
<tr>
<td>University of Minnesota</td>
<td>X</td>
<td>Differential</td>
<td>Ground Position System (DGPS)</td>
</tr>
<tr>
<td>3M Company</td>
<td>X</td>
<td>Magnetic tape</td>
<td></td>
</tr>
</tbody>
</table>

The 3M Company has designed a magnetic tape and a sensor unit capable of capturing a magnetic signal and converting it into lane position information. Originally, this technology was developed to obtain vehicle position information with respect to the centerline. It was first applied for use in the Automated Highway System demonstration. Later, it was seen as an option for specialty vehicle operations. Snowplows seemed to be a particularly appropriate platform for this technology, as they frequently face low-visibility conditions during snow removal operations. The system could increase a snowplow operator’s efficiency by keeping plows on the road longer. Furthermore, if state and local governments could inexpensively and easily integrate the system into their existing fleets, snow removal operations could be simplified and their economic impact on a region reduced (3M Company, 2000).
SECTION 2 – UNDERSTANDING THE OPERATIONAL ENVIRONMENT

Introduction

The first step in our design process was to attain a thorough understanding of the nature of the work, the environment, and the general context in which the 3M™ Lane Awareness System (LAS) would be used. By clearly understanding snow removal operations, their constraints and limitations, we could be confident that the interface would meet the users’ needs.

Two approaches were used to gain this understanding. First, we conducted focus group interviews and ride-along drives with active snowplow operators. These provided us with practical knowledge about both the work and work environment. The drives also exposed us to the demands and constraints imposed on drivers. Using information gathered in the interviews and drives, we then developed an extensive survey that helped us quantify the fundamental operating issues in snow removal operations.

Ride-along drives and interviews

The data collection process began with a series of ride-along drives and interviews completed during winter storms in Iowa. The ride-along drives provided first-hand experience of plowing operations during storm conditions. They enabled us to observe how snow removal operators adapt to various roadway configurations and traffic conditions, and how operators divide their attention between various plowing tasks. Of particular interest was how different in-cab configurations influence these tasks. The focus group interviews made it possible to assess snowplow operators’ need for lane awareness technology, and to determine how such a system could or would be used.

Operator survey

The information gathered during the ride-along interviews was then integrated into a survey focusing on snowplow operators’ knowledge of and experience with factors affecting forward visibility and lane position during snow removal operations (see Appendix A). The survey sought to gather information specifically
related to the design of the 3M™ LAS operator interface. It was used to evaluate five different issues:

1. Driver demographics
2. Snow removal vehicle configurations
3. Snow removal routes
4. Vehicle alarms and devices
5. Low-visibility operations

**Driver demographics**

Surveys were distributed to active snow removal operators in the Iowa and Minnesota DOTs. While Minnesota and Iowa by no means represent all snow removal operations, they do exemplify non-mountainous, Midwest operations. Aside from the traditional demographics of gender and age, respondents provided information about their education, experience with snow removal operations, and computer literacy. Knowing respondents’ level of experience (measured by number of winter seasons on the job) helped us to understand drivers’ overall mental model of snow removal operations. For example, an experienced driver might have had the opportunity to experiment with different vehicles and plow configurations, as well as with varied snow routes and conditions, and could be expected to provide very specific recommendations for the interface design. Potential users’ level of experience with computers is an important consideration in the design of any computer-based operator interface.

**Snow removal vehicle configurations**

Respondents provided information on the number and type of vehicles they typically drove during a winter season. Knowing whether operators were assigned mostly to one vehicle or to several helped us understand their level of familiarity with the controls and displays of a particular cab. It was important to know whether there was a need for consistent in-cab configurations across vehicles. Identifying specific vehicle models operated by the Minnesota DOT (Mn/DOT) and the Iowa DOT enabled us to determine how consistent cab configurations were across vehicles.
Plow types and plow configurations were also considered. Identifying the most frequently used plow configurations helped us establish a baseline in terms of driver visual demands. The demands are very different, for example, for a front-mounted plow only versus a combination of front-mounted plow and right wing plow. Furthermore, drivers using either a left or right wing plow must mind the shoulder more closely and monitor for shoulder-based obstacles. We were also interested in information such as on which mirror drivers most commonly focus their attention. Understanding the attentional differences between mirrors helped us further increase our knowledge of visual resource allocation during snow removal operations.

**Snow removal routes**

The survey included questions about route length, type of roadway, and number of routes operators typically drove—all important considerations when designing this type of interface. Four-lane divided freeway operations require a different set of driver resources than narrow rural highways; cues available to identify lane position on an interstate might be different or unavailable on a country road. It was also important to establish the number of routes drivers plowed, and whether or not one of the routes was designated a “primary” route. When drivers are assigned to only one “primary” route, their familiarity with the particulars of that route provides them with a situational awareness advantage relative to those driving several unfamiliar routes.

**Vehicle alarms and devices**

The next section of the survey asked about vehicle alarms and devices. The goal was to identify all current displays and alerts so as to ensure that features chosen for the LAS interface would not be masked by or confused with existing warnings. Familiarity with the alerts already present in snowplow vehicles also helped us to determine the priority for lane exceedence warning strategies relative to existing alarms. Finally, we were interested in learning which displays and alarms drivers considered the most annoying.
Low-visibility operations

In one of the most important sections of the survey, drivers evaluated key aspects of low-visibility plowing operations. First, specific weather and environmental conditions were examined, with drivers rating which conditions (e.g., night, day, and drifting or falling snow) caused the worst forward visibility. Operators were also asked about the effect of wind direction and specific driving scenarios that could affect their forward visibility (e.g., meeting trucks or buses, being passed by a passenger vehicle). Questions regarding other factors that might undermine forward visibility, such as plow type and plow configuration, were also included. Furthermore, to ensure consistency, we asked drivers to consider only the 1998-1999 winter season while answering these questions. Unfortunately, that winter season was mild and experienced a very limited number of snow events. As a consequence, drivers’ answers are most probably more conservative than in reality.

Determining what cues drivers use to maintain their lane position was a primary interest of the survey. Identifying these cues was an important element in understanding the snow removal operator’s visual search, as was determining drivers’ primary reference points (e.g., shoulder line, tree lines, or own vehicle’s tracks). Additional questions gathered information on whether drivers intentionally crossed the centerline while plowing—an important consideration for the interface design since reducing nuisance alarms is a key concern.

Drivers were asked how frequently they had had to stop during the previous winter season due to low-visibility conditions. We were also interested in the duration of low-visibility events, as this has direct implications for the basic information display architecture (the interviews and ride-along drives suggested that momentary loss of all cues was common). Respondents were then asked about the consequences of losing sight of the roadway. Because Mn/DOT reports that drivers striking bridge abutments with wing plows is a costly problem (Minnesota DOT, 1998), we also asked whether operators knew of someone who had run off the road or struck an object during snow removal operations. We felt that drivers might be reluctant to discuss personal road departure experiences, but that asking about others’ might elicit some useful information.
Finally, the survey addressed snow removal operator safety concerns. In designing the interface, we were interested in integrating other potential safety improvements, if possible. For instance, the ride-along drives and interviews suggested that getting struck from behind is one of drivers’ primary safety concerns. A lane awareness system that displayed continuous and reliable cues might reduce drivers’ need to slow down—or worse, to stop their vehicles—and risk being struck from behind.

Survey findings

In this section, we present the results from the ride-along drives, the interviews, and the surveys. Three separate appendices provide summaries of answers to the survey: Appendix B contains a complete summary of all answers to each of the individual survey items; Appendix C is a summary of all answers to the last item of the survey, the comment section; and Appendix D presents a brief summary of comments written in the margins of the survey.

Ride-along drives and interviews

In late February and early March 1999, University of Iowa researchers conducted focus group interviews with Iowa DOT snowplow operators based in the Iowa City area (Oakdale garage) to gather preliminary information on snowplow operations during low-visibility conditions. Researchers then rode along on snowplow operations with different drivers, on different routes and in different types of vehicles. Vehicles included single-axle and tandem vehicles, and drivers’ experience varied from part-time employees with limited snow removal experience to seasoned drivers. During the course of the drives, researchers experienced a wide range of visibility conditions and drove on roadways ranging from the interstate to two-lane rural highways to four-lane city streets.

Ride-along observations

One of the primary observations of the ride-along drives was that plow crews drive several generations of equipment. Controls varied tremendously across different vehicles, even within the same vehicle make and model. For example, some of the plow
controls were located on the dashboard, underneath a plastic cover, requiring operators to use both hands to activate them; some were located on a control panel situated between the driver and passenger seats; and others were more traditional hydraulic levers positioned between the driver and passenger seats. Because of their orientation, some of the controls forced operators to turn and look sideways in order to operate the plow.

Another important observation was that operators often customize their cabs. Several of the drivers interviewed complained about the lack of control over interior cab lighting. Some drivers taped over display lights to reduce the distraction from their primary tasks. Having a dark cab free of distractions was of paramount importance to drivers—some even dimmed speedometer and tachometer lights to the point of turning them off. When drivers were asked about auditory warnings, most thought that additional auditory alarms would be too intrusive. In short, drivers preferred having the ability to control information display intensities in the cab.

During the ride-along drives, we also observed that differences in road configuration, traffic level, and geographical location (e.g., wide open spaces, city limits) affect forward visibility, as does the snow removal technique used. For example, two-lane interstate highways required the use of left-wing and right-wing mounted plows, both of which have specific operations issues. We also found that drivers used a wide range of cues and techniques for identifying and maintaining lane position. Depending on the roadway and its environmental characteristics, operators relied primarily on the shoulder, the tree or grass line, car tracks, post delineators, and/or other traffic. However, as visibility conditions were reduced, drivers consistently described shedding these visual cues, thus revealing the importance of knowing a route and its specific characteristics as visibility is reduced.

Finally, although seemingly unrelated to the lane-monitoring task, window fogging and icing emerged as another significant safety issue. The ride-along drives clearly demonstrated how windows lacking defrosters—or equipped with inadequate ones—can ice up very quickly, thereby exacerbating low-visibility conditions. Window icing appeared worse in conditions where there was a crosswind and the operator was using a wing plow located on the crosswind side. Under such conditions, several drivers chose...
to turn the cab heat as high as it would go and to drive with their side windows down in order to see the shoulder line and/or their freshly plowed tracks. Other tactics included frequent stops to clear ice from side and front windows—a practice that can be hazardous for approaching vehicles.

**Survey respondent demographics**

The survey was sent to 1,678 State DOT snow removal operators from Minnesota and Iowa. Of those, 1,009 were returned, for an overall response rate of 60 percent (see Table 2).

<table>
<thead>
<tr>
<th></th>
<th>Sent</th>
<th>Received</th>
<th>Response Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minnesota</td>
<td>954</td>
<td>476</td>
<td>49.9 %</td>
</tr>
<tr>
<td>Iowa</td>
<td>724</td>
<td>533</td>
<td>73.6 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1678</td>
<td>1009</td>
<td>60.1 %</td>
</tr>
</tbody>
</table>

Most respondents were male (94.7%). The mean and median age for all respondents was 45 years old. Education levels ranged from 8th grade or less (less than 1%) to 4-year college degree or more (1%). Most respondents indicated that they had completed high school (57.0 %), and about one third had either some college or a 2-year degree (35.8 %). This last finding suggested that the design should assume a high school reading level. Respondents were asked how many winter seasons they had worked as snow removal operators: 101 (10.5 %) answered ‘two or less’ and 36 (3.7 %) indicated ‘more than 30 years’; the average was 13. The wide range of experience in our sample made it possible to compare findings across experience levels to identify potential differences in design requirements.

Another item of interest was operators’ reported use of and experience with computers. A total of 438 respondents (43.4 %) indicated that they did not use a computer on a regular basis either at home or at work. The average rating for experience level with computers was 2.5 (i.e., halfway between beginner and intermediate). It was concluded that the operator interface should minimize the need for computer-related skills.
Snow removal vehicle configuration

In designing the operator interface, it was important to know how many vehicles operators typically drove during a winter season, as well as the configuration of those vehicles. More than one third of respondents (39.5%) indicated that they typically drove only one snow removal vehicle during the 1998-1999 winter season. The remaining two thirds had driven two or more that winter, with approximately 13 percent driving more than three vehicles. The average number of vehicles driven was two. A little over half of the snow removal vehicles (56.7%) had a tandem-axle rather than a single-axle. Although more than six different makes of vehicle were identified, about half of those driven were either International (48.2%) or Ford (45.8%). About one third of the International and Ford vehicles were built in the 1980s. The remaining two thirds were built in the 1990s, with close to one third of vehicles being 1995 models or later.

In addition to vehicle configuration, we asked operators which plow configurations they had used most frequently during the previous winter season. Operators used a front-mounted plow combined with a right wing plow most often (73.1%). The combination of a front-mounted plow with a left wing plow was used much less frequently (14.1%). Respondents were asked what percentage of time on average they had used each of nine different plows or systems. The material spreader had the highest reported percentage of use (mean rating 79.6%), followed by the front-mounted two-way reversible plow (mean rating 73.0%) and the right wing plow (mean rating 64.0%).

Driver’s snow removal route

More than 1,000 operators provided information regarding the number of routes they had plowed during an average snowstorm in the 1998-1999 winter season. Many had always plowed the same route (41.8%), while only a small subset (10.6%) had had to plow more than three routes. The approximate length of drivers’ primary routes varied greatly, with some as short as two lane miles and others as long as a thousand lane miles. The average for the entire sample, which did not include the few extreme upper values, was a little short of 50 lane miles. Primary routes often encompassed different types of roadways. The largest number of respondents had been assigned to one or more of three roadway
types: two-lane undivided highways, on and off interstate ramps, and city roads.

When asked about driving speeds while plowing, respondents’ answers ranged from 1 mph to 50 mph for their minimum speed, and from 11 to 65 mph for their maximum speed. The average minimum speed was approximately 14 mph and the average maximum speed was approximately 35 mph.

**Vehicle alarms and devices**

Table 3 lists the five in-cab visual displays and indicators that respondents considered most annoying. Two additional displays had comparable annoyance levels, but were present in fewer vehicles: cellular phone status (n=84, annoyance = 8.3 %) and under-body plow pressure (n=209, annoyance = 4.3 %). Similar ratings were obtained for visual and auditory alarms. The auditory alarm considered most annoying was the ‘excessive speed while sanding’ (annoyance = 42.5 %).

