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A RURAL FIELD TEST OF THE ROADVIEW SYSTEM^{*}

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ABSTRACT

This final report documents the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center's field-testing of the RoadView[™] Advanced Snowplow (ASP), titled "A Rural Field Test of the RoadView System." This work was performed in cooperation with our research partners, the California Partners for Advanced Transit and Highways (PATH) at the University of California at Berkeley, and the Western Transportation Institute (WTI) of Montana State University. The RoadView system applies Intelligent Vehicle (IV) and Advanced Vehicle Control and Safety Systems (AVCSS) technologies to enhance the safety and efficiency of snow removal. RoadView includes lane position indication, lane departure warning, and forward collision warning. RoadView technology was integrated onto three Caltrans 10-wheel 10-yard plows, and tested through the winters of 2000 - 2002 at two sites in California: the California Advanced Winter Maintenance Testbed on Interstate 80 near Donner Summit, and the California Rural Winter Maintenance Testbed on State Route 299 near Burney. The system was also tested for one month at a similar site on US 180 near Flagstaff, Arizona. The report provides a brief history of the previous phases (ASP I and ASP II), system overview, major subsystems, and functions. It also describes the Human-Machine Interface (HMI), the magnetic sensing system, and the radar-based Collision Warning System (CWS) in detail. Most important, the report provides the methodology and results for the system fieldtesting. The report also discusses improvements made based on previous research, as well as evaluation, conclusions, and future research. A supplemental report provides a detailed technology needs assessment, and a detailed cost-benefit tradeoff analysis for the RoadView system.

EXECUTIVE SUMMARY

Project Overview

Winter maintenance operations, including snow removal, are subject to increased risk. Snowplows must operate in the worst of conditions, including completely covered roads, very low traction, and complete visual whiteout. In addition, in California and other states, the consequences of road run-off are more severe due to the mountainous terrain. Additional danger comes from hidden objects covered in snow, and improper visual cues resulting from previous plowing. The operating environment and the nature of the risks indicate a significant opportunity to enhance the safety of the maintenance operator and the traveling public through the appropriate application of near-term Advanced Vehicle Control and Safety Systems (AVCSS) and Intelligent Vehicle (IV) technologies. Under the Phase One and Phase Two Advanced Snowplow (ASP-I and ASP-II) programs, the Advanced Highway Maintenance and Construction Technology (AHMCT) Center at the University of California - Davis (UCD) developed driver assistance, in the form of lane position indication and forward collision warning to increase the safety of the snowplow operation. AHMCT performed this work in conjunction with its partners, the California Partners for Advanced Transit and Highways (PATH) of the University of California at Berkeley (UCB), and the Western Transportation Institute (WTI) of Montana State University (MSU). The California State Department of Transportation (Caltrans) and its research partner, the Arizona DOT (ADOT), both provided test sites and snowplow operators. ADOT provided substantial effort in this first phase in developing a second (more rural) test site, and in providing access to a second set of plow operators [19]; ADOT continued in these key roles in follow-up project phases [20-22]. The California and Arizona DOT operators proved to be invaluable resources, not only for testing the system, but for providing input and guidance throughout the development phase as well. Lateral reference information was based on the California Partners for Advanced Transit and Highways (PATH) discrete magnetic reference marker technology, while forward collision warning was based on a millimeter wave radar sensor system developed by AHMCT. Under ASP-I, the efforts of this research team allowed first field-testing in the Caltrans maintenance fleet in just over half a year's time [42].

Based on the accomplishments of the ASP-I program, the US Department of Transportation's Intelligent Vehicle Initiative (IVI) Specialty Vehicle Partnership (now known as the IVI Infrastructure Consortium) funded continued development of the Advanced Snowplow Driver Assistance system with a Phase Two Program (ASP-II)—the objectives were to further develop functions for the snowplow guidance system in order to provide a more rugged and functional system for deployment testing, to develop an enhanced Human-Machine Interface (HMI) for snowplow guidance, and to develop quantitative Measures of Effectiveness (MOEs) to allow comparison of results for Winter Maintenance research. The purpose of these MOEs was to ensure that individual Winter Maintenance research projects are responsive to the broader goals of the IVI Specialty Vehicle Partnership (later known as the Infrastructure Consortium) and the IVI Specialty Vehicle Platform with the U.S. DOT IVI program. The ASP-II technical team consisted of the AHMCT Research Center and the California PATH program. Caltrans was the lead organization on the study, and provided test site infrastructure as well as input from snowplow operators and equipment personnel. ADOT completed the closed-loop of its rural test site, and provided access to their snowplow operators and valuable feedback on the operation of

the system [19, 20]. The system was successfully tested through the winter of 1999-2000. Operators at California's Donner Pass test site used the system regularly from December 1999 until the end of the snow season. In addition, the system was tested for approximately three weeks at the Arizona test site [20]. Operator feedback was quite positive.

Building on the technical success of the ASP-I and ASP-II programs, the current study, "A Rural Field Test of the RoadView System," provided a more comprehensive field test over a wider variety of conditions. In particular, more extensive testing in rural environments was performed on a new rural test site near Burney in Shasta County, CA. To support this field-testing effort, two new snowplows were equipped with the latest generation of RoadView technology, and the original ASP vehicle was upgraded to the current generation, providing a total of three RoadView ASP vehicles tested over two winters at three diverse test locations. As part of the effort, the component technologies and software were enhanced for the RoadView upgrade. In particular, the Collision Warning System was enhanced to provide improved false warning suppression. The resulting performance of this subsystem was much improved over earlier phases; however there is still room for improvement on this key aspect. The RoadView project was a multi-state pooled fund study, with California as the lead state, and Arizona as our valued research partner. ADOT has provided companion reports detailing their perspective on the RoadView Advanced Snowplow program, with reports available at the ATRC web site [22].

Summary of Conclusions

The RoadView Advanced Snowplows were deployed to the Caltrans maintenance fleet in December, 2000. Caltrans operators used them on a regular basis through the winters of 2000-2002, sometimes continually for several days straight during periods of intense storm activity. Additional testing occurred in February of each winter in our partner state, Arizona, on US 180 near Flagstaff. Research engineers continued to analyze and improve the performance of the system, as well performing minor preventive and responsive maintenance on the system, throughout the testing; however, changes were essentially transparent to the operators, so that the data collection was consistent over the two winters' testing. Data regarding operator use of the system was collected during ride-alongs by the research team. Analysis of this data is presented in Chapter 5; results are generally positive, and identify key areas for future improvement in a commercialized system.

Qualitatively, the survey results presented in Chapter 5 indicate an increase in the level of comfort with the ASP system relative to Phase I results. Specifically, the fraction of drivers indicating that achieving comfort would take less than three days shifted from about half to about three quarters. With respect to the Collision Warning System specifically, the presence of extraneous warnings on high-curvature rural roads yielded a lower qualitative operator survey response. Specific causes for extraneous warnings have been identified via quantitative analysis of video and recorded data, and remedies are being considered for follow-on research. Quantitatively, the Collision Warning System provided 73% correct detection, which represents a significant improvement from earlier phase research, but does leave room for improvement.

It is clear that the RoadView HMI has the potential to be quite beneficial to driver safety and confidence. Quantitative findings suggest that, even with limited instruction, the interface was intuitive and easy to learn. Most drivers were observed to reach a stable level of performance

after driving the RoadView ASP for one run or less. Anecdotal comments and experimenter observations also suggested that the display could easily be used either for reference or as a primary driving mechanism.

