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Development of a Driver Assist Interface for Snowplows Using Iterative Design

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A system to aid snowplow operators during adverse, low-visibility conditions was developed using a quick, low-cost iterative design process. The system provided display-independent visual information on lane edges, lateral position, and potential forward collisions. Short practice curves were seen on a prototype lateral assist system with drivers achieving a steady state within 3 trials. The subsequent operational system resulted in positive driver feedback and quick learning periods. Drivers had positive impressions regarding ease of use, appeal, and safety. Behavior data showed that the short learning curves seen with the prototype could also be associated with the operational system. Using the framework of this snowplow problem, an iterative design process is also described that is robust to variations in available time and resources. Application specific and process design lessons are also discussed.

Besides pushing snow, a snowplow driver has to give simultaneous attention to a set of secondary tasks (see also Neale, Wierwille, & Dawes, 1999; McGehee, Raby, & Nourse, 2000). First and foremost, they need to stay on the road, a somewhat difficult task during whiteout conditions. Experienced drivers learn to feel the road surface through the plow blade. The change in texture or pitch of the shoulder can provide subtle vibration cues through the truck body and the steering wheel. Traditional wisdom recommends that the driver come to a stop and wait out the period of low visibility. However, in mountainous terrain, drivers are often reluctant to do this as stopping on an incline or in a potential avalanche area is undesirable. In addition, stopping places the driver in jeopardy of being struck from behind (McGehee, Raby, & Nourse, 2000).

A subtask of staying on the road is maintaining a position within a lane. Even during periods of good visibility and without deep snow, this can be difficult because road markings are not easily perceived (Figure 1). Furthermore, pavement may not be exposed even during ideal plowing conditions due to restrictions on salt spreading activity. This can pose a problem where a team of plows is used in formation. The lateral position of the lead plow is especially important as trailing drivers will adjust their lateral position based on the lead plow. Poor lane positioning by the lead driver can result in poor plow distribution and reduced efficiency.

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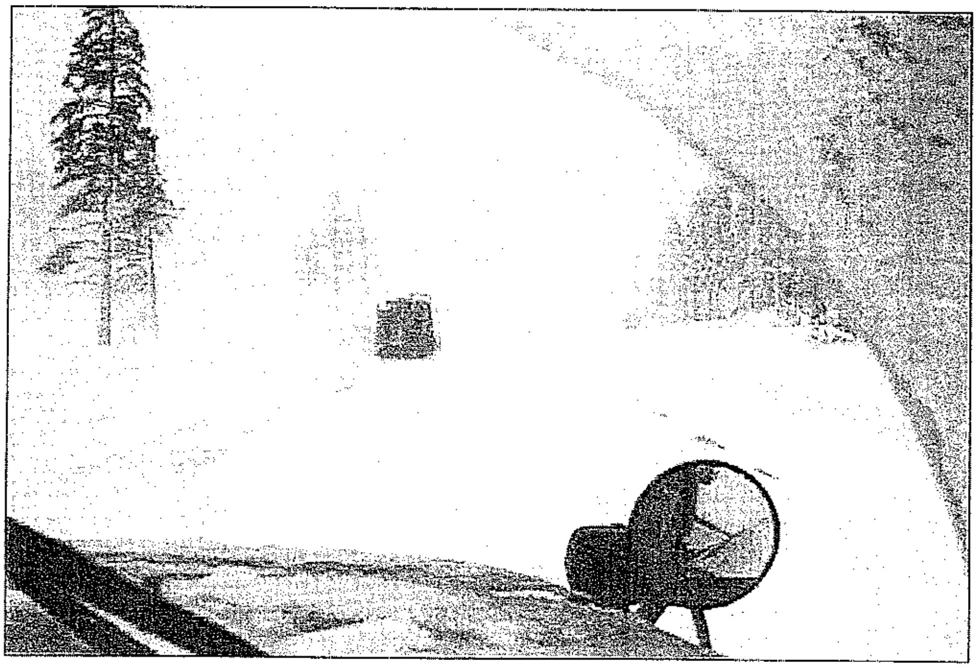

FIGURE 1 A typical view from the cab of a snowplow at Donner Pass (a forward plow is seen at the left shoulder, the lead plow is barely visible)

Another fundamental task is to avoid driving the plow into an obstacle (e g., a car stuck in a drift). In low visibility conditions, a plow driver will feel the plow blade make contact with such an obstacle. Usually the driver has dropped to a very slow speed and the initial contact is not extreme Furthermore, the driver can stop the plow very quickly by dropping the plow blade into the ground This stopping technique is even more effective when the plow is equipped with a wingplow (a large plow mounted on the side of the truck) Even with this rapid stop, it is possible to damage the obstacle and snowplow.

The driver's basic duties are further affected by a series of potential hazards Low visibility can occur because of whiteouts, malfunctioning or iced headlamps, or a soiled windshield. Perception of the road edges is affected during deep snow conditions in that the only indication of the edges are tall snow stakes placed just off the shoulder Additionally, vehicle dynamics can be adversely affected by icy roads, plow vibration, and icepacks. When a wingplow is in use, low ballast (sand depletion) can also lead to extreme torque on the truck These difficulties can easily lead to elevated levels of mental workload and stress.