<table>
<thead>
<tr>
<th>Displays and Indicators</th>
<th>Present in the Cab (number of times selected)</th>
<th>Annoying (percent time selected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-way radio channel scan</td>
<td>843</td>
<td>36.8 %</td>
</tr>
<tr>
<td>Salt spread over speed</td>
<td>373</td>
<td>10.7 %</td>
</tr>
<tr>
<td>Material rate control</td>
<td>799</td>
<td>8.3 %</td>
</tr>
<tr>
<td>Salt-brine control</td>
<td>500</td>
<td>6.4 %</td>
</tr>
<tr>
<td>Material spread width</td>
<td>647</td>
<td>3.2 %</td>
</tr>
</tbody>
</table>

The results indicated that respondents considered visual displays less annoying than either visual or auditory alarms. This finding was supported by written comments in which respondents stated that while conversations on the two-way radio channel are annoying, the display itself is not.
Low-visibility operations

Factors affecting forward visibility

Operators were asked to rate their experiences with a set of weather and wind conditions on a scale of 1 (never causes poor forward visibility) to 7 (always causes poor forward visibility). Figure 1 summarizes the mean ratings for both daytime and nighttime weather conditions. Results suggested that respondents consider conditions with drifting snow and snowfall to have the greatest potential for causing poor forward visibility, especially at night.

A similar set of analyses was conducted for wind conditions. ‘Plowing the right lane with a crosswind from the right’ received a higher mean rating (mean rating = 5.27) than any other condition, followed by ‘plowing the left lane with a crosswind from the left’ (mean rating = 4.81).

Figure 1. Mean Ratings of Weather Conditions for Potential to Reduce Forward Visibility

Respondents were also asked to rank ‘driving situations’ and ‘plow configurations’ on the same 1–7 scale. Responses indicated that ‘being passed by’ trucks or buses and ‘meeting’ trucks or buses caused the worst problems in terms of poor forward visibility.
visibility (mean ratings of 5.26 and 4.50 respectively). In a similar analysis comparing plow configurations, front-mounted V-plows and front-mounted reversible plows reduced forward visibility the most (mean ratings 4.26 and 4.10 respectively). Large right wing plows had a slightly higher mean rating than left wing plows (3.41 and 3.01 respectively). The combined findings suggested that the worst possible conditions for reduced visibility occur during nighttime plowing when there is both drifting snow and snowfall. Plowing a right lane with a right wing plow and a crosswind from the right reduces visibility even more, as does being passed by trucks or buses.

Methods used to maintain lane position

Identifying the cues drivers used to maintain their lane position was essential to the design of the LAS operator interface. Table 4 summarizes the three cues rated most important (out of a possible set of 12 cues) by respondents.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Mean Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Looking ahead to evaluate distance from shoulder line</td>
<td>1.76</td>
</tr>
<tr>
<td>Evaluating distance from center line</td>
<td>1.81</td>
</tr>
<tr>
<td>Evaluating distance from milepost delineators</td>
<td>1.83</td>
</tr>
</tbody>
</table>

When methods used to maintain lane position were examined as a function of the plow configuration most often used an interesting pattern emerged, as shown in Table 5. Right plow users selected the shoulder line cue more frequently than left plow users (53.7% vs. 41.2%). Right plow users also preferred the shoulder line cue to the centerline cue (53.7% vs. 44.3%), whereas left plow users preferred the centerline cue to the shoulder line (49.6% vs. 41.2%).

These findings suggested that the shoulder line and the centerline are both critical to maintaining lane position, and that if possible, the operator display should provide information
regarding both. Plow configuration seems to influence which of these two reference points will be used by the operator.

Table 5. Most Frequent Method or Cue for Maintaining Lane Position by Plow Use

<table>
<thead>
<tr>
<th>Methods</th>
<th>Plow Users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left (n=141)</td>
</tr>
<tr>
<td>Looking ahead to evaluate distance</td>
<td>41.2 %</td>
</tr>
<tr>
<td>from shoulder line</td>
<td></td>
</tr>
<tr>
<td>Evaluating distance from center</td>
<td>49.6 %</td>
</tr>
<tr>
<td>line</td>
<td></td>
</tr>
<tr>
<td>Evaluating distance from milepost</td>
<td>38.2 %</td>
</tr>
<tr>
<td>delineators</td>
<td></td>
</tr>
</tbody>
</table>

Crossing roadway line markings

As part of their snow removal operations, operators may sometimes unintentionally cross into the oncoming or passing lanes and at other times intentionally cross into them. It was important to document how frequently these crossings occurred and how far drivers plowed into the other lane(s) in order to determine the need for a scale and alarm threshold of the operator display. Almost two-thirds of the operators reported unintentionally crossing into other lanes (62.9 %), while slightly more than half reported also intentionally doing so (52.6 % vs. 47.4 % who did not cross lanes). The majority of those who intentionally crossed into other lanes indicated that they did so by 1 to 3 feet in both average and low-visibility conditions. They also stated that they crossed into both oncoming and other lanes (see Table 6). The following table shows that snow removal drivers intentionally crossed lanes more often during average-visibility condition than during low-visibility conditions.

Table 6. Intentionally Crossing into Oncoming or Passing Lanes

<table>
<thead>
<tr>
<th>How far into the lane?</th>
<th>Oncoming Lane</th>
<th>Passing Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Visibilit y</td>
<td>Low Visibilit y</td>
</tr>
<tr>
<td>1 to 3 feet</td>
<td>68.8 %</td>
<td>51.7 %</td>
</tr>
</tbody>
</table>
Losing sight of the roadway and associated consequences

One reason snow removal operators unintentionally cross into other lanes is because they lose sight of the roadway. When asked how often and for how long they had completely lost sight of the roadway during the worst snowstorm of the 1998-1999 winter season, one third of respondents answered ten or more times (31.8 %). Most drivers chose '4 to 9 seconds' for the average duration (47.7 %) and '1 to 19 seconds' for the longest duration (53.6 %) of these periods of no visibility. However, when asked whether they had ever had to stop because they could no longer determine their lane position, a little over half the respondents indicated that they had not (56.2 %). Finally, when queried about whether they had ever hit an object because they could no longer determine their lane position, less than 10 percent (9.3 %) indicated that they had. Of those who reported striking an object, most had hit either a guardrail or curb.

The findings suggested that snow removal operators experience frequent episodes when they can no longer see the roadway, most often for periods of less than 10 seconds. This was critically important information. Moreover, when they do lose sight of the road, drivers usually choose to slow down rather than to stop. The reason for this may have been reflected in operators’ ratings of their three most important safety concerns. The three top safety concerns were: (1) ability to be seen by a vehicle approaching from behind, (2) ability to continuously see the roadway in front of the vehicle, and (3) risk of being hit by another vehicle.

The information gleaned from the survey, and the observations made during the ride-along drives, provided us with a better understanding of the context in which the new operator interface would be used. They helped us identify the constraints or limits on system performance specifications, which in turn influenced how the new interface would be designed (Bailey, 1982). Rather than list the system’s performance requirements and constraints we chose to convert them into preliminary design recommendations.
Preliminary design considerations

The following interface design recommendations were developed based on the ride-along drives, interviews, and surveys. Supporting rational is provided for each recommendation.

Design recommendation 1: The operator interface of the 3M™ Lane Awareness System should be a driver “aid.” Since drivers reported that they lose sight of the forward roadway more frequently for brief (4 to 9 seconds) rather than for extended time periods, the operator interface of the LAS should be designed as a driver “aid.” (This principle also influenced the name of the system: “Lane Awareness System.”) In fact, during the ride-along drives, snowplow operators reported that complete whiteout conditions for extended periods were extremely rare. This observation was confirmed in the survey, where only 6% of respondents reported experiencing complete loss of visibility for periods greater than 30 seconds in the 1998-1999 season.

By driver “aid,” we mean that the interface should be designed to augment the driver’s current visual references, providing an additional, constant reference point that complements normal visual cues in the environment. This is in contrast to a “primary” command display that assumes the driver has no other visual cues. A number of such display “aids” have been used in aviation design as instrument landing aids (Stokes, Wickens, & Kite, 1990). Boeing currently uses such an aid to help 747 and 777 pilots taxi down the centerline of the runway.

Design recommendation 2: The warnings should use peripheral cues. Ride-along observations indicated that snow removal operators must devote most of their visual attention to looking into mirrors and searching for road position and cues—even in very low-visibility conditions. Snowplows can have up to six different mirrors the operator must monitor: left and right window, left and right front plow, and left and right underbody. We concluded from these observations that drivers do not have visual resources to spare for a dedicated display.

Design recommendation 3: Displays should be designed to inform drivers of the distance traveled from the reference tape. The survey found that operators often intentionally drive 1 to 3 feet over the centerline or tape reference point, even in low
visibility. This is an important finding in terms of fundamental warning philosophy. Because some crossings are intentional, displays should be designed to inform the driver of the distance (e.g., in feet for US operations, meters or decimeters for international operations) their vehicle has traveled over the centerline or reference tape.

**Design recommendation 4: Display should be selectable for either centerline or shoulder-line points of reference.** Centerline and shoulder-line points of reference appear to be the most helpful and intuitive cues for left and right lane plow operations. In the survey, drivers recommended a centerline reference; however, shoulder lines were also cited as a common lane reference. It is likely that once drivers see how the lane position aid works in context, it will become clear which lane reference marking is more useful. Since roadways may be equipped with magnetic tape on either the centerline or the shoulder line(s), the display should be selectable for either reference point.

**Design recommendation 5: The warning thresholds should be adjustable.** As drivers intentionally drive over the centerline, they should have the ability to make warning thresholds adjustable. Drivers on the ride-along drives were observed to increase their line crossing behavior under better visibility conditions. Allowing drivers to adjust the warning thresholds will not only increase driver control and the flexibility of the LAS, but will also reduce nuisance alerts.

**Design recommendation 6: All displays should have adjustable intensity.** Although the survey indicated that only a few auditory alarms or warnings are considered annoying by drivers, the ride-along drives suggested that all displays should have adjustable intensities. In the case of visual displays, many drivers complained of intrusive lighting; some lights were taped over in cabs and some alarms were silenced. Visual displays should have dimmers and auditory displays (if used) should have volume controls—or the ability to be turned off all together.

**Design recommendation 7: Backgrounds on visual displays should be black.** Based on the ride-along drives, backgrounds on visual displays should be black for nighttime operations. This means that some hardware—such as liquid crystal or CRT displays—should not be used, as it would make it impossible to generate a black
background. Bright days with drifting snow raise a different set of design considerations. Any display with the potential to be washed out by high ambient light should not be considered.

**Design recommendation 8: Provide better defrosting capabilities.**

Although this recommendation does not pertain to the design of the operator interface, we consider it to be critical to snow removal operations and thought it important that we call attention to it. The fact that 80 percent of surveyed drivers reported problems with window icing and fogging indicates a significant safety problem that exacerbates low forward visibility. Vehicles need to have better defrosting capabilities for their front windshield and side windows.

The ride-along drives, interviews and survey, provided the initial design requirements. In the next section we describe how these design recommendations were corroborated, further refined, or eliminated through use of an analytical methodology designed to identify the system’s tasks, functions, and constraints and their influence on the design. By further identifying the system tasks, functions, and constraints, we can supply specific rational for each design decision.
SECTION 3 – TASK ANALYSIS AND FUNCTION ALLOCATION

The survey findings and ride-along interviews were the basis for the next stage of our system process design. The goal was to uncover critical functions that would dictate how the system should be designed. In this second stage, the goal was to use the knowledge gained previously to detail tasks to be performed by operators, analyze how these tasks are interrelated, identify the system’s functions and associated cognitive demands, and finally, decide how these should be allocated to the operator and/or to the new technology. The objective was to design a system that would not entail additional visual or cognitive burdens for the operator. The information gathered in the task analysis and function allocation allowed us to compare design options (i.e., using trade studies) and to make informed interface recommendations with rational to support each design decision.

Operator function model and cognitive task analysis

To create a design that conforms to operational requirements and drivers’ attentional limits, one must use a method that can simultaneously define engineering requirements and constraints while linking them to a description of the cognitive limits of the driver.

The Operator Function Model (OFM) is a human factors methodology that enables designers to identify the operator activities that are relevant to using a new technology. By categorizing these activities, listing the conditions that cause one activity to transition into another, and describing how they are interrelated, we can get a better understanding of the system’s functions (or roles) and how they impact the design (Lee & Sanquist, 2000). In other words, the OFM details what snowplow drivers have to do, what would trigger or change the status of their activities, how these activities interact or relate to one another, and finally, what the system’s (which includes both the new technology and the operator) functions are. Thus, OFM facilitates the designer’s role by ensuring that all pertinent operational requirements have been considered and that critical functions and tasks have been identified and assigned to the appropriate entity (i.e., human operator or new equipment).
There is one drawback to this classical human factors methodology. While the OFM stipulates what activities the operator should perform to accomplish a task, it does not detail any of the cognitive demands or processes associated with these tasks (Jones & Mitchell, 1989; Mitchell, 1999; Mitchell & Miller, 1986). Although the OFM is an efficient technique for exploring a system’s procedural and situational constraints, it does not point to the cognitive components of operators’ activities.

The Operator Function Model – Cognitive Task Analysis (OFM-COG) is an emergent human factors methodology that attempts to fill this gap. The OFM-COG was developed to consider the cognitive demands imposed on an operator by specific activities (Lee & Sanquist, 2000). The OFM-COG adds a component known in human factors research as a cognitive task analysis (COG) to the OFM. The role of the COG component is to describe pertinent cognitive tasks and mental demands associated with the activities listed in the OFM. The advantage of the OFM-COG approach is that it identifies limitations that are independent of the system studied. The mental demands associated with a given activity are linked to the type of activity and not to the system per se. As a result, it is possible to uncover hidden or excessive cognitive demands and thus to minimize the risk of human errors that may otherwise be associated with new technologies.

We chose this novel human factors methodology in part because it had the advantage of requiring fewer steps than the more traditional approaches. The OFM-COG analysis integrated the results of the observations and surveys into a series of state transition diagrams and summary tables, as illustrated below. Simply put, a state transition diagram is a graphical representation of an operator’s activities and the conditions that trigger a transition from one activity to another. These are called system states and transition conditions, respectively. Figure 2 shows an OFM-COG state transition diagram and Table 7 summarizes the cognitive demands associated with the sub-function ‘Estimate Distance from Centerline.’
Figure 2 shows, for example, that 'monitor lane position' is a key function associated with snow removal operations. Corresponding to each function are certain sub-functions (e.g., estimate distance from centerline) and various system state transitions (e.g., obstacle identified). Figure 2 also suggests that because drivers must 'monitor for obstacles' and 'monitor lane position,' any driving aid must consider both of these activities.

Another key function documented in Figure 2 is 'adjust lane position.' Unlike the traveling public, in determining lane position snowplow drivers must consider snow removal objectives. The survey found that more than half (52.6%) of operators intentionally drive 1-3 feet over the centerline frequently (even in low visibility). This suggests that any system that alerts a driver the moment they cross the centerline will be perceived as a nuisance. We concluded that the display should be designed to inform the driver of the distance over the centerline and should
have an adjustable warning so that drivers can plow over it without receiving nuisance alerts.