Based upon analyses of objective data, the system allows drivers to more consistently maintain a stable position near the lane center. Driving with the system appears to be quantifiably similar, if not slightly better, than unaided driving. In addition, note that many of the comparisons between "display on" and "display off" were made under less than whiteout conditions. Under whiteout conditions, the display will allow plowing operation to continue in situations where it would not be safe to plow without such a device; this was the primary motivation and goal of the RoadView ASP development.

The results of this RoadView study demonstrate the safety and efficiency that can be obtained through judicious application of Intelligent Vehicle technologies for a maintenance vehicle operating in a harsh and hazardous environment. Under whiteout conditions, the system eases the workload of the snowplow operator, while simultaneously enhancing the safety and efficiency of the operation. This concept is applicable across the Special Vehicle category (maintenance, police, fire, and emergency medical), where operators must perform their duties in all conditions in order to ensure public safety and availability of facilities. Appropriate care must be taken in extending results from snowplow-based work into other vehicle types, particularly with respect to intended use and human factors issues. However, in the long term, there are no foreseeable limitations to the application of the RoadView concept, i.e. it appears to be applicable across all vehicle platforms, including light vehicles, commercial vehicles, and transit vehicles, under the appropriate operating conditions.

Based on the results for Phase I and II along with RoadView testing, backed by strong interest from several State DOTs, the system concept as embodied in the RoadView research prototype is a viable launching point for future commercialization. The AHMCT center is investigating methods to transition the system to a state that is ready for a private entity to adopt and provide as a commercial product. An important part of the current effort involved the Caltrans Equipment Service Center in instrumenting one of the two new plows; this effort provided a clear indication that a DOT would be capable of installing this system were it available in the appropriate after-market kit form. From a technical feasibility standpoint, the concept of driver assistance for snowplow operators has been proven as effective in terms of enhancing safety, and desirable from the operator's point of view. In addition, the technology has been shown to be field-ready through four winter's testing in some of the harshest snow environments in the lower 48 United States. Clearly, RoadView is a research prototype, and improvements are needed in terms of manufacturability, further robustness, packaging, cost, etc. However, the research team continues efforts to enhance the state of the system, and to work with commercial entities to ensure that this valuable addition to the winter maintenance arsenal can be transitioned from a research prototype to a commercially available system.

Summary of Future Research and Development

At this stage in the program development, the magnet guidance based RoadView system is mature from a research standpoint. The system as embodied in the RoadView prototype vehicles is now ready for transition to detailed commercialization; however, there are a number of open questions that can be pursued in future research and development.

The RoadView CWS is in general quite effective for forward collision warning on rural roads. Some improvements are needed with respect to false warnings, but this can be achieved through incremental changes in the system, rather than a major revision in the concept or implementation. Additional safety improvements could be made by adding rear collision warning, i.e. for impact from a vehicle behind the snowplow. Additional modes of providing operator alerts (audible, other visual means, haptic, tactile, etc.) should be investigated in detail to determine the appropriate mix of alerts in the context of the noisy and high-distraction snowplow operating environment.

As part of the commercialization process, improvements can be made in the in-vehicle sensing systems. Significant steps have been made in this regard by AHMCT, with the development of an Intelligent Sensing Architecture, currently targeted for sensing of discrete magnetic markers, i.e. as a replacement for the existing sensing system in ASP-II. This intelligent system provides numerous advantages over the existing technology. All data transmission is digital, so that electronic noise is eliminated and cabling requirements are vastly reduced. The resulting system is more robust and maintainable, while simultaneously being an order of magnitude cheaper. Sensing algorithm modifications can be made so that the system can provide key information over a wide range of speed, all the way down to zero velocity, thus facilitating use in other operations, such as low-speed bus docking. The signal processing algorithm can be extended to support both discrete and continuous magnetic reference marker systems. In addition, the processing unit can be extended to encompass other aspects of the invehicle system, ultimately leading to a "black box" that could be easily retrofitted in an existing vehicle, e.g. in the snowplow cab, allowing a commercial entity to develop a feasible aftermarket kit suitable for installation by a vehicle manufacturer or a DOT. Lab and preliminary vehicle tests for this system have been performed and the design and algorithms have now been confirmed [4]. Research and development on this sensing system continues at AHMCT, and early versions of the system are currently being considered for commercialization.

Other areas of research may include vehicle and environment modeling, and further integration of vehicle tracking and process data into GIS management solutions. Vehicle and environmental modeling can improve the overall driver assistance and control, as well as providing sensing and control solutions for special-case high-danger situations, such as ice-pack induced accidents. In addition, the driver assistance system can log data that is useful for snow and ice management. Integration of this information into a comprehensive GIS database could enhance the DOT's ability to more effectively keep roadways clear. In addition, real-time knowledge of plowing activities could be integrated into the broader traveler information system, which could prove very useful to the traveling public. One area of concern for some DOTs relates to the magnet installation and durability, and associated impacts on pavement. ADOT has performed tests over several years, and their results can be found in ADOT ATRC research reports.

The RoadView ASP program has applied discrete magnetic marker based lateral sensing and forward collision warning to provide driver assistance, thus keeping the driver in the loop and allowing deployment of these technologies on public roadways in mixed traffic in a safe manner. The lateral guidance technologies employed in RoadView clearly evolved from PATH's earlier full vehicle control work, such as that performed under the NAHSC program [25]. Thus, application of these technologies for full automation in appropriate winter maintenance tasks is a reasonable next step. One such project, currently in progress, is the "Development of the Advanced Rotary Plow (ARP) for Snow Removal Operations," a pooled fund study, led by Caltrans, with participation by the Alaska DOT. This project includes full lateral control, along with forward obstacle detection to reduce ingestion of objects into the blower head. Application of precision lateral control for the blower will reduce or eliminate contact with the guardrail, while also improving the repeatability and accuracy of the work performed. Collision hazards are introduced by the presence of natural objects, such as large rocks and debris, as well as abandoned vehicles. Obstacle detection technology will provide added safety, as well as reduced DOT liability, repair costs, and downtime.

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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California – Davis, and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

The contents of this report reflect the views of the author(s) who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

Acronym	Definition	
3M	Minnesota Mining and Manufacturing Co.	
AC	Asphalt Concrete	
ACMS	Advanced Construction and Maintenance Systems	
ADOT	Arizona Department of Transportation	
AHMCT	Advanced Highway Maintenance and Construction Technology	
APS	Applied Physics Systems	
ASP	Advanced Snowplow	
ASP-II	Advanced Snowplow, Phase II	
ATRC	Arizona Transportation Research Center	
AVCSS	Advanced Vehicle Control and Safety Systems	
AWMT	Advanced Winter Maintenance Testbed	
Caltrans	California State Department of Transportation	
CWS	Collision Warning System	
DGPS	Differential Global Positioning System	
DOT	Department of Transportation	
EMI	Electromagnetic Interference	
FLD	Front Lateral Displacement	
FWSS	False Warning Suppression System	
GPS	Global Positioning System	
HMI	Human-Machine Interface	
HUD	Head-Up Display	
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991	
I-80	Interstate 80	
ITS	Intelligent Transportation Systems	
ITSA	Intelligent Transportation Society of America	
IV	Intelligent Vehicle	
IVI	Intelligent Vehicle Initiative	
LCD	Liquid Crystal Display	
LD	Lateral Displacement	
LIDAR	Light Detecting and Ranging	
MMW	Millimeter Wave	
MOE	Measure of Effectiveness	
MP	Milepost	
MSU	Montana State University	
NAHSC	National Automated Highway Systems Consortium	
PATH	Partners for Advanced Transit and Highways	
PCC	Portland Cement Concrete	
RF	Radio Frequency	
KFI DEL	Radio Frequency Interference	
KPM DTOG	Raised Pavement Marker	
RTOS	Real-Time Operating System	
KWMT gdd	Rural Winter Maintenance Testbed	
SBC	Single Board Computer	
UCB	University of California at Berkeley	
UCD	University of California-Davis	
WTI	Western Transportation Institute	