HUMAN FACTORS GOALS FOR A SPECIFIC APPLICATION

The development process for the Advanced Snowplow (ASP) project will be used as an example of how human factors design and research can be applied to the problem of safe and efficient snow removal The ASP project was initiated to assist snowplow drivers during the harsh conditions often experienced over Donner Pass on Interstate 80 in the Lake Tahoe, California region (for more information see Stone, 1998; Zhang, Lasky, & Jenkinson, 1999). Snowplow drivers along this route experience some of the heaviest snowfall in the United States and often encounter whiteouts due to the sheer quantity of snow as well as blowing winds in the mountainous terrain During the frequent winter storms, drivers operate snow removal equipment 24 hr a day as Interstate 80 (I-80) is the major land conduit into Northern California

The primary human factors goals of this project were to provide to the driver with information on lane edges, lateral position, and potential forward collisions so that they could navigate more safely, efficiently, and confidently through low visibility conditions A secondary goal was to provide lateral information in a manner that would improve positioning of the lead plow during snowpack scenarios where lane markings were not visible. Another secondary goal was to develop a system that was easy to learn with a minimum of training.

HUMAN–MACHINE INTERFACE DESIGN CONSIDERATIONS

Only visual interfaces were examined during the first phase of the ASP project. A simple display that could be used with a quick glance was a major design goal due to the already high driver workloads. Auditory warnings were initially considered, but dropped because of development time concerns Ride-alongs in the snowplow also suggested that loud auditory signals would be necessary due to high ambient noise levels Tactile and haptic systems were not examined due to cost and the short development time. These modalities may be revisited in the future should the resources become available.

Lane Keeping and Positioning Assistance

As previously mentioned, this concern is twofold. There is the macroscopic concern of staying on the road as well as the microscopic concern of accurate lane positioning during formations The former is for safety, whereas the latter is for efficiency. An additional issue is that the display should not decrease safety, especially during good conditions. Lane position should be easily and rapidly gleaned from the display with a minimal amount of distraction. Drivers should also be able to rapidly achieve a stable lateral state so that the system does not monopolize visual attention and other visual tasks can be executed. Design recommendations by McGehee, Raby, and Nourse (2000) reinforced this stipulation.

Tactile steering wheel displays and automated steering corrections are often recommended for lane departure crash-avoidance systems (e.g., Dingus, Jahns, Horowitz, & Knipling, 1998). The basic snowplow activity of scraping a large piece of metal along pavement or concrete induces considerable vibrations in both the steering wheel and the cab. Thus, tactile steering wheel displays may not be as useful as in other vehicles. Automated steering corrections (e.g., Schumann, Lowenau, & Naab, 1996, and Hsu, Chen, Shien, & Yeh, 1998) were also considered and are within the design team's capabilities (Tan, Guldner, Patwardhan, Chen, & Bougler, 1999), but like tactile steering wheel displays, they were deemed too expensive and time consuming to pursue Dingus et al. (1998) also recommended curve approach advisories using beacons and transmitted signals. Freestanding curve approach advisories were considered during the initial development process, but the need for continuous lane positioning led to the realization that these two pieces of information could be integrated into one system

Padmos and van Erp (1996) found that drivers could perform moderately well on lateral tasks when driving with a camera view. Their findings suggest that it is possible to maintain an acceptable lateral state without looking directly at the road. In related research, Summala, Nieminen, and Punto (1996) showed that lane-keeping performance degraded as a secondary task display was moved away from the vanishing point. Participants were asked to keep their foveal vision on number-based tasks and to drive using their peripheral vision. This led to a second finding that increased driving experience could result in better use of peripheral vision for lane-keeping purposes. With regard to snowplow applications, these findings are valuable yet are thought to have less impact. The method used by Summala et al. is similar to a driver using foveal vision to attend to a lane positioning display However, such a display is replacing foveal vision of the road scene with a logical representation of the same information rather than a number-based task. Thus, the introduction of a lateral assist display may not be too detrimental if some peripheral information is still visible and the logical representation of the road scene is well designed Furthermore, low visibility conditions will lead to limited perception of the road scene in general (foveal and peripheral), thus, a moderately acceptable display will be better than none at all.

Forward Obstacle Warning

California Department of Transportation (Caltrans) snowplow drivers were consulted during all stages of development. A common theme regarding the collision-warning system (CWS) was that they wanted to know the distance to a potential obstacle. Drivers indicated that knowing the amount of room between them and the obstacle would permit them to react in an appropriate manner given that they often encounter steep grades and poor traction For example, a slow moving truck 75 m ahead on an incline can easily be avoided when traveling at 5 mph. However, a closer target may require a more aggressive stop (e.g., driving the plow blade into the pavement).

Past explorations of forward collision warnings have emphasized time-based headway warnings (e.g., Dingus et al., 1997; Horowitz & Dingus, 1992) and discrete maneuver warnings (e.g., Yoo, Hunter, & Green, 1996). As this display was designed for scenarios where the plow would be traveling at low speeds (< 10 mph), a time-based display was deemed to be somewhat cumbersome for the driver In addition, it was felt that a distance-based headway display would be easier to transition to should a sudden whiteout obscure an actively watched forward obstacle. Discrete maneuver warnings were deemed unsafe given the likelihood of low traction. Another design goal was to provide some representation of lateral position of the obstacle with respect to the plow so drivers could disregard objects outside of their plowing coverage

Head-Up Displays (HUDs)

The concept of using HUDs in automobiles to provide an augmented reality (e.g., Steinfeld & Green, 1995, 1998) is an enticing design route. However, there are theoretical and practical reasons to choose a head-down or auditory option. In the literature, several potential problems are identified with using HUDs that lead to solid concerns regarding snowplow tasks.

The first, and most worrisome, problem is that of cognitive capture (Weintraub & Ensing, 1992). Specifically, a driver who begins to ignore the real world in favor of a HUD may not notice forward obstacles that are missed by sensors. The most likely case is when a member of the general public exits their car after running off the road. Current collision-warning technology has difficulty sensing "soft" targets such as people. This concern, coupled with high workload levels and long shifts, has the potential for significant consequences. Although head-down approaches remove the driver's attention from the forward road scene, they also carry an implicit feeling of uneasiness when looked at for too long. This uneasiness, coupled with low complexity imagery, may lead to a lower likelihood that the driver will trust the display more than the real world.