Table 7. OFM-COG Analysis for the “Estimate Distance from Centerline” Sub-function of the OFM.

<table>
<thead>
<tr>
<th>OFM Function / Sub-function</th>
<th>Driver Cognitive Tasks</th>
<th>Input</th>
<th>Human Information Processing Resources</th>
<th>Output</th>
<th>Task &amp; Environmental Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine Lane Position / Estimate Distance from Centerline</td>
<td>SEARCH</td>
<td>Center and shoulder lane markings through snow cover</td>
<td>Sustained attention; Perceptual sensitivity</td>
<td>Intermittent lane markings; Varying distances between lane marking &amp; plow edge</td>
<td>Visibility; Ambient lighting; Rates of change; Time available</td>
</tr>
<tr>
<td></td>
<td>CATEGORIZE</td>
<td>Intermittent lane markings; Varying distances between lane marking &amp; plow edge</td>
<td>Perceptual sensitivity; Long-term memory</td>
<td>Categorized as accurate plow positioning or critical lane deviation</td>
<td>Expertise; Vehicle’s motion; Rates of change; Other cues</td>
</tr>
</tbody>
</table>

While Figure 2 identifies functions, sub-functions, and system states, Table 7 summarizes the cognitive tasks, human information processing resources, and environmental demands associated with the sub-function “Estimate Distance from Centerline.” The table highlights the center and shoulder line points of reference.
(cues) as primary inputs to the sub-function. Similarly, the survey results indicated that right plow users favored the shoulder line reference (53.7%) while left plow users preferred the centerline (49.6%). We concluded that since most snowplow vehicles are equipped with a wing plow, the display should be selectable for left or right plow operations. Furthermore, since drivers have to estimate their vehicle’s distance relative to the tape reference, mechanisms are needed for identifying when the vehicle has deviated from the lane and by how much. The OFM-COG analysis also pointed to the need to differentiate which lane is being plowed. This becomes more of an issue in mountain areas where shoulders are narrow and the magnetic tape may have to be located on the outside edge of the roadway.

Another function identified in this analysis was the constant monitoring for obstacles. This task was also identified in the ride-along portion of the project. Forward obstacle detection systems, when mature, will be a crucial component of low-visibility operations. The current state-of-the-art, however, is plagued with nuisance alarms since such systems detect every bridge abutment, overpass, guardrail, and street sign. More advanced forward obstacle detection systems will be able to map out cultural features of the roadway environment, and thus filter out non-threatening roadway obstacles. As the technology currently stands, however, the high nuisance alarm rate would likely diminish the effectiveness of the LAS. Therefore, for this design project we decided to concentrate just on the lane awareness portion of the interface.

As briefly shown, the OFM-COG helped us to identify the functions and sub-functions that snowplow operators usually perform while cleaning the roadway. It also enabled us to identify the cognitive demands associated with those tasks, and to learn how operators obtain the information necessary to accomplish a given task. The next step, developing trade studies, will help us ascertain the most appropriate ways of presenting the information drivers need during snow removal operations.
SECTION 4 – INTERFACE DESIGN AND OPERATING CHARACTERISTICS

Introduction

This phase of the system design process focused on integrating the information gathered thus far to specify interface options. With a basic understanding of snow removal operations and a description of the functions and tasks to be accomplished by the system and the operator, it was possible to concentrate on the design elements. Ultimately, the prototype would depend on the design rational chosen. In this section we describe how we identified the design interface recommendations and the interface that resulted.

Design rationale

One essential component of any alerting system is the means by which it conveys information gathered by sensors to the driver. Which design is most appropriate depends on the purpose of the alert. In general, the goal is to gain drivers’ attention without distracting them from a potentially precarious situation or to orient their attention to a hazard (Hanowski et al., 1999; McGehee et al., 2002). Visual warning displays increase the probability that drivers may have their attention drawn away from the hazard. Alerting displays must at the same time be designed to minimize additional cognitive demands like driver workload, and to avoid causing inappropriate driver responses. Furthermore, designers must consider several other factors, including the vehicle’s ambient noise, lighting, and vibration levels, when selecting an alert modality.

In a lane awareness system, the goal is to alert drivers of lane deviations; their options are then to take corrective action immediately or risk a head-on or shoulder-based impact. Our analyses indicated that snowplow operators need flexibility in specifying their lane deviation boundaries. For example, they may not want to deviate more than a foot into the oncoming traffic lane, but may be willing to accept as much as a 4-foot incursion onto a paved shoulder without guardrails or bridge abutments. It is important not only to provide this information but also to present it in such a manner that the driver can interpret it quickly and make the proper response. One way to compare design
alternatives and identify the most appropriate option for a given design is through the use of trade study analysis.

Trade studies

A trade study is an analytical tool for comparing and evaluating different design alternatives to identify the one(s) that best satisfies opposing performance requirements (DOE, 1996; Ullman, 2001). It represents one component of system engineering design, and takes place after possible design alternatives have been identified (DOE, 1996). Using trade studies, we consider several design factors and objectives, and then decide which objectives to compromise in favor of others. The overall goal of a trade study analysis is to maximize the design advantages. Trade studies can help designers avoid the tendency to make design decisions based on the latest technological trend or on personal preferences, and instead can help implement the product design that best satisfies the users’ requirements.

A formal trade study follows a structured and systematic approach for comparing and deciding amongst design alternatives to ensure that the evaluations are as rational and unbiased as possible (DOE, 1996; Hulse et al., 1998; Jahns, 1996). The first step is to have a clear intention—in our case, comparing different display options for the purpose of warning drivers of lane deviations. The next step is to consider all feasible and practical design alternatives. These alternatives should be well defined and should cover a broad range of options. For this project, we limited the design options to those that could realistically be integrated into a snowplow cab. The third step is to establish decision criteria that enable design evaluators to differentiate alternative solutions without bias. Decision criteria should be mutually exclusive, quantifiable or estimable, and clear to raters. Criteria could include, for example, accuracy, safety, cost, reliability, and usability. We selected six decision criteria. Numerical weights are assigned to each decision criterion, subjectively or objectively, to identify their relative importance (weight) in the decision process. We opted for a 1 to 10 scale, with 10 indicating the most important criteria. Next, experts score the design alternatives on each of the elected criterion [we chose a scale of 1 to 5]. Finally, the findings are tabulated and weighted scores are calculated for each design alternative (see Table 9). Ideally, a sensitivity
check should be done to validate the results by demonstrating that small changes to values of attributes, weight factors, or raw scores would not alter significantly the final ranking. The preferred alternative should emerge from this analysis with, ideally, all potential adverse effects to the design having been considered. (DOE, 1996; Hulse et al., 1998)

For this project, the trade study analysis compared different warning modalities. Warning modality refers to the manner in which the alert information is conveyed. Alerting information can be provided to the driver through visual, auditory, or haptic modalities, or any combination of these. By haptic, we mean a display that drivers can feel rather than hear or see (Tijerina et al., 2000). It is a display that provides tactile feedback such as mechanical vibration or electrical impulses (Sanders & McCormick, 1993). Within the automotive industry, the most frequently used modalities have been visual, auditory, and a combination of visual-auditory. Until recently, very limited use has been made of in-vehicle haptic information; the most current usage has been with experimental collision avoidance systems (Tijerina et al., 2000) and the series of pulses that are felt when antilock brakes are activated.

Each modality, or combination of modalities, has its advantages and disadvantages. Deciding which one or which combination would be the most effective depends on the nature of the system and its purpose.

Table 8 summarizes some of the advantages and disadvantages of the various presentation modalities in the context of LAS requirements.

<table>
<thead>
<tr>
<th>Modality</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Visual   | • Continuous lane position information  
• Driver can discriminate the intake of information (ignore unwanted information)  
• Peripheral vision displays can provide information to the driver indirectly (i.e., eyes) | • Must intentionally look at display to gather information  
• Increases visual attention workload  
• Draws gaze away from roadway  
• Distraction potential |
| • foveal   |                         |
| • peripheral |                       |

Table 8. Advantages and Disadvantages of Display Modalities for a Lane Awareness System

The University of Iowa
<table>
<thead>
<tr>
<th>Modality</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>• Alerts driver without visual overload&lt;br&gt;• Calls for immediate action&lt;br&gt;• Attracts user’s attention regardless of eye gaze and head position&lt;br&gt;• Does not require focus of attention&lt;br&gt;• Parallel processing&lt;br&gt;• Best used for simple, short information&lt;br&gt;• Best for information that is already acoustic in nature, or for use when the user expects a sound</td>
<td>• Not applicable for the hearing impaired&lt;br&gt;• Can be intrusive and distracting by nature (Stokes &amp; Wickens, 1988)&lt;br&gt;• Auditory message may confuse driver and cause disruption&lt;br&gt;• May be difficult to differentiate amongst numerous signals&lt;br&gt;• Annoyance&lt;br&gt;• Masking potential&lt;br&gt;• Speech-based displays are not appropriate for international use.</td>
</tr>
<tr>
<td>Haptic</td>
<td>• Alerts driver without visual overload&lt;br&gt;• Does not require focus of attention&lt;br&gt;• Minimizes risk of startling reaction&lt;br&gt;• Can make use of the same control properties as the actions required by the driver (e.g., deceleration cue)&lt;br&gt;• Depending on the presentation mode chosen, can provide directional control (e.g., directional seat vibrations are compatible with lateral movements, not longitudinal)</td>
<td>• Human body must be in physical contact with the vehicle component used to transmit the signal (Lee, Carney, Casey, &amp; Campbell, 1998)&lt;br&gt;• May provide ambiguous cues. As a sole means of providing control, haptic displays have not been as efficient as visual guided control ones (Tijerina et al., 2000)&lt;br&gt;• May misdirect attention&lt;br&gt;• Response conflict (e.g., steering vibration may interfere response)&lt;br&gt;• Perceptions may be degraded by low temperatures and heavy clothing (Lee, Carney, Casey, &amp; Campbell, 1998)&lt;br&gt;• Annoyance potential&lt;br&gt;• May be difficult to retrofit older vehicles</td>
</tr>
</tbody>
</table>

Table 9 summarizes the primary alerting modalities for the operator interface. In this trade study analysis, presentation modalities were rated on six different criteria. Each criterion...
was assigned a weight that established its relative importance compared to the others on a one-to-ten scale. Each presentation modality was rated using a 5-point scale, averaged across raters, then multiplied by the weight of the specific criterion.

Table 9. Trade Study for the Modality Presentation of the Lane Awareness System

<table>
<thead>
<tr>
<th>Operator Interface</th>
<th>Assigned Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visual Demand</th>
<th>Annoyance</th>
<th>Response Time</th>
<th>Implementation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>AW</td>
<td>A</td>
<td>AW</td>
<td>A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Foveal</td>
<td>2</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Peripheral</td>
<td>3</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Auditory Modality</td>
<td>__________</td>
<td>__________</td>
<td>__________</td>
</tr>
<tr>
<td>Non-Speech</td>
<td>5</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>Speech</td>
<td>5</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>Haptic Modality</td>
<td>__________</td>
<td>__________</td>
<td>__________</td>
</tr>
<tr>
<td>Steering Wheel</td>
<td>5</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Seat</td>
<td>5</td>
<td>50</td>
<td>4</td>
</tr>
</tbody>
</table>

A: Average Score.
AW: Average Score multiplied by Weight.

The first criterion, visual demand, deals with the elements of information complexity, quantity of information, and saliency of information for snowplow drivers. It also refers to the sampling frequency required for drivers to obtain the information needed to determine their lane position. Because ride-along interviews showed that drivers do not have many visual resources to allocate to a display, this criterion was given a maximum weight. Driver annoyance is an important criterion, as systems that are considered intrusive by operators tend to go unused or even to be
turned off completely, defying any potential benefit. The annoyance criterion also considers other comparable systems already present in the vehicle’s cab. The next criterion, response time, focuses on the elements of time and the necessity of responding to the information presented. This criterion deals with the severity of outcome of a driver missing, ignoring, or responding late to the presented information. The ability to implement the hardware into the cab environment and to integrate the LAS with existing in-cab components deserves attention. Depending on the space available, the final location chosen for the system may influence driver behavior and system use. Finally, cost of operator interface is an important consideration. Maintenance agencies must allocate their funding judiciously to competing needs, and the benefits of such a system would be weighted heavily against its associated costs.

The trade study analysis summarized in Table 9 favors the haptic modality [highest total score - 291] over either the visual or auditory modalities [232 and 208 respectively]. One explanation for this result is that both the auditory and haptic modalities are less taxing on visual demands, the criterion with the largest weight. The haptic and visual modalities outranked the auditory modality in terms of being considered less annoying, as well as possibly resulting in a quicker response time. Surprisingly, the visual modality surpassed the auditory modality, most probably due to a lesser annoyance factor.

As to which haptic option should be chosen—seat or steering wheel—the difference lies mainly in the implementation. Inserting a haptic component into a seat is feasible and does not involve modifying the steering system, which might have safety implications. With regards to the visual modality, the difference between the foveal and peripheral options is much more distinct—peripheral was favored due to its lower cost. A similar difference was found between non-speech and speech-based auditory warnings. Non-speech was rated more favorably due to implementation factors. The trade study analysis points to some additional design conclusions. In summary, it appears that with regards to warning modalities, the design should satisfy the following criteria:
1. Haptic is the favored warning modality. Because of lower cost and ease of implementation, the haptic seat is preferred over the haptic steering wheel.

2. Peripheral warnings, although vision-based, are favored over non-speech auditory warnings. Although they add to the driver’s visual demands, they are potentially less annoying.

3. Foveal warnings should be discarded even though they have the advantage of being central to the driver’s attention because they are both difficult to implement and costly.

4. Non-speech auditory warnings could be considered as potential warning modalities; however, driver annoyance should be assessed carefully and conflicting cab warnings evaluated thoroughly.

**Preliminary interface design**

The trade study analysis pointed to warning options that maximized peripheral modalities, rather than further taxing visual resources. We investigated some of these options and chose to integrate more than one warning modality, thus giving snowplow drivers the flexibility to choose the warning or warning combinations that best fit their needs for a given situation. The user interface we propose has three components. Two primary cues for lane departure warnings involve peripheral displays, while a third cue is intended to act as a secondary supporting visual reference. The primary peripheral cue is a directional seat vibration. The other peripheral lane departure warning consists of lights that use large-format LEDs mounted on the windshield. The final cue, the control unit, provides detailed information to the operator on exact lane position relative to the sensor.