LIST OF ACRONYMS AND ABBREVIATIONS

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CHAPTER ONE: INTRODUCTION

This report documents the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center's continued development and testing of the RoadView^{TM1} Advanced Snowplow (ASP), titled "A Rural Field Test of the RoadView System." The current project provides detailed field-testing in a rural environment of the ASP driver assistance system developed previously under the Phase I and Phase II ASP efforts. Under the current project, additional system robustness and design improvements have been incorporated, and two new snowplows were equipped with current-generation RoadView technology. The main focus of the current project was detailed field-testing and evaluation, along with a detailed cost-benefit analysis and a thorough needs assessment. This is the main final report for the research project. The cost-benefit analysis and needs assessment are provided in a supplemental report; this portion of the work was performed by the Western Transportation Institute (WTI) of Montana State University (MSU). The document provides motivation including a brief history of previous phase developments, system overview, major subsystems, and functions. It also describes the Human-Machine Interface (HMI), the magnetic sensing system, and the radar-based Collision Warning System (CWS) in detail. Finally, it provides conclusions and recommendations for future research. Appendices provide further detail on the RoadView hardware and software, as well as the questionnaire form used to obtain operator feedback.

Motivation

Winter maintenance operations, including snow removal, are subject to increased risk. Snowplows must operate in the worst of conditions, including completely covered roads, very low traction, and complete visual whiteout. In addition, in California and other states, the consequences of road run-off are more severe due to the mountainous terrain in which much of the snow removal operations must be performed. Additional danger comes from hidden objects covered in snow, and improper visual cues resulting from previous plowing. The operating environment and the nature of the risks indicate a significant opportunity to enhance the safety of the maintenance operator and the traveling public through the appropriate application of near-term Advanced Vehicle Control and Safety Systems (AVCSS) and Intelligent Vehicle (IV) technologies. Under the Phase One (ASP-I) and Phase Two (ASP-II) Advanced Snowplow programs, the Advanced Highway Maintenance and Construction Technology (AHMCT) Center at the University of California - Davis (UCD) developed (ASP-I) and improved (ASP-II) driver assistance, in the form of lane position indication and forward collision warning to increase the safety of the snowplow operation. AHMCT performed this work in conjunction with its partners, the California Partners for Advanced Transit and Highways (PATH) of the University of

¹ RoadView is a trademark (U.S. registration number 2,830,001) of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, in the Dept. of Mechanical and Aeronautical Engineering at the University of California – Davis. The "TM" symbol will be omitted for the remainder of this document.

California at Berkeley (UCB), and the Western Transportation Institute (WTI) of Montana State University (MSU). The California State Department of Transportation (Caltrans) and its research partner, the Arizona DOT (ADOT), both provided test sites and snowplow operators. ADOT provided a four-mile test site north of Flagstaff as a substantial portion of its Phase-I effort; in addition, ADOT provided critical testing of the embedded magnet infrastructure, and the methods used to install these magnets and protect the highway infrastructure [19]. The California and Arizona DOT operators proved to be invaluable resources, not only for testing the system, but for providing input and guidance throughout the development phase as well. The efforts of this research team allowed deployment of ASP-I into Caltrans' maintenance fleet in just over half a year's time [42, 43]. Arizona's perspectives on the Phase I project can be found in the related ADOT report [19].

Researchers at the AHMCT Center, as well as our research partners at Caltrans, have long considered the benefits of providing guidance information and/or control to enhance winter maintenance activities. The ASP Driver Assistance System clearly demonstrates the near-term benefits of AVCSS technologies in general, and for winter maintenance in particular. The main goal of the on-going ASP program is to assist the snowplow operator in safely and efficiently performing snow removal. A subsidiary goal is the demonstration of the beneficial near-term application of AVCSS and IV technologies for maintenance operations. A guiding principle for the development of the ASP system has been the use of relatively low-cost, commercially available components, with lateral sensing provided by infrastructure-embedded elements for maximum reliability, and display imagery developed in a hardware-independent fashion to allow for future advances in display technology or cost reduction. The ASP-I system was tested successfully through the winter of 1998 – 1999 in both California and Arizona. After hardware and software improvements made during the beginning of the ASP-II project, the ASP Driver Assistance System was field-tested in Caltrans' Advanced Winter Maintenance Testbed (AWMT) on Interstate 80 near Donner Summit, during the 1999 - 2000 season. ASP-II was also tested for approximately three weeks at Arizona's test site on US 180 in Kendrick Park, near Flagstaff [19, 20]. Arizona testing during the prior phases, as well as for the current project, typically lasted three to five weeks each year. As part of ASP-II, ADOT added two additional lane-miles to their test site, yielding a complete six mile closed-loop.

Based on the accomplishments of the two phases of the ASP program, Caltrans has pursued detailed field-testing of three RoadView snowplows (an updated version of the original ASP, Caltrans C#7005, along with two new RoadView-equipped snowplows developed under the current project, Caltrans C#7228 and C#8467). The objectives of the RoadView project were:

- to further improve the design, robustness, and subsequent commercial viability of the RoadView component technologies,
- to develop two new RoadView-equipped snowplows, one for the existing Advanced Winter Maintenance Testbed at Kingvale, and one for the new Rural Winter Maintenance Testbed at Burney, California,
- to develop a detailed test plan and perform rural field-testing and data collection at Kingvale, Burney, and at Kendrick Park near Flagstaff, AZ, followed by system evaluation,

• and to provide a detailed cost-benefit analysis and a thorough needs-assessment with respect to RoadView technology across a wide spectrum of DOT organizations.

Prior to the RoadView phase of this program, the IVI Specialty Vehicle Partnership funded two concurrent studies investigating various approaches to enhance safety of snowplowing operations. The ASP-II study [43] (precursor to RoadView) used a cooperative vehicle-infrastructure system to provide high reliability and robustness for lateral vehicle position sensing. The Minnesota study used a GPS-based approach to provide lateral sensing, removing the need for additional roadway infrastructure. This approach does require a detailed, high-accuracy, GIS database for the roadway and surrounding infrastructure, a high-accuracy GPS receiver in the vehicle, and GPS base stations and radio links, including FCC licenses unless using spread spectrum, for differential corrections. With respect to collision warning, the ASP-II project provided full three-lane coverage with two-dimensional position sensing ahead of the vehicle, while the Minnesota study provided forward and rear collision warning augmented by GPS and GIS to reduce nuisance and false alarms [8]. Further details of the Minnesota study are available in the University of Minnesota final report.

The RoadView technical team consists of the AHMCT Research Center, the California PATH program, and the Western Transportation Institute. Caltrans is the lead organization on the study, and has provided test site infrastructure as well as input from snowplow operators and equipment personnel. Caltrans' partner in the pooled-fund study, the Arizona DOT, has provided a second rural test site, access to their snowplow operators, and valuable feedback on the operation of the system.