The problem of cognitive capture is amplified when conformal imagery (also known as contact analog) is presented. For example, in a static study in which participants were asked if HUD images of highlighted intersection road edges matched real-world backgrounds, there was one case in particular in which high response times and error rates were recorded (Steinfeld & Green, 1995) This case was for a mismatched scene where a cross intersection (conformal HUD imagery) was shown over a T-right scene with a driveway on the left. Even though the HUD imagery was for a different intersection, and therefore unaligned and incorrectly drawn, participants repeatedly indicated that the HUD imagery matched the road scene. When recognized correctly, the response time was slower than other less confusing combinations

Tufano (1997) documented several problems related to automobile HUDs that have added weight in a snowplow environment. A primary safety problem is the opportunity for misperception of distance in the real world One can easily see how this poses a potentially significant problem in collision scenarios Another safety problem presented by Tufano is poorer performance on responses to unexpected objects and obstacles. Although snowplow drivers are often cautious of potential collisions and learn to anticipate problems in their path, long shifts and high workload levels may lead to a higher frequency of unexpected events.

Although these arguments may indicate to a conservative reader that HUDs should not be used at all, they are acceptable if interfaces are designed in an appropriate manner. In fact, HUDs were briefly considered for this project but rejected for practical reasons The largest practical problem when using a HUD in a snowplow cab is contrast interference due to large changes in ambient illumination (e.g., Gish, Staplin, Stewart, & Perel, 1999) Most plows at Donner Summit are driven 24 hr a day so the brightness of the HUD imagery needs to be adjustable through a wide range This problem is further compounded by the high likelihood of green, blue, and orange being prominent in the road scene (trees, sky, and other snow removal vehicles respectively) Pale HUD imagery also requires a high level of brightness to create a legible contrast on bright, snowy backgrounds.

The first HUD that was considered for this project was a goggle-based system that was flatly rejected based on previous Caltrans experience. Past exposure to head-mounted equipment strongly discouraged future attempts. This design suggestion was initiated prior to the human factors practitioner's participation, thus reinforcing the need for human practitioners to become involved at the earliest design stages. Cab size constraints led to rejection of the off-head HUD examined The only usable location was to place the imagery in the sky by mounting the unit near the visor at the top of the windshield This was viewed as not satisfactory in that the driver's head might collide with the unit during a crash or quick deceleration Projections from behind the driver onto the windshield were not considered due to cost and the lack of space behind the driver's seat. In addition, there were safety concerns with having a projection unit mounted next to the driver (e g., body motions during side impact crashes) or above the driver's head (a driver can be jolted out of the seat when the front plow blade hits an icepack). The distinct possibility for vibration and degraded sensor capability raised generic HUD concerns regarding imagery vibration and alignment

These concerns essentially distill to the conclusion that although HUDs are attractive, important design and human factors issues must be resolved and overcome before they can be recommended.

DESIGN METHODOLOGY

To complete the interface development task of this project, the team utilized a combination of brainstorming, literature review, and iterative design. The initial activity in the design process was to conduct brainstorming sessions with the goal of producing viable design subsets within the project constraints For the purposes of this article, a *design subset* is defined as any general solution that has mutual physical or cognitive features yet is specific enough for an example implementation to be readily apparent (e.g , haptic feedback through the steering wheel for lane maintenance). Within the project described here, the constraints primarily consisted of a limited budget and a short fabrication time. The project did not have enough money to explore more expensive display hardware (e g., custom built HUDs) and the prototype plow needed to be delivered to the maintenance center within 4 months This timeline was further compressed by the need for at least a month of final system testing and geographical separations between subunits of the development team as well as the end users

Several brainstorming sessions were conducted starting with a large and diverse kickoff session Interested parties from Caltrans, Arizona Department of Transportation (ADOT), and the development team were present including experienced snow removal operators from the eventual deployment sites. Additional sessions at later dates typically included Caltrans and development team members. Several clusters were observed during the subset generation sessions The snow removal operators often advocated design subsets that incorporated graphical representations of the road Other salient clusters included bar, peripheral, and auditory displays.

The next phase of the method, the selection of a candidate subset, was short and based on system capabilities and literature review The operating environment within the plow cab led to the elimination of several sets rather quickly. Single modality auditory and vibration displays were deemed not likely to lead to an optimal design as a result of high noise and vibration levels. HUDs were avoided for both physical constraint reasons as well as concerns raised from a review of the literature (as previously mentioned)

Following the design subset selection, a process of iterative design was used to refine the subset into a specific prototype. Various iterative design processes have been used successfully in human–computer interaction development (e g., Gould & Lewis, 1985, and Knutson, Anand, & Henneman, 1997) Typically the number of iterations and the depth of each test or experiment are directly affected by the allocated time for development and the amount of resources available The rapid product cycle time in the computer industry has led to fast, cheap, iterative studies with limited depth and statistical resolution. Although this is not ideal, the outcomes are often reasonably good designs that are efficient and readily usable.

The main benefit of iterative design is the ability to start with a somewhat vague concept rather than a small set of almost final designs This provides flexibility for midcourse corrections and reduces the support overhead on the development process; initially only one prototype needs to be generated and iterations can extend and refine the original work. With respect to this project, this process is best manifested by a series of developmental studies in which the software and underlying control equations were extended, refined, and eventually used for the deployed prototype (as described in more detail in a later section).