**Directional seat vibrations**

The rational behind adopting a directional seat vibration as the primary cue for the lane departure warnings has two sources. First, as evidenced by the trade study analysis, haptic warning information minimizes demands on drivers’ visual resources—a primary concern. Although it does not frequently appear in the context of warning displays (Lee et al., 1998; Tijerina et al.,
haptic information has been used successfully in a tracking-task display where a combination tactile-visual display performed better than a combination of visual displays (Sanders & McCormick, 1993). Second, haptic warnings can be configured to provide subtle directional information, thereby assisting operators in better visualizing the location of the hazard and/or recognizing what action(s) will be necessary.

In their human factors design guidelines for tactile alerts, Campbell and colleagues (1996) suggest that the type of haptic alert and its location are important factors in whether drivers associate the warning with the proper response. In their review of candidate haptic display concepts for rear-end collision avoidance systems, Tijerina and colleagues (2000) mention controller displays and non-controller displays—that is, haptic displays that are linked to a vehicle control such as the steering wheel or the accelerator pedal and ones that are not. According to their review of the literature, steering display applications tend to offer either directional torque of a given magnitude and direction or a non-directional vibration that varies in duration, amplitude, frequency, and/or waveform. The former has been used in lane change crash avoidance systems (CAS) and in roadway lane departure warning systems, whereas the latter is utilized more as a generalized warning. They define seat haptic applications as ‘non-controller displays’ and report their use as a generalized warning.

Because of their non-directional information (i.e., entire seat shaking or vibrating), current haptic seat applications fail to provide any information as to the nature of the abnormal situation and how to correct it. However, if one could provide directional information with seat vibration (reinforcing the idea of ‘movement compatibility,’ which states that a display should be consistent with the direction of movement—e.g., a left thigh ‘buzz’ indicates you are crossing the centerline [Sanders and McCormick, 1993]), it would transform a generalized warning capability into a very specific directional warning. With this concept in mind, we researched current haptic technologies with the goal of finding one that could be modified to include a directional component, as well as be easily and economically implemented in a snowplow cab. The InSeat/Relaxor® technology fit our requirements and offered interactive alert seats for automotive and long-haul industries.
(see Figure 3). Relaxor’s vibro-tactile technology initially targeted driver comfort through the use of massage transducers mounted in the seat. These transducers create a vibration that is felt through the seat. Their latest technology aims at driver safety by integrating an alert component into the comfort one. The alert component can be used for monitoring driver’s alertness (i.e., drowsy driver deterrent), for monitoring non-emergency systems, and as on-board safety signal monitoring vehicle electronics (Relaxor® website, 2002).

Figure 3. Directional Seat Vibration System (modified Relaxor® seat)

It is a logical step to apply this technology in a lane departure warning system. By using the massage transducers to create a directional vibration in the thigh bolster (rather than throughout the entire seat), it is possible to associate an alert with a specific direction (i.e., with the left or right thigh bolster). At the same time, one can create the analogy of
encountering a shoulder rumble strip, as if the driver had deviated too far onto the left or right roadway shoulder. In our application, the seat vibrations are directly coupled to the magnetic sensors. When the snow removal vehicle deviates from the magnetic lane beyond the distance specified by the driver and the system, the massage transducers are activated and drivers feel a vibration in their left or right thigh.

**Peripheral vision lights**

The second lane departure warning is similar to the first in that it also involves a peripheral modality. Unlike the directional seat vibration alert, however, the peripheral lights are visually based. Despite this fact, the lights do not tax drivers’ central visual resources because the warning occurs in periphery. Snowplow drivers can continue to look forward as they perceive the peripheral warning.

Human attention is drawn to visual displays that are large, bright, colorful, and/or changing (e.g., flashing or blinking). The trick is to attract drivers’ attention without diverting their gaze—that is, to design an alert that snowplow operators will perceive at onset even as they continue to look forward to the roadway. One way of achieving this goal is to use an ‘abrupt stimulus onset,’ such as turning a light on, especially if the stimulus occurs in the operator’s visual periphery. (Wickens & Hollands, 2000).

The advantage of using peripheral vision is that it frees up foveal (central vision) resources. This approach becomes even more appealing when you consider that a very high percentage (as much as 90%) of visual stimulation can be acquired from the peripheral visual field, and this without too much effort (Stokes, Wickens, & Kites, 1990). Even when vision is focused on a given spot, information can be extracted from the periphery. Peripheral vision is particularly sensitive to motion, change of status, and luminosity (Kantowitz & Sorkin, 1983; Stokes, Wickens, & Kite, 1990). Information presented in the periphery is often processed automatically and unconsciously, thus enabling operators to better handle stressful situations and high workload conditions (Stokes, Wickens, & Kite, 1990). While the human visual system is more sensitive to movement in its periphery, there is generally an involuntary tendency to then turn and look
directly at a moving stimuli. Therefore, operators must be trained to simply sense the movement (e.g., blinking lights) while maintaining their forward gaze.

For the LAS, we decided to use large-format light emitting diodes (LED) mounted on the windshield (see Figure 4 and Figure 5). Flashing lights were adopted because they provide an "abrupt stimulus onset" (see above), especially when they are bright and contrast with the surrounding environment. Because of the need to minimize glare and blinding effects at night, we opted for red flashing lights. The disadvantage of this color is the risk that the alerting lights will disappear or get blended into the profusion of external lights, especially traffic lights, associated with night driving in cities. As a consequence, and in light of our ride-along observations, we offered snowplow operators the option to adjust the light intensity to accommodate day or night snow removal operations.

Figure 4. Peripheral Vision Lights mounted on the upper portion of the windshield (left and centered).

These peripheral vision lights (PVL) can be positioned in various locations inside the cab, or even on the outside, for example on the hood and headlamps. To minimize damage due to severe driving conditions, we opted to mount them inside the vehicle. After analyzing the cab’s space and geometry, we elected to mount them on the windshield, rather than on the dash or the roof. Where to position them on the windshield was established through an experiment conducted at Kansas State University specifically for this project (Smith, Ward, & Anders, 2001). Using a stationary...
University snowplow vehicle—an International Harvester dump truck—researchers simulated night- and without-vision conditions and asked 24 University students to respond to flashing lights by pushing a button located on the steering wheel. Eighteen blinking LEDs were mounted on the windshield, with nine of them distributed in the upper portion of the windshield (approximately 17 degrees above the driver’s normal line of sight) while the other nine were positioned approximately 35 degrees below drivers’ line of sight. Angular distribution ranged from 20 to 50 degrees left and right of the normal line of sight. Smith and his colleagues concluded that the optimal location for the PVL is on the upper portion of the windshield at horizontal eccentricities of 20 degrees from the operator’s line of sight—in other words, in the upper left corner and middle (near the rear-view mirror) portions of the windshield (see Figure 4).

![Figure 5. Detailed View of Peripheral Vision Light (round suction cup)](image)

In our application, the PVL are directly coupled to the magnetic sensors. When the snow removal vehicle deviates from the magnetic lane more than the amount specified by the driver and the system, the PVL located on the deviation side is activated, directing the driver to steer away.

**Control display unit**

The control display unit (CDU), although the most salient and visible of the three components, is intended to be the most secondary one. The control unit has two main purposes: 1) provide
control activation of the peripheral warnings, and 2) display reference information as to the vehicle’s exact position in relation to the magnetic tape. Because we wanted the CDU to act as a secondary reference, as opposed to a ‘primary command’ display, we chose to position it in the operators’ periphery (see Figure 6). We opted for the mid-upper section of the dashboard where it would not occlude any of the critical plow controls and would cause minimal obstruction of the external reference visual cues. The control display unit was designed to offer drivers confirmative and detailed position information. This information was intended as a compliment to external visual cues and the peripheral warnings.

In light of these design functional characteristics, the control display unit not only had to provide important lane reference information and lane departure warnings, it had to do so without increasing drivers’ visual demands. This information had to be easily accessible without overpowering the operator’s field of view. As with any visual display, the information presented needed to be accessible, clear, and accurate, as well as easy to interpret and assimilate (Sanders & McCormick, 1993).

The design also had to satisfy environmental and operational constraints. In the context of snow removal operations, any in-cab visual display must be clearly visible and readable at night. On the other hand, the cab’s darkness dictates that lighted displays must not cause any additional glare, distraction, or
annoyance. This same display had also to operate in entirely opposite ambient light—that is, in a fully bright and blinding environment such as day whiteout conditions in which blowing snow causes low visibility.

Considering all of these constraints, we proposed an electro-luminescent (EL) display. The EL display minimizes background glare during night operations and is readable in dark and bright conditions. Other visual display hardware such as CRT, LCD, and automotive-grade HUDS have the disadvantage of being washed-out in high ambient light conditions, and have backgrounds that are over illuminated during nighttime conditions. For instance, the ‘black’ background of CRT and LCDs are not truly black. They appear gray or silver in darkness, creating a potential distraction or annoyance by over-illuminating the cab’s environment. This is especially true at night, when snow removal cabs are similar to airplane cockpits in that, during normal operations, the cab environment tends to be dark and quiet. Such an environment makes any alert more salient to the operator. Keeping with this same theme, we opted for a visual display that would maximize these conditions.

Figure 7 presents a schematic view of the control display unit, along with corresponding numerical identifiers describing its components. Since this system may be used internationally, its graphical components are non-language based. SAE and ISO standards were used when possible, and some new icons were developed specifically for this interface (see details in Appendix E).

The first item (1) is a toggle to select the left or right side sensor. As the LAS is capable of selecting the magnetic tape on either side of the roadway, the toggle switch enables the operator to alternate between sensors. This feature was included so that drivers can select either the centerline or shoulder line, depending on their current operation. In the Midwest, vehicles are typically equipped with wing plows on the right or the left. In this configuration, if the driver is plowing the right lane with a right wing clearing the shoulder and the centerline is instrumented with magnetic tape, the toggle switch would be set to the left sensor. Because of changing roadways and magnetic tape configurations, the interface provides flexibility for drivers to choose which lane(sensor) to use. Switching to the
left or right sensor changes the tail of the icon (7), which represents the rest of the plow.

Figure 7. Schematic Representation of the Control Unit with Numerical Identifiers

As mentioned previously, to account for the wide variety of ambient light conditions that operators may experience, a dimmer (2) regulates the control unit’s electroluminescent (EL) display. Item (3), the system’s power button, is provided so that drivers can elect to turn off the system.

One of the most critical items of the control display unit is the warning threshold adjustment control (4 and 5). One of the survey’s principal findings was that drivers frequently intentionally drive over the centerline and shoulder line to clear the whole roadway. Since it is critical that the system not create nuisance alarms, an adjustable warning threshold control was created. The knobs (4) adjust the warning threshold indicators (5). By turning the warning threshold adjustment knobs to the right or left, operators can set the indicators to where
they want the warning to trigger. Warning threshold indicators are designed to move across the lane marking indication (6) for specialized lane clearing operations.

The lane marking indication is referred to as the magnetic reference tape indicator. It is a vertical dashed line that provides a fixed marking of the magnetic reference tape installed onto the pavement. The magnetic reference tape indicator is used together with the moving sensor position indicator (7), which is a moving icon that shows the sensor position relative to the magnetic reference tape. The icon representation changes sides when the toggle selection for the sensor side is switched. Finally, the distance to magnetic tape (8) presents the distance between the plow’s sensor and the magnetic tape at any instant. The scale is presented in either decimeters or feet to the magnetic tape. The scale ranges between 0 and 3 feet because the system’s sensors have a detection range specification of +/- 3 feet with respect to the center of the tape.

The primary lane awareness cue is a haptic vibration system built into the left and right thigh bolsters of the operator’s seat. The control knob for this modality (9) adjusts the intensity of the vibration that operators experience when they cross the pre-selected warning threshold. To get a continuous feel of the vibration while adjusting intensity, the knob can be pushed to temporarily activate both thigh bolsters. A second push of the knob will deactivate the bolsters, or they will stop vibrating automatically after thirty seconds. The seat vibration can also be turned off all the way, or adjusted so that it is scarcely noticeable.

The second peripheral modality used by this system is a set of large format LED lights mounted on the upper edge of the windscreen. To provide a sense of motion, the PVL flash on the warning side at a rate of 4 Hz, with a 50% duty cycle. The control knob (10) for the PVLs adjusts the brightness intensity. To get a continuous feel of the flashing while adjusting brightness, the knob can be pushed to temporarily activate both PVLs. A second push of the knob will deactivate the PVLs, or they will stop flashing automatically after thirty seconds. The PVLs can also be turned off completely.
The previously described components comprise the unit’s core controls and displays. However, during normal operations, a set of dynamic messages may also appear to inform drivers of lane departures or system malfunctions. For example, when the vehicle exceeds the 3-foot range threshold on the left, the system will indicate which direction the driver needs to steer to reacquire the magnetic reference tape (Figure 8). If the reference tape signal is not reacquired within five seconds, the display will go to the “no tape” indication (see Figure 9). Similar displays, with arrows pointing in the opposite directions, will appear if the driver drifts too far to the right.

To check system malfunctions at start-up, a ‘self-test display’ appears at system start. A check mark is displayed if the sensor passes the diagnostic test, and an ‘X’ is displayed to indicate failure. If there is no communication with a sensor, a sensor icon is displayed with a cross through it, and no self-test result icon is displayed. During actual operations, if a sensor
communications failure occurs, the sensor icon is displayed with a cross through it.

Figure 9. No Tape
SECTION 5 – DESIGN EVALUATION

Introduction

A concept cannot become an effective tool until it is tested and evaluated. Testing and evaluation are integral components of the design process. As an idea develops into a conceptual drawing, a functional mock-up, a prototype, and finally, an actual system, users need to be involved at every step—critiquing, testing, and evaluating the new product. In a systematic approach to product development, every design decision is evaluated as designers and users determine what components will go into the new product (Sanders & McCormick, 1993).

Such evaluation can take various forms. A basic evaluation would ensure that each system component is actually doing what it is supposed to do, and that it is operational and functional. However, in the context of a human factors evaluation, we are concerned with the adequacy of each component with regards to operator performance. That is, the evaluation needs to assess how each new product component affects users’ tasks and performance. There are different ways of conducting a human factors evaluation. One can, for example, opt for a ‘controlled experiment’ or systematic test aimed at explaining the relationships at work. The goal of a controlled experiment is usually to prove or disprove a hypothesis. Another approach is to use what Meister terms ‘personnel sub-system measurement,’ in which human performance is measured in operational terms (Sanders & McCormick, 1993). This type of evaluation examines not only how the system performs per se, but more specifically, how it performs in its intended operational context. It focuses on how human performance is affected when the new product is used in the environment and in the manner intended. Which approach to choose depends on the goals of the evaluation.