The RoadView system provides significant improvements over the state of the system as of the completion of the ASP Phase One study (ASP-I). Technical improvements include a complete update of the system electronics and the environmental enclosure. In addition, new radar mounting systems were designed to provide more flexibility with respect to manufacturer variations in vehicle hood and grille designs. The steering encoder mounting bracket was also redesigned to improve reliability and robustness. In addition, the magnetometer sensor enclosure and mount system was greatly improved, including addition of break-away mechanisms to protect this crucial sensing component from impact. Additional revisions were made to improve the operator interface and unify the presentation in the three test vehicles. Finally, a thorough redesign of the cabling system allowed much of the required cabling to be outsourced, saving significant development time and effort, while also enhancing the commercial viability of the RoadView system. We also improve the use of full two-dimensional radar information, along with lateral position data, yaw rate, and steering angle, enabling detailed false warning suppression. Additional improvements include augmented HMI display information and further robustness enhancements to the magnetic sensing system.

The research prototype vehicles have now been through four full winters of field-testing and operation. The first winter provided a proof-of-concept for the system (ASP-I), and indicated areas of the system that required redesign [42]. The ASP-II program addressed these issues, and the resulting system was tested through the winter of 1999 - 2000. Detailed data collection was performed through both winters [43]. However, the research team recognized the need for more detailed testing, data reduction, and analysis; the current project addressed this need, including

testing of the original ASP vehicle and two new RoadView ASP vehicles at three test sites over two additional winters.

Project Overview

The RoadView system functions include lane position indication, lane departure warning, and forward collision warning. Lane position indication and lane departure warning were developed by PATH using their embedded magnetic reference marker system for lateral position indication within the lane. Feasibility of this technology was shown at the National Automated Highway Systems Consortium (NAHSC) 1997 Demonstration; the technology is robust and well-suited for the current application. The Collision Warning System (CWS) was developed by AHMCT, using a millimeter wave radar system, which performs well in the snow environment; this system detects vehicles and other inorganic objects buried or obscured by snow. The ASP-I CWS was based on the Commercial-Off-The-Shelf (COTS) Eaton VORAD EVT-200 sensor, which provided range and rate to targets, and supported serial communication via the RS-232 standard. The ASP-II CWS (essentially the RoadView CWS) was vastly improved through use of a pair of front-mounted EVT-300 sensors, which provide higher quality range and rate information, in addition to azimuth angle to multiple targets. Dual radars allowed full coverage of three lanes ahead of the plow (useful when using left or right-mounted wingplow), and azimuth angle data allows the system to map detected obstacles to their lateral location, i.e. the system can inform the driver in which lane the obstacle is located. AHMCT and PATH jointly developed the Human-Machine Interface (HMI). AHMCT integrated all subsystems on the snowplow, including numerous improvements in hardware (sensor enclosures and mounts, cabling connections, and electronics enclosures), documented in detail in Chapter 3. The overall system architecture used for RoadView is based on an open architecture, so that other sensors and subsystems can be incorporated in the future. Caltrans provided the snowplow. One of the RoadView plows, re-deployed into operation in December 2000, can be seen in Figure 1-1, during testing in Arizona. The dual radar system can be seen mounted in front of the grille, above the snowplow blade.

Caltrans snowplow operators tested the system in storm conditions starting early in December 2000, and continued through the winter of 2001-2002. Feedback from the operators, one of the key contributions of this research effort, is discussed in Chapter 5. The Caltrans operators were involved with the design of the system, particularly the HMI, from early in the Phase One project. Arizona operators also tested the system for several weeks in February 2001 and February 2002, and also provided very helpful feedback. CA and AZ DOT operators and managers continue to provide valuable feedback, and the research team continues to improve the system based on these suggestions. The rapid deployment of this system into operation in a maintenance fleet represents an early success in the application of Intelligent Vehicle and AVCSS technologies for Specialty Vehicles.

In addition, in the development of the two new RoadView research prototype vehicles provided an opportunity for close and productive cooperation between the AHMCT research team and the Caltrans Equipment Service Center (EqSC). AHMCT performed significant hardware redesign during the development of the first new RoadView vehicle, including development of new cabling methods and outsourcing, along with significant efforts to provide the RoadView subsystems in a "kit" form, with an eye toward future commercialization. With

this effort, AHMCT then worked directly with Caltrans EqSC to support their integration of the component technologies for the second RoadView system. This effort included cooperative development of component and installation specifications, development of components by AHMCT and vendor sources, and complete component installations by EqSC. The success of this effort bodes well for the feasibility of a commercial vendor providing the RoadView system in a component form for subsequent vehicle manufacturer or DOT installation on standard snowplows. While much work remains in this area, the successful cooperation of AHMCT and EqSC in this key area represents a significant achievement in the RoadView project. The AHMCT team would like to thank EqSC for their support and cooperation in this effort.



Figure 1-1: ASP-II during Testing on US 180 near Flagstaff Arizona

System Cost

The cost for equipment and labor to develop the ASP prototype vehicle is estimated at approximately \$45,000. Based on foreseen revisions in hardware and installation approaches, the current estimate for a volume production unit is in the range of \$20,000 - \$25,000. These estimates do not include vendor profit margin, and represent the best current available estimates of material and labor only. Cost of infrastructure installation for the test sites was approximately \$18,000 per mile, including surveying, installation, and magnets. The cost is evenly divided between surveying and mechanical installation of the magnets. AHMCT concurrently conducted a technical feasibility study of automation of the mechanical installation process for the discrete magnets, including development of a prototype magnet installer [12]. With such a system, work crew reductions may be achieved. In one example installation, a work crew of eight performed the mechanical installation. With automation, the crew may be reduced to two, with both crew members safely contained within the support vehicle. Detailed investigation is needed regarding

equipment cost amortization, number of anticipated installations, manpower costs, automation production rate, and resulting lane closure time. As such, projections for cost reduction, if any, would be preliminary at this time.

Test Site Infrastructure

The RoadView systems were field-tested in Caltrans' Advanced Winter Maintenance Testbed (AWMT) on Interstate 80 near Donner Summit over the winters of 2000-2002. One of the RoadView vehicles was also tested for approximately three weeks in both February 2001 and 2002 at Arizona's test site on US 180 in Kendrick Park, near Flagstaff, Arizona. Magnets were installed at both sites in the summer of 1998 and 1999.

During the summer of 1998, Caltrans developed a test corridor for field-testing and demonstration of ASP-I, with additional installations in subsequent summer seasons. This AWMT, located on Interstate 80 (I-80) in Nevada County near Donner Summit, currently has approximately 22.5 km (14 miles, 7 miles in each direction) of lane two (three-lane Portland cement concrete (PCC) road) instrumented with the discrete magnetic marker system. The test track is at a high elevation (1,950 - 2,190 m, or 6,400 - 7,200 ft) and records large snow accumulations (as much as 16.5 m (54 ft) of snowfall a season with roadside accumulations reaching 6 m (20 ft) high). Whiteouts are common due to blowing wind and the sheer volume of snow. The approximate location of the magnet is as follows, when driving on the eastbound segment (westbound is approximately the same in reverse). The magnets begin at milepost (MP) Placer-69.2, just west of the Kingvale undercrossing. The first stretch of magnets is approximately 4.8 km (3.0 miles), and ends at MP Nev-2.5. This is followed by a stretch without magnets of approximately 4.2 km (2.6 miles). The magnets begin again at MP Nev-5.1 near the Castle Peak interchange, and continue for 6.4 km (4 mi) to the Donner Lake Interchange at MP Nev-9.1. The westbound Donner Lake to Castle Peak section is the original test section, installed as part of the ASP-I study. The remaining sections were installed as part of the ASP-II and RoadView studies. In this region, I-80 is a divided, restricted-access highway with three lanes in each direction, and wide shoulders. Donner Lake Interchange is about halfway up the northern slope of the Donner Lake valley, and Castle Peak is at the pass summit on the west end of the valley. The entire site is located in mountainous terrain, with steep grades and many curves. The location was selected because this portion of I-80 typically closes before other sections of the road due to weather patterns and has a relatively high vehicle per hour traffic count.