As is typically done in transportation research, tightly controlled comparison studies to other prototypes or field operational tests are preferred prior to deeming a particular design as being optimal. However, in a development process with a short cycle time and limited resources, the process we describe here allows a practitioner to reach a design space that is above the threshold of good usability

PROTOTYPE DEVELOPMENT

Using the design methodology described earlier, the development team was able to progress through a series of design steps resulting in a viable prototype. Initial design subsets included a variety of bar displays, peripherally located LEDs, HUD imagery, flat panel displays, and nonvisual displays (auditory, vibration, and haptic displays) For a variety of reasons, including the aforementioned difficulties with HUD, auditory, and vibration displays, the team selected the single–multiple bar display subset as the starting point for iterative work

Three small development studies were conducted to examine the impact of the initial design iterations. All three development studies used an Automated Highway System equipped Buick® LeSabre (e.g., Rajamani, Tan, Law, & Zhang, 2000; Tan, Rajesh, & Zhang, 1998) Modifications were made by disabling the steering actuator action and processing the lateral deviation information to reflect lane position All studies were conducted on a nonlooping, 320 m long, closed-track course that included several short, small-radius curves For the first two studies, members of the development team who had not yet been involved in the project were enlisted as drivers. An author was the participant for the third study on practice. Previous studies on practice effects have shown that such an arrangement is feasible when cost and time are constrained (e.g., Sumie, Li, & Green, 1998). Recruiting experienced snowplow operators was considered too expensive given the geographical separation between them and the research team, and the project's budget did not contain money for externally recruited participants Additional detail on the methods and findings for these development studies can be found in Steinfeld and Tan (1999).

The initial development study on the suitability of bar displays examined 0, 5, 10, and 15 m look-ahead distances. To test this, the lateral deviation from the centerline (predicted for all but 0 m) was presented on a small bar in a Delco HUD. Drivers were tested with a covered windshield (simulated whiteout) and the speed was fixed and automated at 13 mph (6 m/s). The findings suggested that the larger look-ahead distances produced better lane-keeping performance. Drivers also commented that this display method required uncomfortably high concentration levels. It was felt that the addition of one or two additional bar code indications (e g., reflecting the road and vehicle trajectory change) might help drivers improve performance

As such, a design iteration based on this suggestion led a midcourse correction towards flat panel displays. Specifically, this correction allowed miniature, graphical road scenes to be examined This design was reinforced by previous comments by snowplow drivers that strongly suggested a visual display that indicated lane position and road edges. Figure 2 presents an example of one of the text-based prototype displays that were created

A prediction feature was added into the top line of the display because the first development study suggested that a look-ahead information was valuable The single "X" showed the future lateral position 10 m ahead corresponding to the magnitude and direction of the steering wheel angle (e.g., turn left, the "X" moves left) The current lateral position ("XXXXX") was shown in the bottom row The graphics represented a displayed distance of 10 m with a 1 m width between the "curbs." As in the first ministudy, the windshield was covered to mimic the worst-case whiteout condition (Figure 2). A third development study on learning curves was also conducted under similar conditions.

During the second and third development studies, a promising learning curve was present with mean speed increasing and mean lateral displacement from the center of the lane decreasing dramatically within three trials The practice effect was also visible during informal observations When demonstrating the system to other team members, drivers typically adapted to the system after two runs Drivers who had experienced the initial bar design commented that the system was much easier to use. Although these findings should be treated as very preliminary due to small sample sizes and participants who were not snowplow drivers, the results were still quite promising. Cumulatively, they suggested that a driver could adapt quickly to the display.

OPERATIONAL SYSTEM

The ASP contained two sensing methods, a computer to process the signals, and a display. The lateral position was detected by two sets of magnetometers that sensed the magnetic fields generated by magnetic nails embedded down the middle of the lane every 1 2 m. These

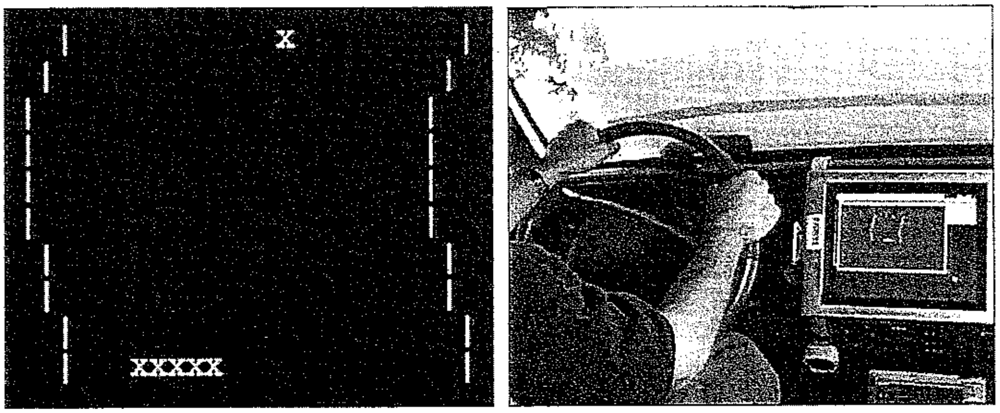

FIGURE 2 The text-based prototype

magnetometer sets were positioned behind the front wheels and under the rear bumper (revisions for the second winter led to the removal of the rear set). Potential forward obstacles were detected with a forward-looking millimeter wave (MMW) radar sensor mounted on the front grill of the truck. This sensor could track three targets at a time and was positioned so that it had a clear line of sight when the front plow blade was lowered. Prior to the second winter a matching MMW radar sensor was added to improve angular coverage.