The LAS operator interface was evaluated using two different approaches. The first approach was a field operational evaluation in which the system was used in actual snow removal operations. The LAS and operator interface were installed in a DOT snowplow vehicle, and drivers were free to use the system in their normal snow removal operations. The field operational evaluation took place in Minnesota and Arizona, with the former occurring over a two-winter period while the latter consisted of only a few
outings that were part of drivers’ initial training with the system.

The other evaluation, a closed-course usability study, was more structured—a compromise between the ‘controlled experiment’ and the ‘personnel sub-system measurement’ approaches. We wanted the rigor of a controlled experiment but the flexibility and operational validity of a field study. To achieve this goal, we decided to conduct the evaluation on a closed-course setting rather than on actual rural roadways. This was not only safer, it also enabled us to better control some of the experimental conditions, such as forward visibility and roadway geometry.

It should be noted that the University of Iowa team was responsible mainly for the closed-course usability evaluation. However, we did assist the Arizona DOT in their ongoing field evaluation by developing a short survey that snowplow operators completed following their initial training with the system. We will report these findings after we describe the procedures and results of the closed-course study.

Closed-course usability evaluation

The purpose of the closed-course usability evaluation was to assess how snowplow operators who had varying levels of experience with the lane awareness system maintained their lane position using the different warning modalities during simulated low-visibility conditions. By choosing the fixed environment of the closed-course test track, where no traffic was present, we were able to control several environmental conditions. One of the most important was our ability to manipulate visibility conditions. Using a visibility reduction mechanism, we were able to simulate a wide range of low-visibility conditions in a controlled and consistent manner. An important strength of this evaluation and setting is that it allowed us not only to obtain drivers’ subjective experiences using the system, but also to examine their driving performance under a completely controlled set of conditions.

This evaluation of the LAS operator interface was specifically designed to explore how drivers used the system in a variety of low-visibility circumstances on straight and curved road segments. The survey indicated, for example, that one of the most
common low-visibility scenarios was short, intermittent periods of whiteout when trucks pass, and we wanted to replicate this condition. In conducting the evaluation, we monitored performance-based information such as lane position. We were looking for evidence of the system’s role in enhancing drivers’ ability to maintain lane position such as smaller and less frequent lane deviations, an increased and/or more constant speed, and smaller and less frequent steering position adjustments. Finally, we also were interested in how each of the warning modalities was used, either individually or in combination.

**Methodology**

In this closed-course usability study, experienced snow removal operators used the latest version of the 3M™ Lane Awareness System while driving in simulated low-visibility conditions on the Minnesota Road Research Project's Low Volume Roadway (Mn/Road). Data were collected with and without the system during a variety of short and longer-term low-visibility lighting conditions.

**Participants**

Professional snowplow operators currently employed by the Mn/DOT took part in the study. A Minnesota DOT supervisor selected the drivers from a pool of volunteers who had answered a request for participation posted at DOT garages located near the Mn/Road facility. The primary selection criteria were drivers’ experience on-board similar snowplow vehicles, their experience level with the LAS, and their work schedule (i.e., total number of work hours) during the testing period. Four drivers participated in the final data collection effort. Two had experience with the lane awareness system; the other two had never used the system before. All participants were males, ranging in age from 42 to 55 years old. Two had been snowplow drivers for 2 years; the other two had 13 and 25 years’ experience. While the two LAS-experienced drivers were used to the experimental vehicle, the two LAS-inexperienced drivers operated either a single axle or tandem axle Ford vehicle.
Vehicle

The snow removal vehicle used was a Mn/DOT tandem-axle 1998 International snowplow from the Gaylord Maintenance Garage configured with a front and a right-wing plow. Although drivers did not actually plow during the course of the evaluation, the plows were configured to simulate plowing configurations. The front plow was chained up approximately 3 inches above ground, while the right-wing plow remained in the ‘down’ position, again several inches above ground. The sandbox was loaded to mid-weight capacity to simulate the vehicle-handling characteristics encountered in winter conditions. All running lights were masked to reduce any vehicle-based ambient lighting.

Route

In the fall of 2000, the 3M Company installed their Magnetic Tape Series 2000 on the pavement of the Mn/Road. The Mn/Road test track facility is located in Otsego, MN, near I-94 about 40 miles northwest of the Minneapolis-St Paul metropolitan area. This 2.5-mile low-volume portion of the 40-mile test road is closed to traffic. It consists of two straight roadway segments of approximately 0.8 to 0.9 miles in length connected by two tight curves each approximately 0.35 to 0.40 miles. In some ways, the geometry of this low-volume roadway makes for quite a challenging drive, especially at night, as the curves are tight hairpin turns borded by a lake on either side (see Figure 10).

To minimize distraction and to control for the lighting conditions created by the I-94 eastbound traffic, Mn/DOT deviated traffic to the furthest lane, located near the westbound traffic lane (see Figure 10). This increased the safety margin as well. Also to control for extraneous lighting, all floodlights located on nearby properties were turned off for the duration of the evaluation. To minimize potential damage from collisions, we protected and identified all critically located Mn/Road instrumentation cabinets using safety cones and reflective markers. To further prevent any damage to these cabinets, we conducted the test drives in a clockwise pattern, on the inside lane of Mn/Road, as illustrated by the semi-trailer in Figure 10.
The Mn/Road facility is used to test different pavement and roadway surfaces. The entire roadway is divided into sections with different load cells embedded in the pavement (see Figure 11). Unfortunately, during the scheduled week of testing, Section 26 was damaged severely, forcing drivers to slow down to less than 5 mph at this section. Sections 31-32 also had some pavement surface damage, thereby reducing the effective test section to the two curves and the eastern straight segment. Several ‘bumps’ were actually encountered between Sections 30-32, and drivers started to slow down at or near Section 29 in anticipation of the damaged area. Finally, to simulate roadside obstacles such as bridge abutments or guardrails, we positioned two plastic jersey barriers on the far right portion of the right shoulder at the intersection between Sections 33 and 34 and between Sections 38 and 39. We picked these locations to ensure that the obstacles would be encountered during the visibility reduction events, and yet be far enough from the onset or end of the curves.
Lane awareness system infrastructure

The 3M™ Lane Awareness System for snow removal operations is a driver assistance system for lane exceedence monitoring that uses a sensor and processor unit mounted on the snow removal vehicle to detect a signal from a magnetic tape. The plow-mounted sensors then transmit lane position information to the driver through the operator interface. For the purpose of this evaluation we used the following tape and sensing electronics.
3M™ Magnetic Tape Series 2000

The lane awareness system uses the 3M™ Magnetic Tape Series 2000, manufactured by 3M. This tape marks the pavement with a magnetic reference line, which can then be tracked. It is a preformed, patterned, skid-resistant pavement marking tape with pressure-sensitive adhesive and can either be glued, grooved, or installed under the last layer of pavement (3M Company, 2000). For this test, 3M personnel applied the magnetic tape by means of factory-applied adhesive.

3M™ Truck-Mounted Sensing Electronics

The sensor system’s rugged electronic package contains the sensing and signal processing electronics and connects to the vehicle to obtain power and speed information. The sensor then detects the magnetic tape, calculates the distance from the tape, and transmits this information to the operator interface. The electronic package was mounted on the front bumper of the snow removal vehicle, approximately one foot (20 cm) above the pavement surface (see Figure 12). With a detection range specification of +/- 3.1 ft. (90 cm) with respect to the center of the tape, the detection accuracy and relative location of the truck could be identified with a 2 in. (5 cm) accuracy, even at the extreme lateral ends of the detection zone, at speeds from 5-25 mph (8-40 kph) (3M Company, 2000). The sensor was positioned such that the left edge of the forward plow blade extended approximately one foot to the left of the centerline when the center of the sensor bar was directly over the tape.
Visibility reduction mechanism

One of the most critical aspects of this usability evaluation was the ability to specify, control, and replicate visibility conditions. We wanted to simulate low- and near-zero visibility conditions at will, and to observe how drivers used the lane awareness system under those conditions. To accomplish this, we built a visibility reduction mechanism that simulated low forward visibility conditions by re-directing headlamp beams downward. We also minimized natural lighting conditions by conducting the evaluation during a new-moon cycle and when the roadway and surrounding areas were free of snow.

Visibility reductions were simulated using a set of louvers (see Figure 13). Positioned over the vehicle’s headlamps, the louver system directed the light from the headlamps down at predetermined angles. The louver position was integrated into the data collection system and could automatically reduce forward visibility from unobstructed to completely obstructed for any specified time period. The visibility levels (zero, low, clear) were specified in terms of distance covered by the headlight beams. The activation of a specific louver position was triggered according to distance traveled along the test track. On the test nights, engineers calibrated the headlamps to approximate normal

Figure 12. 3M™ Sensing Electronics Mounted on the Front Bumper
forward lighting during snow removal operations. Manipulations were then made from this calibrated baseline position.

Data collection instrumentation

Data collection unit

The Gaylord vehicle was equipped with a self-contained unit for data collection. Its purpose was to gather continuous driving and system information whenever the LAS was in use. We selected the existing micro-DAS data acquisition system for this purpose. The micro-DAS was developed by the National Highway Traffic Safety Administration (NHTSA) to be used in long-term field studies using passenger vehicles. Each time the LAS powered on and the sensing electronics detected the presence of the magnetic tape, the micro-DAS began to record a wide range of driving performance data. These data included vehicle performance information such as speed (mph), lateral acceleration (g), longitudinal acceleration (g), and yaw rate from a self-contained gyro unit (degrees). The micro-DAS also recorded driver input information such as steering wheel position (degrees), accelerator pedal position (percent deflection), and brake pedal position (percent deflection). For the purpose of this project, the micro-DAS was configured to record three additional variables. The first two were distance
from the magnetic tape (cm) and the sensor’s position relative to the magnetic tape (left or right). These variables were used to derive lane excursions greater than a pre-determined distance from centerline. Finally, for the closed-course usability evaluation, the micro-DAS was further modified to record the louver positions from the visibility reduction mechanism.

Video and audio recordings

Unobtrusive video cameras were also installed on-board the Gaylord snowplow vehicle. These cameras were integrated into the data collection unit and recorded both driver behavior and external route environment. Four pinhole cameras were positioned in the vehicle cab to record the following views: 1) driver face and hands on the steering wheel, 2) over the driver’s shoulder, 3) forward roadway, and 4) close-up of the LAS control display unit. Furthermore, because the closed-course usability evaluation took place at night, we installed an infrared lighting system in the cab to illuminate all camera views. Finally, an audio-recording system captured any on-board communications.

Experimental conditions

When we set out to design the usability evaluation, we knew there were only 2-3 LAS-experienced drivers from Gaylord. Our experimental design had to take this factor into consideration. We opted for a within-subject Latin-square experimental design, in which each participant experienced all of the experimental conditions in a systematic, balanced order.

As part of the experimental protocol, we manipulated the following independent variables:

Levels of visibility: There were 3 different levels of visibility—100% clear and unobstructed, partially reduced/occluded as specified by forward distance in feet from vehicle (25%), and completely dark or 0% forward visibility. A baseline level or neutral value of 50% visibility was used between events.

Duration of visibility level: There were two different durations for the periods of limited visibility—5 seconds or 15 seconds. The initial experimental design called for each visibility condition (i.e., clear, partially-occluded, and dark) to be presented for each duration. However, because of extremely dark conditions on the test nights, for safety reasons we decided to
discard the 15-sec duration for the dark (zero-visibility) condition.

**System warning options:** Using the three LAS warning modalities: 1) control display unit (visual), 2) peripheral vision lights (lights), and 3) directional seat vibration (seat), drivers experienced a set of five different warning combinations:

1) Baseline (no display at all - None)
2) Seat and lights (no visual - SL)
3) Visual and seat (VS)
4) Visual and lights (VL)
5) Visual, lights and seat (All)

The initial intent was to present each driver with eight warning combinations, adding the following three warning conditions: visual only, seat only, and lights only. Due to driving time constraints, however, we opted to remove those three conditions from the experimental design. Differences between individual warning components would be captured in comparisons of the two-warning conditions against each other, thereby isolating the individual components.

**Road type conditions:** The roadway environment consisted of two types of roadway geometry—straight and curved segments.

**Procedures**

**Pre-drive**

All test drives were scheduled at night, at least one-half hour after sunset, so that drivers would experience conditions as close to complete darkness as possible. Drivers were greeted at the test site facility where they were briefed on the nature of the drives and asked to complete the required forms and a brief pre-drive survey prior to boarding the snowplow vehicle. They were familiarized with the snowplow controls and trained on the system’s operation first in the briefing and then in the vehicle.

**Drive**

An on-board observer rode in the passenger seat at all times during the drive to monitor the data collection equipment, document any relevant activities, and act as one of the safety officers. The on-board observer was in continuous radio contact with the other observers in a passenger vehicle that followed closely behind the snowplow vehicle (without headlights). Thus, if a dangerous lane departure appeared to be imminent, the
snowplow driver was informed immediately. There were no other vehicles on the Mn/Road during the drives. Drivers were asked to plow as they normally would in visibility conditions comparable to the ones simulated. Their driving speed was set at a level they would normally use on a rural highway, in low-visibility conditions at night (i.e., they were instructed to not exceed 25 mph). Drivers were asked to plow the right (inside) lane of the Mn/Road with their plows positioned within 3 feet of the centerline. For drives where the system was in use, drivers were allowed to set the warning adjustment according to their own preferences.

Each driver was asked to drive the 2.5-mile Mn/Road segment a minimum of ten times, stopping after each lap. Except in the baseline condition, during each lap drivers used the LAS while simulating plowing a two-lane roadway in low-visibility conditions. For each lap, the LAS warning modality configuration differed, providing each driver with either no warning at all, a combination of two warning modalities, or all three warning modalities at once. Drivers were assigned to a predetermined order that was balanced for visibility conditions and warning modalities, and thus experienced different visibility conditions for different durations using different operator interface options.

To ensure consistency across participants, the lighting intensity levels, onset, and duration were automated through a direct link to the micro-DAS data collection system. Event onset was determined based on the micro-DAS’s distance from beginning of the tape data; event duration was based on time rather than distance. Each combination of visibility reduction and duration was presented at least once for each system warning modality manipulation. The intent was to present each driver with the same number of events for each of the visibility reduction levels and durations; however, because of road damage, four of the ten scheduled events had to be eliminated.

Following their drive with each warning combination, drivers were asked to rate their perceived workload using the six-item scale of the NASA-Task Load Index (TLX). These items include: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Because of the nature of the task, we added a seventh item, ‘visual demands.’ We also asked drivers two
questions regarding the impact of the warning configuration on their ability to maintain lane position and to continue to look forward to the roadway. Finally, we included two short questions about drivers’ trust of and self-confidence with the system.

Immediately after the drive, all drivers were ‘interviewed’ on their experience with the LAS. The 50-question survey was designed to capture driver’s opinions about the system (see Appendix G). They were then debriefed thoroughly and thanked for their participation.