Arizona's test site, located on a stretch of US 180, consists of a two-lane undivided rural mountain asphalt concrete (AC) road, with frequent whiteouts due to high winds. This installation includes areas of relatively high curvature and steep grades, and provides a complete closed-loop rural test track. The site is approximately 9.7 km (6 miles) in length and located within Kendrick Park, about 32 km (20 miles) northwest of Flagstaff, Arizona. Approximately 6.5 km (4 miles) were installed in 1998, with the remaining 3.2 km (2 miles) installed to close the loop in 1999. This instrumented test-site is situated at roughly 2440 m (8000 ft) in elevation and runs northward from MP 235.0 to MP 238.0 and southward from MP 238.0 to MP 235.0. The northbound 4.8 km (3.0 mile) segment begins in forest, continues through an open, windswept valley and ends with a winding eight percent downgrade. The southbound 4.8 km (3.0 mile) segment reverses the course, closing the loop. This location receives frequent snowfall and is often exposed to winds of varying force, resulting in whiteout conditions and drifting. The

designated road segment is in a relatively high traffic area because it is the shortest route from Flagstaff to Grand Canyon National Park.

For the RoadView project, a key new California test site was added at Burney, east of Redding, California. The Burney test site, known as the Rural Winter Maintenance Testbed (RWMT), is located on State Route 299 (SR-299) which provides access to Burney and several other small mountain communities from the valley below. The site contains steep grades and relatively tight curves. The site consists of 8.0 km (5 miles) of rural two-lane undivided mountain AC roadway with magnets embedded in both the east and westbound lanes (16 km or 10 lane-miles of magnets). Within the test area the roadway passes over the Hatchet Mountain Summit at an elevation of 1330 m (4366 ft). During the winter months the test area receives frequent snowfall and is often shrouded in fog, resulting in poor visibility. Traveling to the west from Burney, the test site is located approximately 8.0 km (5 miles) west of the town of Burney, with magnets starting at MP 70.0, continuing over the Hatchet Mountain Summit at MP 68.2, and ending at MP 65.0.

Report Overview

The remainder of the report provides details of the RoadView system, subsystems, and testing. Particular emphasis and detail is provided for the field test results, as this was a key focus for the current project. As noted, the cost-benefit and needs assessment report by WTI is in a supplement to this final report.

Chapter 2 provides a more detailed overview of the RoadView system architecture, as well as preliminary details on the main subsystems, namely, the lateral positioning system, the collision warning system, and the human-machine interface. Subsequent chapters provide further detail of these subsystems.

Chapter 3 provides detailed information and photos of the hardware installation on RoadView. This includes the sensing systems for both lateral positioning and for obstacle detection. It also includes the in-cab display and controls. Finally, it includes the computing, power electronics, and miscellaneous support subsystems for the vehicle.

Chapter 4 documents the software architecture used in RoadView. The architecture is based on a set of independent processes that communicate through a shared database process. The system is based on the QNX Real-Time Operating System (RTOS).

Chapter 5 provides a detailed discussion of the RoadView Human-Machine Interface (HMI), as well as the key findings from the field tests. The HMI is the most critical aspect of the RoadView, as it is the one means of presenting the driver assistance information to the operator. The chapter discusses the requirements of the operation and the goals for the interface, ministudies used to develop the display imagery (including detailed testing results), and the display imagery itself. Some discussion of operator impressions is also provided, along with results from 2000-2002 testing, including data collected.

Chapter 6 discusses the magnetic sensing system. This system provides the lateral position information needed to show the operator the current vehicle position. In addition, as the system

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allows coding of roadway curvature, with the combination of a steering wheel encoder, the magnetic sensing can also provide critical predictor information to the operator, i.e. it provides a representation of both current and future vehicle location. The chapter provides an overview of the magnetic marker model, noise effects, and the sensing and signal processing algorithms used.

Chapter 7 discusses the radar system used in the Collision Warning System. This chapter provides a review of the sensing requirements, along with an overview of the COTS hardware used, i.e. the EVT-300 radar system. False warning suppression issues and techniques are also discussed, in particular with respect to improved suppression for cases where the snowplow is in one type of road (curved or straight) while an obstacle is in another.

Chapter 8 provides conclusions, lessons learned, and recommendations for future work. Appendix material provides more detailed documentation of survey material.

CHAPTER TWO: SYSTEM OVERVIEW

RoadView technology has been integrated onto three Caltrans snowplow vehicles. Under Phase I (ASP-I), the first generation technology was installed on a Caltrans nose/wing plow vehicle, based on an International Paystar 5000 platform. Under Phase II (ASP-II), many systems were updated for improved performance and robustness. In the current project, two additional Caltrans vehicles were instrumented with the current generation RoadView technology: an additional nose/wing plow vehicle, and a standard snowplow without wing. In addition, the original Advanced Snowplow vehicle was updated to the current generation of technology, resulting in three RoadView-equipped vehicles consistent with respect to hardware and software. This chapter provides a brief description of the main RoadView subsystems: the Lateral Sensing System, the Collision Warning System, and the Human-Machine Interface, all shown in Figure 2-1. Other support subsystems, e.g. computing and power, are discussed in detail in Chapter 3. The RoadView system software architecture is discussed in Chapter 4.



Figure 2-1: System Call-Out for the RoadView Advanced Snowplow, with Key Subsystems

Lateral Sensing

Snowplow operating conditions such as poor road delineation, obscured pavement, reduced visibility due to rain and snowstorm, low temperature, and mountainous roads are a significant factor in the choice of technologies for lateral sensing. There are several well-developed technologies for vehicle lateral guidance for AHS. They may be classified as vision-based, roadway reference system based, and radio wave signal-based methods. Vision-based systems are generally considered inappropriate in poor visibility conditions such as fog, rain, and particularly snow. GPS-based sensing is one form of radio method. As part of the current study, initial feasibility tests have been performed to determine whether a GPS-based approach is reliable in the rural mountainous environments considered in this study. A GPS base station has been established in the Donner test area, and initial GPS readings and radio link tests have been performed. Results for this work are too preliminary to support a conclusion at this time, and the researchers will continue this investigation under ongoing projects. The research team selected a roadway reference based approach, rather than autonomous sensing, such as a vision system, in order to provide the required sensing reliability and robustness [45].

Roadway reference systems include induction wires, radar-reflective tape, magnetic tape [11], and discrete reference markers [15]. Reference system elements may be passive or active. Example markers include magnets, colored paint marks, retroreflective raised pavement markers, and radar-reflective materials. Any optic-based marker detection system faces the same problem as any other vision-based system in a snow removal environment; as such, these systems are not feasible here. In addition, marker technologies at the pavement level or higher are subject to removal by the plowing operation. At Donner Summit, the painted lane markings are usually completely scraped off by the end of the winter season, often much more quickly. PATH experiments using embedded magnetic markers for lateral control have shown a maximum lateral sensing error of 1.5 cm with 1 cm standard deviation [24]. Similar results are documented in recent precision docking experiments [30]. This is well within the 3 cm requirement. Discrete magnetic markers embedded in the roadway can be used for longitudinal position measurement as well as lateral control. Moreover, magnetic markers can be coded with other roadway information by flipping polarities, which each vehicle can read via onboard magnetometers. Magnetic pavement marker tape has been shown to have similar performance [11] for lateral position measurement; however, at this time, it cannot be coded to provide roadway information, and the material appears to be quite expensive relative to magnets; however, installation costs are currently lower for magnetic tape, resulting in comparable overall cost. In addition, the discrete magnetic marker approach provides excellent accuracy, with lateral error generally less than 1.0 cm [30]. Regarding accuracy of the magnetic tape system [18], field tests of magnetic tape on a snowplow show "measured position relative to the actual position ranged from plus or minus six inches when the detector was centered on the tape to about one inch when the center of the detector was between one foot and 30 inches from the tape." However, according to [1], the combined magnetic tape and sensing system can achieve " ± 1 cm above the tape and ± 5 cm at ± 90 cm (± 2 in. at ± 3.1 ft.) from the center of the tape at speeds from 8-40 kph (5-25 mph) (validated in laboratory tests). Based on the maturity and robustness of the discrete magnetic marker technology, it was selected for use in the current study.