Following text-based prototype display demonstrations for members of Caltrans, a more sophisticated and informative display was developed for the plow (Figure 3). The left-hand section of the display contained collision-warning information derived from the MMW radar data. Downward-moving tapes showed the distance to each of the forward targets. Tapes were chosen as they mimicked the forward approach of obstacles. Targets were only shown when they were within 100 m of the plow. The tape changed from yellow, to orange, and then red as the target approached (color changes at 50 and 25 m). Yellow was chosen over green (which is recommended in Wilson, Butler, McGehee, & Dingus, 1996) due to the possibility of a red–green colorblind driver. The number at the bottom of the display was the distance to the closest target in meters (Caltrans is a metric operation). A long range was chosen in order to provide drivers with time to track the object and adjust their plow blade positions. Filtering was used to reduce problems with noise and short-term signal loss. On initial installation, the radar sensor could not identify the lateral position of the targets. This design flaw was corrected prior to the next winter.

To reduce the possibility that drivers would integrate the 100 m collision-warning display with the shorter distance lateral display, a line was used to separate the sections. Conversations with the drivers indicate that this simple design characteristic achieved its purpose. The lateral display was similar to the character display, but included lane position marks and color state codes. In addition, the forward prediction capability was extended to 20 m and the displayed logical lane width was widened to 2 m. The center tick marks indicated the center of the lane, and the exterior tick marks indicated 2-ft offsets. Offsets are used during certain plowing formations and are often done intentionally by snowplow drivers elsewhere in the United States (McGehee, Raby, & Nourse, 2000). Under normal conditions the lines were white and the current and prediction markers were red. If the computer was uncertain of its current longitudinal position on the track, but was detecting position mark-

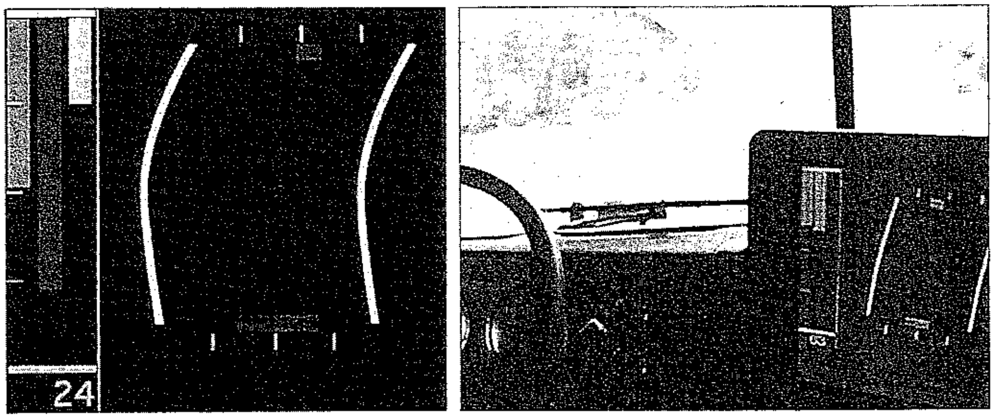

FIGURE 3 A drawing of the operational display

ers, the whole lateral display turned yellow and showed a straight road. This signaled to the driver that the display should not be completely trusted. If the plow left the magnets, the color changed to gray and froze. After a short time off the magnets, the lateral display blanked out. Besides color changes, no lane departure warning was issued.

The display was presented to the driver on a liquid crystal display (LCD) panel in the center console area (Figure 3). This panel was in line with the wingplow mirror on the right nose of the hood. Both plow blade controls were to the right of the driver immediately behind the floor-mounted, 13-speed gearshift. The sand spreader controls were mounted facing the driver on a stalk to the right of the LCD panel. This arrangement incurs high physical workload and task sequencing demands as the need for simultaneous gearshift and plow blade position changes are not uncommon.

The display location was chosen based on severely limited space and the presence of essential dials and controls on the dashboard. The choice of using the LCD panel seen in Figure 3 was because of time and cost constraints. Field observations of the display during the first winter indicated that the "black" on a LCD was not black enough during night conditions. Thus, the display was switched to a much smaller LCD with a darker black background for the next winter. Both iterations included brightness and contrast adjustments available to the driver. Should there be the opportunity, future design iterations will include explorations of other display techniques (e.g., HUDs, auditory assistance, etc.).

IMPLEMENTATION AND ON-ROAD FINDINGS

During the winter of 1998/1999, the ASP was used in two locations. The plow was based at Donner Summit in California for the bulk of the winter. However, there was also a 2-week demonstration at U.S. Highway 180 (US 180) north of Flagstaff, Arizona during March 1999. Design iterations occurred over the summer of 1999 and the ASP was returned to operation for the 1999/2000 winter.

California Operation, Winter 1998/1999

The system was introduced during December 1998 to the Lake Tahoe, California test track. The magnet track was in an area of high elevation, frequent low visibility, and large snow accumulations (as much as 54 ft of snowfall a season with roadside accumulations reaching 20 ft high). The stretch of road instrumented with magnets was a divided, restricted-access highway (I-80) with 3 lanes and wide shoulders traveling 3.9 mi between the Donner Lake interchange (6,400 ft) and the pass summit (7,200 ft) on the west end of the valley.

Caltrans driver training consisted of a description of display characteristics, a short run over a line of magnets in the maintenance yard, and a longer run on the instrumented test route. Although computer-based driving data was not systematically collected for the Donner Summit installation due to other development activities taking precedence, the authors had numerous discussions and ride-alongs with the drivers. The drivers expressed that they liked the lateral assist system and that it enhanced their confidence during adverse conditions. They were generally positive about the implementation and displayed very short learning periods (as seen with the prototype).