**Challenges of the closed-course evaluation**

The closed-course usability study posed some predicted, as well as some unforeseen, challenges. During the planning and actual testing, we encountered several technical problems that limited the statistical power of our objective driving performance data. The primary challenge was few participants. Three factors worked to limit the number of participants: (1) only two drivers had prior experience with the LAS, (2) drivers had to be experienced snowplow operators selected from nearby Mn/DOT maintenance garages, and (3) drivers’ availability for testing was constrained by duty cycles. Our pool of potential drivers was also hampered by calibration delays in the microDAS system, which caused us to cancel two participants.

One of our greatest constraints in planning the study had to do with scheduling. Three factors affected when we could conduct the study. To better control the visibility manipulations, we scheduled our testing on the darkest nights of the month (new moon). We also had to ensure that there was no conflict with Mn/Road’s scheduling, as our testing involved re-directing I-94 Eastbound traffic. Finally, in order to make valid comparisons in terms of visibility, we needed several clear days in a row without rain or snow.

Despite our best efforts to schedule a test time that would satisfy the above criteria, we could not foresee that the pavement surface of the Mn/Road would get extensively damaged a couple of days before our scheduled testing dates. Although the damage occurred on a relatively small portion of the roadway, its influence on our testing protocol was considerable. We had to modify the driving procedures and redefine entirely the
visibility event sequence, which resulted in dropping four of the ten scheduled events per drive during the data analysis phase.

Finally, we encountered several technical difficulties with the microDAS. The micro-DAS hardware failed on our first night of testing, forcing us to switch to one installed on-board the 3M/Uof I Ford Expedition. Unfortunately, the two systems were calibrated differently, which caused a major delay during the data reduction phase. Each data channel (e.g., vehicle speed, accelerator pedal position, etc) had to be recalibrated and revalidated.

Data reduction and analysis

We evaluated the system with two complementary approaches. The first was a closed-course usability evaluation and the second was a field operational evaluation that was conducted in Arizona. In this section, we will be describing the findings for both evaluations.

Closed-course usability evaluation

The closed-course evaluation was specifically designed to examine how drivers used the system in a variety of controlled visibility and roadway conditions. Our interest was in identifying the system’s role in enhancing drivers’ ability to maintain lane position. We also wanted to explore how the warning displays would be used, either individually or in combination. Drivers experienced a set of five different warning modality combinations:

1) Baseline (no warning at all - None)
2) Seat and lights (no visual - SL)
3) Visual and seat (VS)
4) Visual and lights (VL), and
5) Visual, lights and seat (all warnings - ALL).

For the closed-course usability evaluation we collected subjective and objective data. The objective data capture driving performance information while the subjective information was used to assess driver acceptance and reliance. In addition to these measures of performance, each driver completed a 50-question survey following the drive. The post-drive survey focused on

Snowplow Lane Awareness System: Operator Interface Design and Evaluation 57
The University of Iowa
their reactions to the system. Drivers expressed their opinions on the system’s annoyance, potential usefulness, and possible safety benefits.

Subjective assessment

Pre-drive background surveys

Prior to taking part in the experiment, all four drivers completed a ‘background’ survey. The twenty-two questions covered three topic areas: 1) experience as a snowplow operator, 2) education and computer experience, and 3) sleep and work schedule. The survey questions and participants’ answers are available in Appendix F. We will focus our summary of finding to drivers’ work and rest schedule.

All drivers had worked several hours on the day of the experiment and had slept less than an ideal 8-hour period. At the time they completed the survey, all had been up for a minimum of 15.75 hours. One LAS-inexperienced driver had been up for over 19 hours, and two others approximately 18.75 hours. All drivers had worked a minimum of 9.5 hours that day, with the LAS-inexperienced driver having worked as many as 14.5 hours. This same individual reported sleeping the least (5.5 hours compared to 6 hours for the other LAS-inexperienced operator). The two LAS-experienced drivers had had at least one hour more of sleep than the LAS-inexperienced ones (6.5 and 7.0 hours). All but one LAS-experienced driver reported good-quality sleep, with total scores of 20 or 21 on a 25-point scale.

It is interesting that the two drivers who drove the later shift of the evaluation (starting at midnight) reported feeling much more alert (ratings of 8 and 9 on a 10-point visual scale) than the drivers who did the earlier shift (ratings of 4 and 5 respectively). Neither reported napping earlier in the day. The LAS-experienced driver had attempted to nap, but was unsuccessful. The difference might be explained in part by the fact that these two drivers were the most experienced snowplow operators, with 13 and 25 years experience, compared to two for the other two drivers. It might also be attributed to their work/rest schedule, considering that one of the early shift drivers had driven the most and slept the least in the previous 48 hours and that the other one, although he had the longest
sleep period (7 hours) of all four, reported the poorest quality of sleep (13 compared to 20 or 21).

As soon as they completed the drives for the closed-course study, drivers were asked again to rate their alertness. Surprisingly, the two drivers who drove the late shift (i.e., midnight to early morning) reported feeling less sleepy than the early shift drivers (average of 7 out of 10 compared to 2.5). This pattern was the same as in the pre-drive surveys. All drivers seemed a little more tired at the end of the drive, as evidenced by a slight decrease in alertness ratings.

Post-drive surveys results

Following their test drive, participants completed a one-on-one interview with the research analyst, answering the post-drive survey questions. Appendix G contains their responses. To better understand some of the findings, we differentiated between drivers who were inexperienced with the system with those who were experienced with the system during the course of their regular snowplow operations. Both LAS-experienced drivers reported utilizing it more than ten times during low-visibility conditions, one LAS-experienced operator reporting using it as many as 75 times that winter.

Overall, drivers seemed satisfied with the LAS operator interface. None had encountered any major difficulties or problems. Drivers found the system to be very intuitive (6 out of 7), easy-to-use (6.5 out of 7), flexible (6 out of 7), and not frustrating (6.5 out of 7). They also considered the system to be extremely useful in helping them maintain their lane positions (6.5 out of 7). Assessing the usefulness of each component separately, drivers found the seat vibrations to be the most useful (6 out of 7), followed by the peripheral vision lights (5.3 out of 7), then the control unit (4.5 out of 7).

Drivers were asked to evaluate each operator interface component separately. All drivers appreciated the seat vibrations. Everyone found them to be extremely salient (6.9 out of 7). During the field test, no one felt the need to adjust the intensity of the vibrations. However, one LAS-experienced driver mentioned the importance of this capability; he mentioned frequently adjusting the vibration intensity as a function of clothes worn and time.
into the drive. In summary, all drivers seemed satisfied with this warning component and no one suggested changing anything about it.

Drivers considered the peripheral vision lights to be very noticeable (6 out of 7) and quite distinguishable from other lights (5.5 out of 7). However, one LAS-experienced driver reported that the lights were difficult to see during daylight, especially during blinding snow conditions. He suggested making them brighter, and providing drivers with the ability to adjust their height and left/right positions. All drivers seemed to use them as intended—that is, they continued to look ahead when they were flashing. One LAS-inexperienced driver reported looking at them without moving his head.

The control display unit (CDU) is the operator interface component that received the most negative comments, especially in regards to its in-cab location (4.3 out of 7). Three of the four drivers did not like its location in the center of the instrumentation panel. Not only did it prevent the installation of a cup holder—an important item for most snowplow drivers—it also requires drivers to redirect their gaze to capture lane position information. The two LAS-experienced drivers got used to it, but one felt the visual portion of the control display unit should be converted into a HUD and positioned closer to the center of drivers’ vision, ideally directly in front of the steering wheel. When they used the system in very low-visibility conditions, both LAS-experienced drivers tended to ‘track’ the visual display, i.e., closely monitor it for any deviations. Doing so forced them to divert their attention away from the roadway. It is possible that they chose to ‘track’ the visual display rather than glance at it occasionally because they felt the system was too slow in recovering from a lane deviation. Both drivers considered the lag time too long. Specifically, when the vehicle got too far from the tape and the ‘double-arrow’ warning appeared re-directing the driver to the appropriate side of the road, the LAS-experienced operators felt the system took too long to regain an accurate signal. They indicated that this ‘error’ occurred rather frequently at a few specific locations on Highway 17. One LAS-experienced driver pointed out that this phenomenon even occurred on several occasions while negotiating the East curve of Mn/Road.
On the positive side, all drivers found the control unit’s visual display to be relatively easy to interpret; in other words, they could find their vehicle’s position in relation to the tape (5.5 out of 7). They also considered the scale of ±3 feet to be appropriate and sufficiently readable (5.5 and 6.5 out of 7). One LAS-experienced operator warned that any future design iterations should have an equivalent complexity level—i.e., he felt it should not be more complex than the current version. One design suggestion was to include the roadway configuration so that drivers could see upcoming curves. Drivers also liked being able to adjust the light intensity.

Drivers also rated their annoyance with the LAS operator interface. When asked about which component they found the most annoying, all drivers said none. Of the four components, the two LAS-experienced drivers found the control display unit to be the least annoying as they had learned to not watch it. Drivers’ annoyance ratings for the peripheral vision lights and the seat vibration were very low (1.5 and 1.3 out of 7, respectively). We also asked them to imagine driving this system for 12 hours and to rate how annoying they would find it. Their ratings varied, including 1 (not annoying at all), 2, 4, and 6 out of 7 (extremely annoying). The LAS-experienced driver who gave a ‘1’ rating reported using the system for over 5 hours continuously in a severe storm and never found it to be annoying. The LAS-inexperienced operator who gave the highest annoyance level (6) felt there was a lot of information to watch, and that this made it difficult and annoying, especially during a storm. When asked which operator interface component they would eliminate, drivers did not agree; one LAS-experienced driver would eliminate the seat if he had to pick one component, the other LAS-experienced operator selected the control display unit, and one LAS-inexperienced driver chose the peripheral vision lights. None of the drivers would add any additional system options. One driver reported that the cab would get too crowded and that there was enough hardware involved, while another driver mentioned that adding a auditory warning would be too much.

An important component of this post-drive survey was documenting the LAS operational characteristics. Drivers felt that the system would make them somewhat more aware of their lane position (5.5 out of 7). We asked whether the system augmented drivers’ traditional outside visual cues. From the answers we obtained,
the system seemed to add to their outside visual cues (5 out of 7), however, two of the drivers felt that the question was poorly phrased. They also felt that the warnings would enable them to respond quickly to a lane departure (6.3 out of 7). One LAS-experienced driver reported that he tends to adjust his warning indicators (thresholds) more tightly when he wants to make the system safer, so that he is warned as soon as a small deviation occurs. When asked whether the LAS had caused inappropriate actions that resulted in an errors of judgment, the two LAS-inexperienced operators indicated that it had not. One LAS-experienced driver mentioned that it had, but said he had known not to directly follow positional information.

When queried about the workload implications of this new system, drivers indicated that the system would not necessarily free up much time to look for stopped vehicles/objects (4.3 out of 7) or to perform other tasks (4.3 out of 7). They felt the system enhanced their ability to drive on straight and curve segments (6 out of 7) compared to not having the system, even though they did not feel it reduced their workload much (5.3 out of 7).

An important factor in the successful implementation of any new technology is operators’ willingness to trust the information it provides. It is also critical that operators feel confidence in their ability to use the system effectively and appropriately (Lee & Moray 1994). Unanimously, drivers indicated that they trusted the LAS to provide them with accurate and reliable information (9 out of 10). The two LAS-inexperienced drivers also trusted the LAS could help them maintain their lane position better than their own abilities alone (9 out of 10). The two LAS-experienced drivers were more skeptical about this, however (5 out of 10). One LAS-experienced operator indicated that his skepticism was due to the LAS lag time and the several ‘false alarm’ signals (double arrows) he received while negotiating the curve. The other LAS-experienced driver attributed it to the fact that any device should be considered an ‘aid,’ and that ultimately one needs to rely on one’s own judgment rather than on a device. A similar, although less defined, pattern of findings was observed with regards to self-confidence. Drivers with no LAS experience expressed nearly complete self-confidence in their ability to stay in the lane when using the LAS compared to when they did not have the system (9 out of 10), while the LAS-experienced drivers were a little more cautious (7.5 out of 10)—
again probably due to their past experience with false alarms and lag times. Yet, all drivers tended to rely heavily on the LAS during the entire drive (8 out of 10), and even more so during the simulated low-visibility conditions (9 out of 10).

Finally, all drivers believed that the LAS had good potential for improving their safety (6 out of 7). They were a little less certain about its potential to increase their efficiency (5.3 out of 7); one LAS-experienced operator mentioned that it would not necessarily result in faster snow removal operations.

Finally, drivers estimated that the simulated test conditions were somewhat realistic (4.8 out of 7) with regards to plowing a two-lane road in low-visibility conditions. One LAS-inexperienced driver mentioned that his vehicle lights are usually set lower, providing him with more visibility at the road level. This same driver also mentioned that test conditions were not realistic in that they did not have to contend with traffic. Two drivers (one LAS experienced and one inexperienced) felt that the ‘no light’ condition was very similar to being in a real whiteout. The LAS-experienced operator mentioned that he had faced similar conditions two to three times that winter, whereas the LAS-inexperienced driver, who drives mostly on the interstate, reported similar conditions two to three times per shift. He also indicated that being passed by a semi-trailer often causes visibility conditions that are very similar, if not worse, than a complete whiteout, even though they may last only three to five seconds.

**In-situ trust and confidence ratings**

After each lap, drivers were asked to verbally report their trust and confidence with the warning modality combination. Figure 14 summarizes each driver’s ratings of trust and confidence for each one of the LAS warning combinations (V=CDU’s visual, L=Peripheral vision lights, S=Seat), except for the condition in which the system was turned off (Baseline).

At first glance, we note that the two LAS-inexperienced drivers rated their trust and confidence in the system very highly. Both drivers completely trusted the system in providing them with accurate and reliable information. They also felt very confident that all the warning modality combinations would help them
maintain their lane position. However, LAS-experienced drivers showed a little bit more reservation; even though they remained confident that the LAS warning modalities would help them maintain their lane position, they did not trust the system so easily. This finding has important implications for training in that drivers who are using the system for the first time many not know that they should not completely rely on it, but rather use it as an ‘aid’. Since experienced LAS drivers had the opportunity to use the LAS under a variety of operational conditions, they have a stronger mental model of the system’s operations.