Under the ASP-I program, magnets were installed along a four-mile stretch of westbound Interstate 80 (I-80) near Donner Summit, in California. The magnets are installed in the center of
lane two of this three-lane stretch of divided road. This provides the sensing needed to guide the lead plow of a snowplow platoon or echelon formation during whiteout conditions, and in cases where the roadway is completely obscured by ground snow. Once the lead plow has made its pass along the roadway, the remaining plows can use its windrow (snowdrift) as a visual guide. During the summer of 1998, Arizona installed an additional test site on US 180 in Kendrick Park, north of Flagstaff, Arizona. This installation is along a rural, two-lane highway, with areas of relatively high curvature, and very high winds. Under the ASP-II and the current RoadView research projects, the Donner test site was extended in the westbound direction, and a matching stretch of eastbound I-80 was added. In addition, a rural test site (ten mile closed loop) was added on SR-299, a mainly two-lane asphalt concrete road near Burney, CA. This rural test site represented one of the major focuses of the field-testing for the RoadView project, and one of the two new RoadView-equipped vehicles was dedicated to this site.

RoadView plows are instrumented with an array of seven magnetometers located near the front axle of the vehicle. Three magnetometers on front are sufficient for an automatically steered vehicle, while five are deemed necessary with manual driving to allow for human error. In addition, operators often drive with an offset from lane center on the order of 0.6 m (2 ft), which leads to a need for an extra magnetometer on either end of the array, providing a total range of approximately ± 1 m, sufficient to support offset driving. At any given time, three magnetometers are considered active, and an algorithm decides when to shift the active magnetometers based on field strength. PATH has modified its existing sensing algorithms used for automatic vehicle control to meet the specific needs of the RoadView project, including revisions to support detailed data collection. The sensing system provides lateral measurement as well as an estimate of the vehicle's heading with respect to the road. Heading angle is output from a state estimator, based on the lateral measurement history (moving window), road curvature, steering angle, and a dynamic model of the snowplow. In addition, the binary coding in the magnets provides an index, with which the system can reference an on-board lookup table (or database) to determine milepost, landmark, and curvature information. With this combination of information, along with vehicle steering angle obtained from a steering wheel encoder, the system can display current as well as predicted vehicle location with respect to the road, as well as the upcoming curvature. The HMI that displays this information is discussed below, and in greater detail in Chapter 5. Further detail regarding the lateral sensing can be found in Chapter 6, as well as [46].

Collision Warning System

The adverse operating conditions expected in normal operation, including falling snow, snow coverage, and rain, impact the choice of sensing system for the RoadView Collision Warning System (CWS). Additional complications arise for obstacle detection due to road curvature in mountainous areas. Snowplows operating in the mountainous roads of California and Arizona, for example, face roads with high concentrations of varying curvature, which complicate obstacle detection methods.

There are many sensing methods capable of detecting roadway obstacles. The principle technologies used in current highway automation research include vision, ultrasonic, LIDAR / LASER radar, and millimeter wave (MMW) radar. Several of these technologies can be discounted immediately for the snow environment. Vision-based systems, as well as LIDAR

systems, depend on lighting and optical field-of-view, both of which are severely impeded during inclement weather conditions. Ultrasonic sensors are also inadequate in adverse weather conditions. Accuracy of distance measurement is affected not only by wind gusts, but also by rain and snow. Because the speed of sound differs in air, snow, and water, presence of snow or water will induce errors in the distance measurement.

The only viable systems that remain, then, are Laser- and Radar-based. Based on the severity of weather conditions for snowplow operation, including blowing snow from the snow removal operation itself, radar is the best choice. As laser radar operates in the optical range, it is still adversely affected by snow reflections. Calspan [3] concluded the following:

- MMW radar tends to be more robust in terms of weather than laser techniques,
- MMW radar allows for operation in fog, rain, and falling snow,
- and MMW radar was found to be 'very effective even in rain as heavy as 10 mm/hr'.

The radar system used in the RoadView testing was the Eaton VORAD EVT-300, operating at 24.725 GHz. Past experiments [28] show rain and snow do not significantly deteriorate MMW radar performance operating in this frequency range, even when sensors were covered with thick snow. This agrees with observations in the current project. MMW radar systems are sufficiently accurate for the required range, approximately 100 m, for collision detection and warning. MMW radar was tested in snow and near whiteout conditions in Japan, with the system providing sensing out to 110 m [14]. The biggest concern regarding MMW radar in the operating environment is the build-up of thick layers of ice on the radome. This was encountered during the first year's testing, and did adversely effect sensing. During the previous Phase II development, RoadView standard maintenance was expanded to include routine cleaning of the radome. No further problems occurred in Phase II or during RoadView field testing.

The harsh operating conditions of the snowplow environment demand a ruggedized solution for the CWS. Here, a commercially tested unit was preferred. The Eaton VORAD EVT-300 delivers the accuracy and range necessary for the current application, along with the necessary ruggedness demonstrated through testing of previous generations of radar antennas in commercial vehicle applications. This radar provides range, closing rate, azimuth angle, and quality factor for up to seven targets. In addition, through use of the RS-485 standard, the system can be easily interfaced with the industrial PC used for sensing I/O and processing. With these capabilities, this sensor met the robustness needs in a package that could be integrated onto the vehicle in a relatively short time. The EVT-300 also provides an integrated gyro to measure vehicle yaw rate, which has been incorporated into one version of an algorithm to reduce false alarms on curved sections of roadway, as discussed in Chapter 7.

The RoadView CWS is a forward CWS, with two antennas mounted symmetrically 0.4 m (1.3 ft) from vehicle centerline, on a specially designed fixture mounted behind the plow blade near the front of the hood. This CWS will alert the operator of obstacles in the direct path of the vehicle, as well as obstacles in lanes to the left and right. For snowplow operations, where a wingplow may be used on either the left or right side of the vehicle, projecting approximately one lane out from the vehicle, it is essential to provide obstacle detection and warning for the

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lanes adjacent to the plow. The use of two radar antennas provides this range of coverage, which also allows the system to detect oncoming traffic in two-lane rural operations, which is critically important in the test conditions found at Burney, Arizona, and similar rural sites. In addition, the availability of target azimuth data allows the system to determine the lateral location of obstacles, so that they can be presented to the operator in an intuitive manner; this information, combined with additional sensing and algorithms, greatly assists in reducing false warnings. The HMI presents information from the CWS in a single coordinated interface, as discussed below and in Chapter 5. Further information on the RoadView CWS can be found in Chapter 7.