Driver comments regarding the CWS display were also generally positive This was not surprising as the drivers had specifically asked for a display that informed them of the distance to forward objects Most negative comments regarding the CWS centered on target acquisition and false alarm problems There was no instance when the system was used during a critical incident as there were no known forward near misses or collisions for the ASP.

Observations during ride-alongs indicated that the drivers were able to use the display either for reference or as a primary driving mechanism. It was also apparent that snowplow driving has the potential for high visual loading in that drivers must monitor plow blade positions, gauges, and surrounding traffic As the Lake Tahoe region is a tourist destination for many people not accustomed to driving on snowpack and ice, snowplow drivers often encounter drivers who have skidded off the road or drive in an unsafe manner.

Arizona Demonstration, March 1999

The instrumented stretch of US 180 in Arizona consisted of a two-lane, undivided rural mountain road with frequent whiteouts from high winds As this road was not a major interstate, there were areas of tighter curves and steeper grades than seen at the California track.

Seventeen ADOT snowplow drivers were introduced to the system in a more controlled manner than at Donner Summit as the plow was present for a much shorter time. Initial training consisted of three ADOT team leaders being instructed by members of Caltrans and the development team The Caltrans trainers rode along with each team leader for one or two circuits along the test route in order to teach the basics of driving the ASP truck. The ASP was quite different from typical ADOT plows in that it had more power, was larger, and had more gears. Following this, a development team trainer replaced the Caltrans trainer and instructed the driver on the use of the driver assist system. An initial circuit with only basic instruction was conducted first, followed by a more detailed description of display characteristics and additional circuits of practice The ADOT team leaders repeated this training pattern for the rest of the ADOT snowplow operators present at the demonstration.

Surveys. At the end of each training session, the drivers were asked to complete a two-page survey on the ASP display. The results (Survey A, Table 1) indicated that the drivers had a high regard for the system The lane-keeping portion of the display scored slightly higher than the CWS. This difference was probably due to a lack of trust of the CWS detection performance A second survey was also given to the drivers that included the time spent on the ASP and ratings on a variety of questions. Two of the questions (Survey B, Table 1) targeted safety and efficiency. Drivers consistently responded in a positive manner for these questions. Only one driver rated the system below a 7 (on a 10-point scale, with 10 being best) for the safety question. His comments indicated concern regarding speed and tachometer maintenance.

Drivers were asked an open-ended question regarding how long they felt would be necessary to become comfortable with the system In general, most drivers felt that they would reach a comfortable state within 1 month. Based on objective driving behavior data collected during the prototype development as well as observations of Caltrans drivers, this estimate is probably very high. Detailed analyses of the surveys implied that drivers with

TABLE 1
Arizona Survey Results

Variable	*M*	*SD*	*SE*	*N*	*Minimum*	*Maximum*
Experience (years)	5.77	3.17	0.77	17	1.5	11
Time on ASP (hr)	4.88	5.06	1.26	16	2.0	20
Survey A: Ratings[a]						
Overall: Easy to use	4.53	0.80	0.19	17	2	5
Overall: Like	4.71	0.59	0.14	17	3	5
Like more with more practice	4.63	0.89	0.22	16	2	5
CWS: Easy to use	4.31	0.87	0.22	16	2	5
CWS: Like	4.38	0.96	0.24	16	2	5
Lane keeping: Easy to use	4.44	0.63	0.16	16	3	5
Lane keeping: Like	4.69	0.60	0.15	16	3	5
Survey B[b]						
Safety	9.18	1.59	0.39	17	4	10
Efficiency	9.12	0.93	0.23	17	8	10
Survey A: Open question (frequency count)	< 1[c]	1–3[c]	4–6[c]	1–3[d]	4–6[e]	
Predicted time to become comfortable with system	3	5	2	6	1	

Note. *SE* = Standard error; ASP = Advanced Snowplow; CWS = collision-warning system.
[a]Ranging from 1 to 5, higher being better. [b]"Potential to improve your" safety and efficiency. Ranging from 1 to 10, higher being better. [c]Measured in days. [d]Measured in weeks. [e]Measured in months.

more experience and more exposure time to the ASP predicted less time to become comfortable with the system (Steinfeld & Tan, 1999).

Driver responses to other open-ended questions on the survey were generally positive. The bulk of the negative comments regarded trust in the CWS and the desire for a more salient indication of lane departure.

Driver behavior data. When the plow was brought to Arizona, it was necessary to calibrate the internal map to the new test site. During system testing, data were collected on speed and lane position characteristics at 33 Hz for about 1,680 m. Prior to the data collection period, the driver drove along a longer stretch (about 4,820 m) under identical conditions. Therefore, the data was collected for the last segment of each run. The data we present are only for one driver and thus should be considered preliminary, at best.