![Graph showing drivers' ratings of trust and self-confidence with each warning combination.](image)

**Figure 14. Drivers’ Ratings of Trust and Self-Confidence with Each Warning Combination**

The figure also points to evidence of using the control display unit as a ‘primary’ display rather than as an ‘aid’. Looking at

---

Snowplow Lane Awareness System: Operator Interface Design and Evaluation 64
The University of Iowa
one of the LAS-experienced drivers (LAS-E1), we observed that when the visual display was not available, his trust and confidence ratings decreased to an average level (5 and 4 respectively). If we cross-reference this information with his reported use of the system in the field, we found that, in low-visibility conditions, he would tend to move the warning threshold indicators closer to the magnetic reference tape indicator, thereby ensuring that he would be alerted as soon as a small deviation would be encountered — which is the intended system’s use. However, he also tended to ‘track the arrow’, possibly suggesting that by not having the CDU’s visual display available, he lost distance-to-tape information. This finding has implications for training and how the system warning combinations are used. It also points to the fact that the other warning modalities (i.e., seat and PVLs) should possibly have means of providing distance-to-tape information.

**In-situ workload ratings**

After each lap, drivers were asked to verbalize their workload experience with each warning modality combination. Workload was evaluated using the NASA-Task Load Index that breaks workload down into six items (i.e., mental, physical, temporal, performance, effort, and frustration). In addition to these six measures, we asked drivers about the ‘visual demands’. We also asked drivers to differentiate between the workload they experienced during the curved compared to the straight segments of the roadway. Figure 15 summarizes the workload ratings averaged over these two portions of the roadway.
There appears to be a difference between LAS-experienced and inexperienced drivers. The LAS-inexperienced driver (LAS-I2) showed a decrease in workload level as the system’s warnings decreased in complexity. This suggests a possible learning or novelty effect that increased his perceived workload. On the other hand, one of the LAS-experienced drivers (LAS-E1) showed a quasi ‘U-shape’ pattern of ratings across display modalities indicating that the visual component played an important role in his use of the system.

One novelty effect of the system is higher workload during the initial phases of use whereas the experienced drivers seemed to rate this system relative to baseline as being less demanding.

Objective driving assessment

Several measures of driving performance were acquired through the data collection unit. These data include vehicle performance
information, driver input information, and lane exceedence information.

As described previously there were a number of challenges that reduced our statistical power. It was largely due to the limited number of participants. Roadway damage further contributed to reducing the amount of data collected. Nonetheless, we were still able to obtain descriptive information. Given the reduced statistical power, caution should be applied when interpreting these results.

Lane Exceedence Performance.
The LAS sensors characteristics served as the basis to our definition of a lane deviation. The driving boundary was defined as a three-foot window that could move to either side of the magnetic tape. Because the survey findings indicated that drivers do intentionally and unintentionally deviate into the incoming lane, we allowed for some of the boundary margin to occur onto the left side. However, because drivers reported to driving no more than one to two feet into the left lane and because we wanted to simulate clearing one traffic lane at a time, we opted for the following definition:

A lane deviation was encountered whenever the snowplow vehicle exceeded the driving boundaries defined as ‘0.5’ to the left and 2.5’ to the right of the magnetic tape.

The analyses focused on three characteristics of lane deviations: number of deviations encountered during a visibility event; duration of the deviations (sec); and magnitude of the deviations (feet). To calculate the number of deviations we considered that one full deviation (counted as 1) had occurred if the vehicle started within the boundary limits, exceeded either to the left or the right and came back within the boundary limits. However, in some instances, at the onset of a visibility event, the snowplow vehicle was already outside of the boundary limits. In those instances, we calculated the number of deviations using the following formula:

1) A full deviation (counted as 1) occurred if the vehicle started outside the boundary limits and remained outside the boundaries for the entire duration of the visibility event.
2) A half deviation (counted as 0.5) occurred if the vehicle started outside the boundary limits, but re-entered it at anytime during the visibility event.

We first looked at the effects of roadway and visibility conditions on lane deviation. Using a repeated-measures model and adjusting for the different display modes, we found, as evidenced in Table 10, that:

- Drivers had a greater number of deviations (p=0.29) during the low-visibility conditions (louvers @ 25%) on the curves (mean=0.510) compared to the straight segments (mean=0.053).
- Drivers had a greater number of deviation (almost significant p=.071) in the curve (mean=0.510) during low-visibility conditions (louvers @ 25%) compared to driving on a straight roadway (mean=0.00) with clear visibility (louvers @ 100%).

These findings are consistent with our expectations. Given the nature of driving in low-visibility conditions, one could anticipate that drivers would deviate more in the curve compared to a straight segment of the roadway, especially during low-visibility conditions. The Mn/Road’s roadway geometry accentuated these conditions due to its very sharp turns.

The descriptive analyses also revealed that for the entire closed-course study, only a total of 18 events showed one or more deviations. Except for one that occurred during clear visibility (100%), all of them occurred during the low-visibility condition. Furthermore, the majority (77.7%) of these events occurred on the curved segments of the roadway. As one might expect, the curved segments also had the deviations with the greatest magnitude or duration.

Table 10. Lane Deviations as a Function of Roadway and Visibility Conditions

<table>
<thead>
<tr>
<th>Mean (SD) for each measure of deviations</th>
<th>25% visibility straight</th>
<th>100% visibility straight</th>
<th>25% visibility curved</th>
<th>P-values from multiple comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of deviations / event</td>
<td>0.053 (.092)</td>
<td>0.070 (0.128)</td>
<td>0.510 (0.093)</td>
<td>1 vs. 2 p=0.993 1 vs. 3 p=0.029 2 vs. 3 p=0.071</td>
</tr>
</tbody>
</table>

Snowplow Lane Awareness System: Operator Interface Design and Evaluation 68
The University of Iowa
| Total duration of deviations / event (%) | 0.007 (0.013) | 0 (0.018) | 0.054 (0.013) | 1 vs. 2 p=0.948 1 vs. 3 p=0.096 2 vs. 3 p=0.113 |
| Maximum magnitude of deviations / event | 0.030 (0.025) | 0.006 (0.035) | 0.114 (0.026) | 1 vs. 2 p=0.850 1 vs. 3 p=0.126 2 vs. 3 p=0.105 |

Note: The 5-sec events for the zero-visibility condition were too short to observe any meaningful deviations and as a consequence were dropped from the analyses. Although we tested three different visibility conditions on the straight roadway segments, for safety reasons, drivers only experienced low-visibility conditions on the curved portion of the roadway.

Because of the limited amount of data we were unable to discern differences between display modalities for either the lane deviation or driver performance measures.

Conclusions

The data analyses for this closed-course evaluation illustrated the need to concentrate/focus on subjective measures of performance. They provided us with more detailed information with regards the LAS’s usability and acceptance. In general, user trust and confidence in the system was one of the most important findings, especially considering that they are important ingredients in the success of such driver assistance technologies.

Arizona DOT operational evaluation

In early March 2001, we sent a 32 question survey to snowplow drivers assigned to Department of Transportation (DOT) maintenance garages near Flagstaff, Arizona (AZ). The survey was distributed to individuals who had received training on the 3M™ Lane Awareness System (LAS). Our goal was to gather information on how the system actually worked in an operational setting. The Arizona DOT purchased a beta version of the LAS and installed approximately 20 miles of magnetic tape in critical portions of their mountainous roadways. At the time they completed the survey, Arizona snowplow operators had received training on the
system and had had the opportunity to use it during a variety of winter conditions.

A total of 16 surveys were completed. A copy of the survey and tabulated answers is contained in Appendix H. The survey had 32 items organized into five separate sections. In the first section, seven questions addressed drivers’ training with the 3M™ System and other systems; in the second, 13 questions evaluated their actual experience with the 3M™ System; the third section focused on drivers’ trust and confidence in the system (five questions); and the fourth section asked for suggestions on how to improve the system (four questions). The last three questions asked about the safety benefits of such systems.

In addition to this survey, supervisor(s) at the AZ DOT asked the same drivers to complete an ADOT Snowplow Training and Evaluation Survey. The ADOT survey was initially designed to evaluate another lane awareness system. However, since drivers completed it in reference to the 3M™ Lane Awareness System and we received a copy of the results, there is some discussion of them in this summary.

**Training & use of the lane awareness system(s)**

In this section, drivers described the training they received on the 3M™ System and on other comparable systems. Training on the 3M™ System took place between November 2000 and February 2001. More specifically, Snowplow Team Leader Activity Reports provided to us by the Arizona DOT indicate that training sessions occurred on one day in November and one day in December 2000, and on four different days in January 2001. The last one was on February 6, 2001.

Sixteen drivers from seven AZ DOT maintenance garages participated in training. They reported an average of 6.4 years of experience operating snowplows (the range was 1 to 13 years). During training, drivers spent an average of 3.6 hours operating the 3M™ Lane Awareness System. When they completed the survey in March, a little less than half (44%) had used the system after their initial training; only three drivers (19%) had used it more than five times. These three 'experienced' drivers had spent between 40 to 150 hours operating the system. The other 13 drivers spent only an average of 1.97 hours on the system after
they were trained. Thus, except for three drivers, the experience level with the system was low, consisting of a few hours of training and, at most, a few hours afterwards.

The proportion of time drivers had spent using the system in low-visibility conditions was of particular interest. Three drivers reported experiencing conditions of less than 100 feet forward visibility eight times or more during the three-month period. However, due to the wording of the question, it was difficult to determine if drivers were indicating the number of outings with low visibility or simply the number of low-visibility events (which could have all occurred during one outing). One driver reported encountering low-visibility conditions at least eight or more times even though he never had an opportunity to use the system after his initial training. In other words, most drivers (at least 75%) received training on and used the 3M™ System in fair-weather conditions. This was corroborated by the Team Leader Activity Reports, which indicated that visibility was ‘over 500 feet’ in all but one instance.

On November 10th, training occurred at night in low-visibility, windy and snowy conditions. Operators were able to use the system to help them maintain their lane position and to stay out of the way of oncoming traffic. Weather information from the reports suggests that in training sessions prior to and including January 27, snow or wind was encountered on two days and ice on one. The roadway was usually covered with snow and drivers were involved in plowing and sanding activities. For the remaining three training days (January 29 onward), the weather was clear, the pavement dry, and drivers did not perform plowing or sanding activities.

To anchor drivers’ opinions about the 3M™ System, we asked about their experiences with other lane awareness systems. Almost every one (93%) had used the California Department of Transportation (CALTRANS) system before; no one had experience with the University of Minnesota system. Although we did not ask drivers how many hours they had spent using the CALTRANS system, we did ask which of the two systems they preferred and why. Drivers liked both systems—43% preferred CALTRANS while 57% favored 3M™. The advantages listed for the CALTRANS system included the visual display (ability to see the curves in the road) and the collision warning capabilities. Where the 3M™ System was preferred, drivers
indicated that they liked the seat component and the fact that it relieved them of the need to look at the visual components. Three people simply indicated that the 3M™ was the ‘better, easier, and simpler system.’ Overall, drivers found both systems attractive, but indicated a slight preference for the 3M™ System.

Drivers’ experience with the 3M™ lane awareness system

Our survey asked drivers to rank various aspects of the 3M™ System on a 7-point Likert scale. Drivers first rated the LAS on its user-friendliness and usefulness. Most found the system very ‘easy to use’ (average ranking of 6 out of 7). This concurred with the rankings for ease of use in the ADOT Survey, where the average rating was 8.8 on a 10-point scale (1=not at all to 10=completely). Drivers also indicated that they found the system ‘satisfying,’ as opposed to ‘frustrating’ (average ranking of 5.5 out of 7), and ‘flexible’ (average ranking of 5.5 out of 7). Still positive, but with a lower mean ranking was their assessment of how ‘intuitive’ the system was. They reported that it was better than average (average ranking of 5.1 out of 7), but did not consider it to be ‘extremely intuitive.’

Of the three warnings available (i.e., visual scale display, peripheral vision lights, and seat vibration), the seat vibration was by far the preferred warning. Drivers rated seat vibration ‘extremely useful’ (average ranking of 6.2 out of 7 on the University of Iowa [UI] survey) and reported that this feature significantly increased their perceived level of safety, as indicated by an average ranking of 9.1 out of 10 on the ADOT survey. Comments in the Team Leader Activity Reports echoed these findings. Drivers indicated that they liked this component because it allowed them to keep looking forward to the road. They also liked being able to adjust the intensity of the vibration (11 out of 16 respondents).

Drivers’ responses to the other two warning modes were mixed. On the UI survey, drivers gave a higher mean ranking (5.6 out of 7) to the visual scale display for its usefulness in helping them maintain their lane position. However, on the ADOT survey, they indicated that the peripheral vision lights were better than the visual scale (8.4 vs. 7.6 out of 10) at increasing their level of safety. One explanation of these results may be that the visual scale display was useful in providing information about lane
position while the ‘peripheral vision lights’ acted better as a warning. This explanation is corroborated by the fact that the majority (11 out of 16 respondents) reported being able to continue looking forward when the lights were flashing.

The UI survey asked respondents which warnings they considered to be the ‘most’ and ‘least’ annoying, and which they would eliminate if they had to choose between them. The majority (10 out of 16) did not consider any of the warnings to be annoying—no one warning emerged as most annoying. Seat vibration was the least annoying (6 out of 16) and would be the last one eliminated, followed by the visual display. If one of the warnings had to be eliminated, drivers suggested it should be the peripheral vision lights (8 out of 16), but an almost equal number felt that all three should be retained (7 out of 16).

In general, drivers’ experience with the system was positive. Apparently, the 3M™ System did not prompt any driver to an erroneous action or judgment (14 out of 16 respondents), and most had no difficulties with the system (12 out of 16 respondents). Drivers indicated that, in general, the LAS made them ‘much more’ aware of their lane position—they ranked this item highly, with an average ranking of 5.9 out of 7. In addition, respondents felt that the warnings enabled them, or would enable them, to respond quickly to a lane departure (average ranking of 5.8 out of 7). The ADOT survey also reflected drivers’ general satisfaction with the system. Drivers rated the display and warnings an average of 8.6 (1=not at all to 10=completely) in terms of being clear and easy to understand. They also felt that the lane awareness system provided them with enough information to be useful (average ranking of 8.6) and that the system responded quickly enough to be useful (average ranking of 8.9).

Drivers did not seem to think, however, that the 3M™ System would reduce their workload significantly and thereby help them to allocate more resources to other tasks, such as radio communications (average 4.4 out of 7). They indicated that the system might help them a little (average 4.8 out of 7) to spend more time looking for stopped vehicles or objects in the roadway. They also felt that it augmented their traditional outside visual cues (average ranking of 4.9 out of 7). Overall, drivers felt that the system was useful but would not ultimately impact their workload (average ranking of 4.3 out of 7).
Drivers’ trust and confidence in the 3M™ system

Drivers seemed to trust the lane awareness system and expressed confidence in its capabilities. On a Liekert scale of 1 (not at all) to 10 (completely), drivers ranked most of the trust items an average of 7 or above. The highest mean ranking (average 7.5) reflected drivers’ confidence in their ability to stay in the lane with the 3M™ System compared to without it. Similarly, they believed that the system could help them maintain their lane position better than their own abilities alone (average ranking of 7.1). They also trusted the system to provide them with accurate and reliable information (average ranking of 7.2). The lowest rating was in response to whether drivers felt they could rely solely on the 3M™ System (average 6.9). However, it appears that drivers considered the 3M™ System to be a reliable tool able to augment their own abilities and current equipment. Of those who had difficulty trusting the system, only one person indicated that this was due to a deficiency in the system (i.e., no ability to foresee the turns in the roadway). Others attributed their lack of trust to the system’s novelty, to the fact that no system is foolproof, and to their feeling that they had not had sufficient experience with the system to judge its reliability and accuracy.