Human-Machine Interface

From the standpoint of the snowplow operator, the Human-Machine Interface (HMI) represents the entire RoadView system. Methods of sensing vehicle position, obstacle detection, etc., are meaningless to the operator, who will only see the display and react accordingly. Thus, considerable thought was dedicated to the method of presenting this information. Early experiments verified the research team's expectation that the system must provide preview or prediction information to the operator. That is, with a look-down sensing system, it is necessary to project data forward so that the operator has an indication not only of where the vehicle is currently at, but where it is heading in the future. To support this, a steering shaft encoder was added to the system to allow prediction of the future vehicle path. In addition, providing upcoming curvature information allows the driver to determine an approximate steering angle, with the flexibility to make minor corrections to this nominal steering angle based on the current and future vehicle locations. The ability to provide prediction is a significant advantage of the magnetic marker-based approach over any strictly look-down (i.e. no prediction) approach, as demonstrated in [33]. In this reference, it was shown that driver performance without prediction exhibited excessive steering oscillations.

The research team investigated available hardware to provide the HMI display for the operator. Initial preference was for a Head-Up Display (HUD), so that any imagery could be presented in the operator's field-of-view, removing the need to look away from the roadway. However, several factors indicated a HUD or similar approach was less than ideal. First, commercially available HUDs that the team could locate did not integrate well into the existing snowplow cab. In fact, many present physical hazards to the operator, as the units must mount very near the operator's head, presenting significant danger in an accident. In addition, there are known perception problems with respect to HUDs, which can lead to misinformation and hazard [27, 35]. With these factors, as well as a preference for a low-cost system for future commercialization, the research team decided to use a Liquid Crystal Display (LCD) panel as the display for the HMI. A guiding principle for ASP system hardware been the use of relatively low-cost, commercially available components, with display imagery developed in a hardware-independent fashion to allow for future advances in display technology or cost reduction.

The LCD is mounted in the location of the vehicle's rear-view mirror; the snowplows used in this study do not have a rear-view mirror, as the rear window is completely obscured by standard snowplow equipment, including the spreader, toolbox, and mounting plates. This location keeps the display out of the way for normal operation, while providing an easy check for the operator in conditions of reduced visibility, e.g. during whiteout conditions. It is a very easy position for the driver to look at, as drivers are accustomed to glancing regularly at the rear-view mirror in a

normal vehicle. In addition, this area of the windshield is typically obscured by snow and ice that is not removed by the plow's wiper blades. The display is divided into two logical areas. The main region displays lateral driver assistance information, including a representation of the current and upcoming roadway curvature, as well as indicators of current and upcoming vehicle position. The left region displays distances to the closest obstacle for each of the three lanes, using a downward moving tape display, which also implicitly conveys rate information to the operator. This portion is for the forward CWS radar. The guiding principle for the display is to provide the necessary information to the operator without any unnecessary information clutter, and in a fashion that is relatively independent of the actual display hardware. The system must not distract from the operator's normal attention, and must be adaptable to future hardware developments. For a more detailed view of the HMI hardware in the snowplow cab, see Chapter 3. Further detail on the HMI and its development can be found in Chapter 5, and [26].

Current System Status

Two of the RoadView systems are based in Caltrans' Kingvale maintenance fleet on Interstate 80 near Donner Summit, while one is dedicated to the Burney maintenance yard on SR-299. Under the RoadView project, Caltrans operators used the plows on a regular basis through the winters of 2000-2002, sometimes continually for several days straight during periods of intense storm activity. Additional testing occurred in our partner state, Arizona, on US-180 near Flagstaff. Beyond the end of the RoadView project, AHMCT researchers are continuing to analyze and improve the performance of the system, as well as performing upgrades and preventive and responsive maintenance on the system. Analysis of data collected during the project appears in Chapter 5. Throughout all phases of the program, operator feedback has led to continuing improvements in system hardware as well as the HMI display, although the imagery was fixed throughout RoadView in order to maintain consistency in Human Factors testing. In its various incarnations, the RoadView system has now been tested for four winters on three vehicles, and has been subjected to heavy use under actual field conditions. This testing has provided a wealth of information regarding system robustness and ruggedization. This information clearly could not have been obtained from lab testing or limited field demonstrations. As discussed in Chapter 8, field-testing and deployment of the RoadView technologies continue at this time. In addition, these technologies are being applied in other winter maintenance systems, in particular, for full automation of a rotary snowplow.

CHAPTER THREE: ROADVIEW SYSTEM HARDWARE

The RoadView driver guidance system is composed of several tightly integrated subsystems. Commercial-off-the-shelf (COTS) items are employed whenever possible to reduce both development time and system cost. However, a few subsystems are custom designed and fabricated. The ASP may be segmented into six subsystems: computing unit, human-machine interface (HMI), sensing system, sensors interface electronics, power supply system, and diagnostic system. Nearly all components, except the sensors and the HMI, are located inside the weather-tight equipment enclosure.

There are three complete RoadView prototype systems installed on Caltrans snowplow numbers C7005, C7228, and C8467. The three implementations differ slightly due to the differences in the snowplows. The equipment box is located behind the truck battery box on the C7228 and C8467 snowplows as shown in Figure 3-1. The RoadView system evolved from the ASP-II system. Several components were modified to increase robustness and data recording capability. The overall RoadView system layout schematic is provided in Figure 3-2.



Figure 3-1: C7228 and C8467 Snowplow Equipment Location Layout Schematic



Figure 3-2: RoadView Snowplow Equipment Location Layout and Schematic

The computing unit consists of an industrial 6 slot computer chassis with a 6 slot PICMG bus passive backplane, a 12VDC computer power supply, an Intel Pentium III single board computer with BX chipset, build-in Intel 82559 network card and 256MB SDRAM, two National Instrument I/O cards (ATMIO-64E and PCTIO-10), a Connecttech Xtreme 104 4-port serial adapter, and a IBM Travelstar 10GB hard disk. Manufacturer documentation of product specifications and operating instructions are located in the appendix. The solid state hard drive may be used instead of the moving hard disk in the final system if research data is not logged during the system operation. In addition, a National Instruments AT-MIO-64E data acquisition board was used to read the analog signals from the magnetometers. Its digital I/O ports were used to read user inputs, such as the "simulation", "plow blade sensor", "LCD monitor", and "override" switches. Furthermore, a National Instrument PTIO-10 timer board was used to interface with the Hall-effect speed sensor on the vehicle transmission to determine the vehicle speed. In addition, its digital input ports were used to detect any magnetometer failures. The Xtreme 4 four-port serial adapter was added to communicate with the two Eaton VORAD radar systems. The steering wheel encoder is connected to the build-in serial port number 1. Most components were selected based on device driver support for the QNX RTOS. The two National Instrument board device drivers were written by PATH. Other device drivers are available either from QNX or the original manufacturer.



Figure 3-3: System Layout, including LCD Panel for HMI

The HMI system display, seen at the top of Figure 3-3, is a high-brightness (900nit) 6.4" LCD panel mounted inside the snowplow cab where the center rear view mirror would normally be. The HMI also includes five control switches located on the center console, illustrated in Figure 3-4: Switches location may vary slightly on different snowplows. There is the main power switch for the driver assistance system, the computing unit reset switch, the "simulation" switch, the LCD display power switch, and the "override" switch. The computing unit reset switch is a momentary switch with a red safety switch cover to prevent accidental activation. The main power should be left in the "ON" position so that the driver assistance system will come on whenever the snowplow ignition key is turned. In addition, a covered "simulation" switch is connected to digital I/O port 2 of the AT-MIO-64E board. The system goes into simulation mode for driver training or static system demonstration when the "simulation" switch is turned on before the system boot up. The HMI LCD panel, which displays the computer VGA signal, provides 640x480 resolution and a maximum brightness of 900 nit, and requires regulated +5.5 VDC and +12 VDC power input for the analog to digital board and +12 VDC for the backlight inverter board. The driver may adjust the brightness and contrast by turning a knob or pushing a button on the display. A custom enclosure was designed and fabricated to minimize interference with other controls. The mount location and hardware are shown at the bottom of Figure 3-4. The passenger display is strictly for debugging and demonstration purposes.