The data collection permitted a comparison of normal and display-assisted driving. The driver was asked to try to drive with only the display during a series of aided runs. It is important to note that there were clear views, dry roads, and the plow blade was lifted. Normal driving in this case corresponds to ideal conditions. The normal run was collected after several aided runs had been completed. Data was also collected for the first, second, and sixth aided run. As the driver became more familiar with the system, performance approached normal, unassisted driving (Figure 4). Analysis of variance (ANOVA) analyses of run (normal, 1, 2, 6) revealed significant differences with both speed, $F(17, 237, 3) = 4140$, $p < .0001$, and front lateral displacement magnitude, $F(17, 237, 3) = 39.8$, $p < .0001$, as dependent variables. Sheffé's F post hoc analyses on the two ANOVAs showed significant dif-

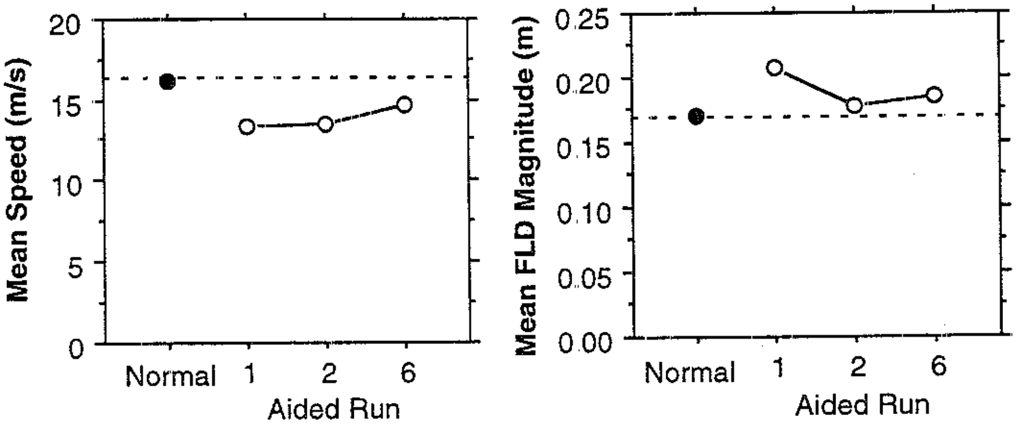

FIGURE 4 One driver's behavior data during system testing in Arizona

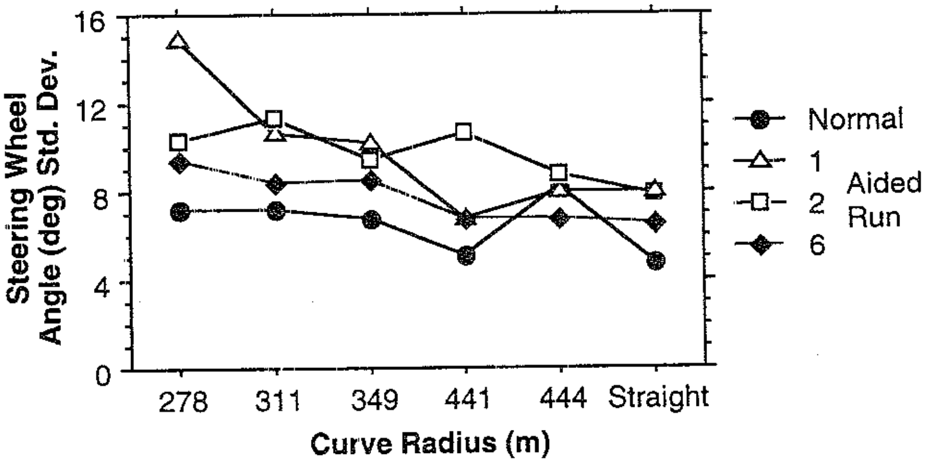

FIGURE 5 One driver's steering wheel angle standard deviation over different curve radii

ferences between all pairs except for aided runs 1 and 2 for speed, and normal and aided run 2 and aided runs 2 and 6 for front lateral displacement magnitude.

Higher steering wheel standard deviations generally imply that a driving task is more difficult. Figure 5 suggests that the task became easier as the driver's experience increased Furthermore, the driver seemed to approach the driving difficulty levels of the normal run. Although these data are from only one driver, this bodes well for low visibility scenarios and implies that it might be possible to reach difficulty levels similar to those of normal driving

Design Iteration and California Operation, Winter 1999/2000

Several improvements were made to the system prior to the winter of 1999/2000 through design iterations. For the display, the off-magnets indication (gray imagery) was enhanced by including a yellow arrow pointing back towards the lane center. This arrow was placed over the lane boundary that was crossed. Also new to the display was the addition of road segment names below the lateral imagery. These names corresponded to the names used by the drivers for specific curves and stretches of road. This iteration also improved the CWS by placing targets in their matching lateral position (left, middle, right) with respect to the plow, improving detection accuracy, and reporting the distance to the closest target in feet Driver comments indicated that although Caltrans promoted meters, drivers were more comfortable with time critical information being presented in feet. Future iterations may include auditory warnings

As previously mentioned, a new flat panel display was also introduced to the system. This panel included an easy to operate brightness knob, an on–off switch, contrast control buttons, and a darker black background (similar features were also suggested by McGehee, Raby, & Nourse, 2000). The display was considerably smaller than the one shown in Figure 3 and was mounted where a rearview mirror would normally be located Most Caltrans plows are not equipped with such mirrors as there is usually a sanding bed blocking the view through the rear window Originally, the display was mounted on top of the dashboard near the driver's right hand However, one of the drivers suggested moving the display to the rearview mirror position so that shorter drivers could have a less obstructed view of the right-hand wingplow mirror (see Figure 1). Interviews with other drivers revealed that this was a popular design modification

Lateral assistance improvements were also made to the control dynamics with the intent of making it easier to reach and maintain a stable lateral state (Tan & Steinfeld, 2000) Parameters were also tuned toward easy learning, reduced oscillation, and limited visual demand All tuning and redesign were done using a simulation of the snowplow consisting of a video game steering wheel attached to a computer and monitor. No formal experiments were run as the control dynamics were being modified daily. Prior to delivering the plow to Donner Summit, closed track system calibration occurred at an abandoned airstrip. During this testing, the development team quickly confirmed the parameter tuning with the help of a Caltrans driver that had no prior system experience