Drivers’ suggestions for improving the 3M™ system

Most drivers seemed to be satisfied with the system and offered few suggestions for improvement. Eight respondents (out of 13) submitted no suggestions on either the UI or ADOT survey. Two drivers suggested adding a feature to the visual display that would allow drivers to predict curves and turns in the roadway (a current capability of the CALTRANS system).

Suggestions for improving the warnings and radar capabilities included adding auditory warnings and the ability to detect both oncoming traffic and vehicles approaching from behind. Perhaps because of their prior experience with CALTRANS, two drivers also indicated they would like to have collision warning capabilities. A technical suggestion was made that the sensor be positioned higher on the vehicle, but it was not clear whether the respondent was referring to the sensor for the CALTRANS collision warning system or the magnetic sensor of the 3M™ System.
**Safety benefits**

In both surveys, drivers were asked about the safety benefits of the LAS. On the ADOT Survey, drivers indicated that the system had a very high potential of improving their safety, giving an average ranking of 9.2 on a scale of 1 (not at all) to 10 (completely). They felt similarly about the system’s ability to improve motorists’ safety (average ranking of 9.1). The UI survey responses were similar—on a scale of 1 (not at all) to 7 (completely), drivers rated the 3M™ System’s ability to improve their safety an average of 5.8. They also indicated that the system had good potential for improving their efficiency (average rating of 5.7 out of 7); this item on the ADOT survey received an average ranking of 8.4 out of 10.

**Conclusions**

The initial evidence suggests that the LAS system is beneficial to snowplow operators involved in mountainous snow removal operations, and it appears to be reliable and useful in increasing a driver’s situational awareness in low visibility—its primary function. In general, drivers trusted the system to provide accurate and reliable information; they also felt quite confident that the system would help them maintain their lane position.
SECTION 6 – CONCLUSIONS, RECOMMENDATIONS, AND FUTURE RESEARCH

This research program endeavored to design and evaluate a lane awareness system (LAS) for snowplow operations. We began this process with no \textit{a priori} assumptions as to how the operator interface of the LAS was to be configured. Using a comprehensive systems-based approach, we designed the interface from the ground up.

Starting with a thorough understanding of the operational environment, we rode-along with snowplow operators in a variety of vehicles during storms to experience first-hand the conditions and challenges drivers face. From these initial ride-along drives/interviews, we were able to establish that the interface needed to be flexible and highly adjustable, allowing users significant control over its operation. The “human-centered” approach has been used successfully in the aviation environment and other highly automated domains. As we found that drivers complained of in-cab lighting and intrusive auditory alerts, we opted to design around a quiet, dark cockpit theme. One advantage of this theme was that it made alerts more salient—the operator did not need to distinguish a specific alert among a sea of bright, distracting lights.

In addition to the ride-along interviews, a large-scale survey with over 1,000 respondents provided critical information for the design of specific features of the operator interface. For example, a principal finding that set another overall interface design theme was that true zero visibility is a rare occurrence. Only 6% of survey respondents indicated that they had lost complete visibility for more than 30 seconds during an entire season. This fact reinforced our thinking that the overall concept of the interface should be that of an ‘aid,’ not a command display. Furthermore, because drivers reported that they must constantly search for roadway obstacles such as bridge abutments, parked cars and vehicles stalled in their lane of travel, we chose a non-visual, peripheral interface that compliments their existing visual cues. The directional seat vibration (via thigh bolster) and peripheral vision lights scored the most highly in a trade study that examined a number of interface options.
The control display unit (CDU) was designed as the final reference in the system. The CDU is used to adjust the warning thresholds, select warning sensors, and control the intensity of seat vibration, PVLs, and the CDU screen brightness. The CDU also provides the driver with information on the vehicle’s exact position relative to the magnetic tape. Where to position the CDU in the cab was an important issue. Since it was not designed to be a command display, we chose to place it to the driver’s right, in the center of the instrument panel.

From the preliminary interface design phase, we moved on to the evaluation stage. This phase allowed us to identify what worked and what did not. We were then able to make recommendations for future iterations of the interface design.

**Principal findings of the operator interface evaluation**

Overall, we found that drivers responded favorably to the peripheral warning strategy and interface design. Drivers learned to use the interface quickly, and understood its function as an ‘aid.’ They related well to the “seat of the pants” driving approach with the directional vibrating seat. The peripheral vision lights were considered a useful complement to the vibrating seat. The control-display unit (CDU) was also easy to understand, and operators who used the system in the field liked the adjustable warning thresholds.

In general, drivers liked the combination of warning components. When asked which component they would remove if they had to, drivers would not select a component. However, of the three warning modalities, drivers had the most difficulty with the control display unit. From our observations, it may be that the CDU was not used as intended. Drivers liked the simplicity of it, but seemed to use it more for lane positioning than we had intended. The CDU was designed as a final reference, not as a command display; drivers were not expected to track the information displayed. Because it was salient in the cab, however, drivers felt compelled to look at it and attempted to use the information presented independent of the peripheral cues. This was confirmed in the post-drive reviews when several operators suggested that the CDU be placed directly in front of the operator, rather than in the center of the cab.
Trust and confidence in the system was also an important aspect of the evaluation. Operators in the closed-course usability study rated the LAS as trustworthy as their own abilities. Drivers with experience with the system trusted it slightly less than inexperienced drivers, however. This was likely due to the experienced drivers having used the system in actual operational conditions, where uncertainties are higher. Drivers in the field have high expectations for such systems; as they get to know the ins and outs of the LAS, trust may be undermined somewhat.

**Observations and suggested design iterations**

In any design process, iteration is the key to an ultimately successful design. Our observations and analyses suggest the need for some design- and training-based recommendations.

**Operator interface issues**

Saliency of the control unit display

The saliency of the control display unit (CDU) was a drawback in our LAS operator interface. During both the field operational evaluation and the closed-course usability evaluations, we observed that drivers perceived the CDU to be a primary command display. They tracked the visual component of the CDU instead of using it to supplement their other peripheral cues. More than one factor may have been involved in this phenomenon. When a driver climbs into the cab, the CDU is physically prominent—it is initially more salient than the other two displays. The peripheral vision lights are small and inconspicuous until you look at the windshield and the seat vibrations are noticeable only upon activation. Another reason may be related to the literature provided to users. In reviewing the LAS marketing and informational materials, we noticed that it emphasized the CDU relative to the ‘hidden’ vibrating seat and inconspicuous peripheral vision lights. Drivers may also have had expectations based on experience with other technologies that the interface would be predominantly visual.

Such an effect has been seen in other research—most notably in the voice input arena. For instance, voice recognition systems in vehicles are designed to around voice commands. Manual input is not required, nor is it necessary to take your eyes off of the roadway. However, in a study by Dingus et al. (2000), drivers
looked away from the road as they spoke and focused attention on the microphone or component they were adjusting (e.g., the radio) rather than looking straight ahead. In observing many operators using the LAS, we noticed this same effect.

To reduce the saliency of the control unit, a feature could be implemented that darkens, fades, or blackens the screen until it is intentionally called up. Minimizing this information-presentation mode for most operations would place more emphasis on the peripheral modalities. This is particularly true for novice users, who may be tempted frequently consult the visual display.

**Training Issues**

Future training should emphasize the peripheral warning aspects of the display. LAS operator training should concentrate on the peripheral modalities of the interface. Driver should, for example, be trained to literally drive 'by the seat of their pants' so they can grasp how these virtual rumble strips operate. By reinforcing the idea that the system is designed to help them keep their eyes ahead and focused on the roadway, we should be able to reduce the tendency to look at the display.

We also found that without specific training in the peripheral modalities, drivers tended to 'chase' the lane position indicator, creating the potential for operator induced oscillations that increased in magnitude as steering became less. Since drivers get their quantitative distance information from the CDU (e.g., exactly how far they are from the magnetic tape), a graded peripheral strategy should be examined in future iterations. Graded displays can be used to pre-cue drivers that an ultimate warning is imminent. The disadvantage of graded alerts is that they trigger frequently, and may be perceived as annoying. It would be best, therefore, to offer the graded alert as an option.

**Sensor electronics**

System’s lag time

Another characteristic of the system noted during the usability testing was the visible lag between acquisition of the magnetic tape and display of lane position information. As noted
previously, drivers occasionally attempted to ‘chase’ the guidance information. The system lag time exacerbated these chasing effects, creating an unstable system. In this first version of the LAS, there was a 100 msec lag time between acquisition and display. Future versions should consider hardware and software options to ameliorate this delay.

Inconsistencies caused by sensors’ position

One of our primary concerns with regards to the sensors electronics was an ambiguity associated with the position of the sensor relative to the tape. In order to protect the sensor bar from environmental elements, the sensor is mounted just under the vehicle’s front bumper (see Figure 12). Since the plow blade edge varies its angle and position during plowing, there is an offset from the edge of the plow relative to the sensor bar. The result is that the magnetic tape icon on the CDU may be offset relative to the actual plow edge by as much as 1.5 feet. In future iterations, the sensor bar and CDU display should be calibrated so that the magnetic tape icon on the display is accurate relative to the actual plow edge.

Design process benefits

From the start of this research and development process, we maintained close contact with active snowplow operators. We often ran ideas past operators in maintenance garages in Minnesota and Iowa before putting them into effect. Close contact with the intended users of a system is critical to its success. Many product designs fail because they do not include input from the ultimate users. Our interactions with snowplow operators and local organizations also gave us a perspective on the limited funding resources available to state and local organizations—a critical factor in making design decisions.

The extensive use of surveys targeting end users throughout the design process yielded a great deal of valuable information. Large-scale survey data identified the most critical operational factors in the design.

The closed-course evaluation enabled us to observe how drivers used the system under controlled, low-visibility conditions. In addition to measuring operators’ lane position performance, we
were able to measure their workload in real-time through each pre-determined change in visibility.

**Limitations and challenges of the evaluations**

There are several limitations and challenges involved in this kind of evaluation. While limitation is a term generally used in design and evaluation, we add another category, 'challenges' to describe areas outside of our control (e.g., weather).

**Weather**

In usability evaluations on either open or closed roadways, weather is a constant challenge. For snow removal operations, snow is clearly a good thing. However, snowfall can vary drastically from winter to winter. In an overall evaluation, participants’ exposure to the system under consideration is directly tied to the weather. We experienced such challenges on this project. During the 1999-2000 winter season, there were few storms, and thus few opportunities for road crews to use the system. Weather is a particular challenge when one is attempting a closed-course study. Factors such as the moon, snow pack on surrounding areas, snow or rain activity, and road conditions can all potentially confound experimental control.

**Infrastructure Constraints**

The overall evaluation of the LAS relied on a few roadways where magnetic tape is installed. One disadvantage of the limited number of sites is that it limited the number of drivers who could fully experience the system in operational conditions. This project was restricted to tape installs in Minnesota (Gaylord) and Arizona. At both sites, only one route was installed.

**Personnel and Vehicle Limitations**

Organizations find it difficult to commit snow removal vehicles to a project such as this due to their high cost and relative scarcity. In addition to the limited number of vehicles, only a few drivers are capable of operating these custom trucks. One of the findings early of this project was that most snowplow operators are assigned a specific route that rarely changes. Some drivers plow the same route their entire career. Since there are
generally only two or three operators assigned to each route, this severely limits the number of operators who can use a prototype system. The rational for having dedicated operators on specific routes is directly related to safety. Knowing every inch of a route is critical to an operator’s situational awareness. Therefore it is difficult to change this operational constraint—even for testing purposes.

**Future directions**

Future interface designs of the LAS might consider integrating two new components into the operator interface: 1) a forward collision warning (FCW) system and 2) a navigational unit.

The importance of a FCW component was demonstrated during the ride-along interviews and in the operational surveys. Drivers value such information highly, as parked vehicles (in or out of lane) are a real and constant hazard. FCW systems are currently very immature technologies, however, and so we chose not to integrate this capability into this initial design. The principal limitation of FCW systems is a high frequency of nuisance alerts generated from non-safety related targets such as signs, guardrails and bridge overpasses. One solution might be to integrate a navigation database containing roadway features likely to cause inappropriate alerts into the system.

Future versions of this operator interface should consider adding a limited navigation component to provide distances and geometries to upcoming intersections and curves. While we intentionally kept the display free of clutter for this first design, operators felt, and we believe, that a simple preview of upcoming roadway features might be useful. Navigation systems that use both “turn-by-turn” and bird’s eye views could be implemented into the interface. The goal would be to further increase an operator’s situational awareness relative to overall route position and roadway landmarks (e.g., intersection, off ramps etc.).

With regard to evaluation tools, an additional tool that should be considered for future studies is the use of a truck simulator with a snowplow cab. Such a simulator would allow even more precise replication of low-visibility scenarios, and would afford more precise situational awareness assessment. Simulation could
also be used to pilot test new iterations of the interface to
determine shortcomings earlier on. An additional advantage of
simulation is that it could be used to explore training
strategies. Finally, because neither environmental conditions nor
schedules would be an issue with a simulator, many more drivers
would be able to participate.

In addition to simulation, future tests should use more field
sites so that more drivers could experience the system. Along
these same lines, perhaps later testing should be conducted on
roadways in areas with higher populations of snowplow operators.
One disadvantage of the Gaylord tape installation was its
distance from other areas. If tape installs occurred in more
urban areas, conceivably more operators could come in and spend a
shift using the system—if and when it snowed.

Conclusions

Our data from this project suggest that the 3M™ LAS is beneficial
to drivers involved in snow removal operations. The LAS appears
reliable and useful in increasing drivers’ situational awareness
in low-visibility conditions—its primary function. In general,
drivers trusted the system to provide accurate and reliable
information. While drivers preferred the haptic seat over the
peripheral lights and the control display unit, they appreciated
the warning redundancy in the interface.
SECTION 7 – REFERENCES


Dingus et al. (2000) DAN PLEASE INSERT


ITSA Website (2002). http://www.itsa.org/resources.nsf/24aebd36f046a5a58525658d00644198


Relaxor®. (2002). Website [www.relaxor.com](http://www.relaxor.com)