A Caltrans driver who used the system during the winter of 1998/1999 testing and was experienced with snow removal in general, received additional exposure to the system during Donner Summit calibration for the winter 1999/2000 iteration His initial comments were that the changes in the system dynamics were much more stable and easier to use. The next day, a new driver was introduced to the system. Suboptimal instruction occurred near the end of a 12 hr storm shift, followed by three runs with the system during sanding operations. Following these three runs, a shift change occurred and the experienced driver continued the sanding duties. His first four runs under identical climate and task conditions are shown in conjunction with the new driver's performance in Figure 6. Note that for mean speed, lateral displacement magnitude, and vehicle-to-road angle magnitude, the new driver quickly reached performance levels comparable to the experienced driver. These findings suggest that the improvements in the system dynamics did indeed improve ease of learning

Subsequent experimenter ride-alongs with Caltrans drivers suggest that the changes in the control system dynamics allow for less attention to be devoted to the display. Drivers have reported being able to easily use the system for lateral position checks and corrections during good visibility conditions. Observations and driver comments imply that visual demand is low and the system can be used as a reference aid.

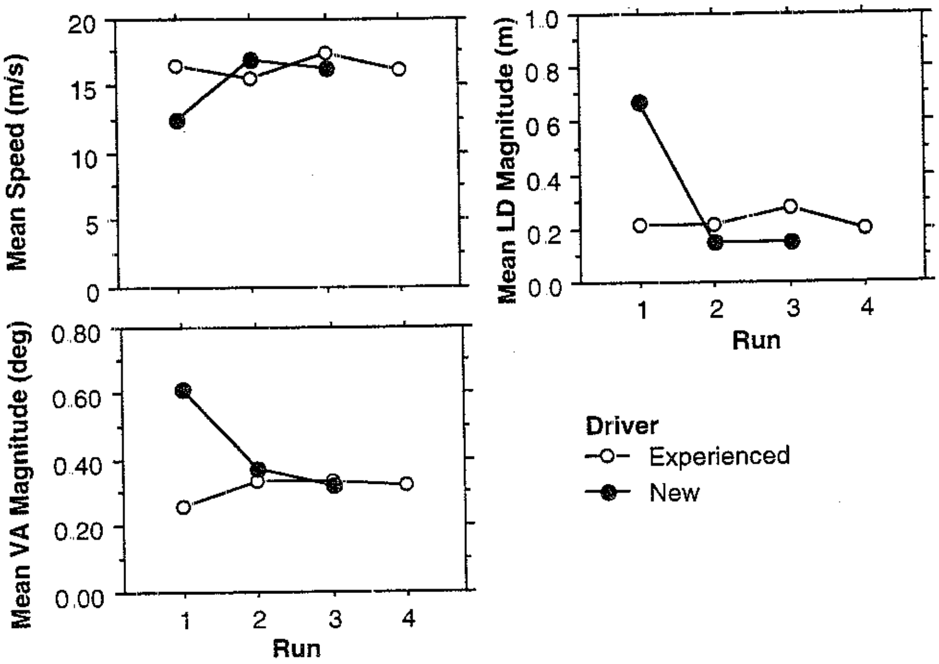

FIGURE 6 On-road learning at Donner Summit after design iteration

DISCUSSION

It is clear that the ASP system has the potential to be quite beneficial to driver safety and confidence The findings from the lateral-assistance portion of the display suggested that, even with limited instruction, the interface was intuitive and easy to learn. Most drivers were observed to reach a stable level of performance using both the prototype and the ASP after three trials or less. Modifications for the 2nd year seem to have reduced the learning period to one Donner Summit run or less (about 4 mi). Anecdotal comments and experimenter observations also suggested that the display could easily be used either for reference or as a primary driving mechanism.

Furthermore, this work suggests that a simple, low-fidelity display reminiscent of early video games can lead to an effective and well-received system. The initial decision to go with a "low tech" image was based on computational concerns and a desire for simplicity However, drivers responded well to the display, and limited field measurements showed good performance can be achieved without computationally intensive graphics or custom hardware.

There were several design lessons that were quite evident during this process. The first is the importance of fully understanding the differences between the end device and what is described in the literature and used in other systems. For example, most lane maintenance and collision-warning devices are primarily developed for high-speed driving. Although this is logical for most drivers, it is less valuable for low-visibility snow removal tasks in which drivers typically stay well below 30 mph However, this does not mean abandoning previous work; they still contain valid recommendations (e g., color shifts for CWS displays; Wilson et al., 1996).

A second design lesson is the often-repeated importance of interacting with the end users of the device. Discussions with the snow removal operators included attempts by the research staff to learn as much as possible about snow removal in general. This provided additional insight on the activities, environment, and organization that surrounded the basic snowplow tasks There were several instances in which design features were specifically added to assist previously unrecognized tasks (e g., the 2 ft offset tick marks).

Finally, integrating a human factors practitioner into the development team and using an iterative process can lead to quickly executed and sufficiently usable designs. As recommended by Knutson et al. (1997), the human factors practitioner for the ASP project maintained a consistently active role during development, often working on tasks not traditionally within the realm of human factors This kept the human factors practitioner readily available to the team and provided the opportunity to ensure that implementation occurred as originally planned.

Admittedly, the design process and example we describe will likely produce designs that are suboptimal and devoid of strong statistical backing. In no way will this process be superior to formal studies in which multiple designs are carefully compared. However, the process we used is an excellent method for attaining an acceptable threshold of usability when time and costs constraints are present. Furthermore, this process provides the human factors practitioner with a formal and defensible reason for maintaining integration with the design team Through this integration the practitioner can make midcourse modifications and protect the design from changes by the team, intentional or otherwise, that will lead to design flaws

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