Figure 3-4: System Power and Reset Switches

The sensor system consists of an absolute encoder, two Eaton VORAD EVT-300 radar antennae, a series of seven magnetometers for magnetic marker detection, and a Hall-effect speed sensor. The absolute encoder, shown in Figure 3-5, measures the steering wheel position, used in predicting future vehicle position. It communicates with the computer through RS-232 serial port number 1 and provides steering wheel location at 10 Hz. The encoder has a resolution of 0.1 degree. The steering wheel resolution depends on the gear ratio between the steering wheel and the encoder. For the two new RoadView snowplows (C#7228 and C#8467), the gear ratio is 3:1, so that the encoder makes one complete turn for every three steering wheel turns, with resulting resolution of 0.3 steering wheel degrees per encoder count. For the original ASP, the gear ratio is 2.17. This parameter difference is accounted for in the encoder driver software.



Figure 3-5: Absolute Encoder for Steering Wheel Angle Sensing

In addition, the collision warning radar communicates with the computer via two RS-232 serial ports. Each EVT-300 V-Bus signal is converted to RS232 signal via a B&B Electronics 232SAER J1708-to-RS232 converter. Following Eaton VORAD instructions, attached in the appendix, the 232SAER converter was modified to specification. The two radars antennae are mounted in front of the radiator as shown in Figure 3-6. Two radars were used to detect objects in all three lanes (left, current occupied and right lane) ahead of the vehicle.



Figure 3-6: EVT-300 Dual Radar Mount

The magnetic marker sensor system consists of an array of seven magnetometers. The magnetometer bank is mounted behind the front wheels (see Figure 3-7). All magnetometers are designed for nominal 20 cm (8 in) height above the ground. Lowering the sensors would provide a better signal-to-noise ratio; however, the sensors must be high enough so that the rare-earth magnetic markers (used in bridge structures) will not saturate the sensors. The magnetometers are mounted 30 cm (11.8 in) apart laterally within each bank, and each has an operating range of \pm -15 cm (5.9 in) from the center of the sensor element. Therefore each bank of magnetometers yields a combined lateral sensing range of \pm -1.05 m (3.4 ft) from the center of the vehicle. The exceptionally large sensing range is required because snowplow operators often drive with up to a 0.6 m (2.0 ft) offset when driving in an echelon snowplow formation. The magnetometers are encased inside a custom designed and sealed 316 stainless steel enclosure to prevent water damage. The output and power cable was routed through a nickel-plated brass liquid-tight domestyle cord grip fitting mounted on the sealed enclosure. A custom steel magnetometer mount was designed to suspend the sensors in their proper locations. Each magnetometer output signal is connected to ATMIO-64E board after passing through a low-pass signal filter board.



Figure 3-7: Magnetometer Sensor Array

In addition, the pulse output from the Hall-effect speed sensor at the vehicle transmission is connected to the PTIO-10 sensor interface board through a speed signal interface board.

The sensor interface electronics provide signal conditioning for the analog sensor output, as well as, overload protection for digital Input to the AT-MIO-64E and PTIO-10 board. Two of the sensor interface boards, namely the speed sensor interface board and low-pass filter board were designed by PATH. They are located inside the equipment box near the computing unit.

Additionally, the digital I/O interface board was designed and built by AHMCT to prevent high voltage spikes from getting through to the ATMIO-64E board in the event of a short in the external wiring.

The magnetometer outputs are low-pass filtered with an effective bandwidth of 140 Hz and connected to the upper 48 A/D channels of the AT-MIO-64E. The anti-aliasing filter must be selected carefully, keeping in mind the intended application and sampling. The present cutoff is only marginally acceptable in the presence of low frequency interference.

In addition, the pulse output from the Hall-effect speed sensor at the vehicle transmission is connected to the PTIO-10 sensor interface board. And finally, four digital inputs are connected to the National Instrument ATMIO-64E digital input ports. Only one digital input, the simulation switch, is required for the final system. The other three digital inputs ("override", display, and plow-blade switches) are used for research purposes. Figures 3-8 through 3-10 show the interface boards.

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Figure 3-8: Low-Pass Filter Board, Top View



Figure 3-9: A Single Segment of Low-Pass Filter Board, Top View



Speed Sensor Interface Board: DB-9: Pin 1 is hi of speed input; 6 is lo; 4 is +5VDC power input; 9

Figure 3-10: Speed Sensor Interface Board

The power supply system provides voltage regulation, power supply conversion, power backup, and fuse protection for all components. This subsystem consists of a ACE980 power supply, two 9 VDC voltage regulator with filtering capacitors, two variable regulators with filtering capacitors, one backup battery, relays, and a fuse system. One 60 Amp-hr sealed gel lead-acid battery is used for the power backup. Battery backup may be eliminated if the system does not require operating for an extended period of time when the engine is off, i.e., it is only required for a research platform but is not needed for the final production unit. A customdesigned power system is required for the final production unit to further simplify the wiring. The total power system current draw is about 6 Amp at 12 VDC or 72 watt. The power distribution panel is shown in Figure 3-11.





Figure 3-11: RoadView Power Distribution Panel

Finally, the diagnostic package includes a video system and a laptop computer running the QNX 4.24 operating system. A Toshiba Tecra 740CDT laptop and Linksys EC2T PCMCIA (PC Card) network card were chosen based on QNX compatibility. The diagnostic laptop is not connected during normal operation, and is used only during software updates and system debugging. The video system includes a forward-looking color video camera, a B/W low-light "lip-stick" video camera to record the driver, a VGA-to-NTSC converter which converts the VGA computer display signal to NTSC video signal, a color quad processor which combines the three NTSC input signals into one NTSC output signal, a 4" LCD NTSC video monitor, and a Sony CCD-TRV95 8mm video recorder. The 4" LCD NTSC video monitor (shown in Figure 3-2) displays the VGA computer NTSC video signal to the snowplow passenger, supporting both system diagnosis and demonstration. However, it can be connected to any of the other three NTSC video signals as desired. In addition, the researcher may also choose to record any of the four NTSC video signals (forward-looking, driver response, computer display, or combined video) using the Sony 8mm recorder. Sample videos are available at <u>www.ahmct.ucdavis.edu</u>.

CHAPTER FOUR: SOFTWARE ARCHITECTURE

The RoadView software architecture is driven by the need for real-time operation. While a RoadView equipped snowplow is traveling at speeds up to 13.4 m/s (30 mph), the RoadView hardware and software are determining the vehicle's present location, predicting its future location, determining if there are obstacles in its path, and displaying all the information in real-time on a Human-Machine Interface (HMI) LCD screen. Because of the real-time nature of this operation and the volume of computations necessary to evaluate eleven magnetic markers per second and ten radar messages per second, it is essential that the different program processes do not interfere with each other.

To prevent interference problems the software architecture is divided into processes of varying priorities. The "process" concept as discussed in this chapter represents a collection of software subroutines, input from more than ten sensors and output to the LCD display. The system diagram in Figure 4-1 shows the processes and their interactions. The magnetic sensing software is given the highest priority. It senses the magnets embedded in the roadway via the magnetometers and determines the vehicle's present location and predicts its future location. The processes are ranked in priority according to the real-time needs of the system. The six processes listed in order of decreasing priority are:

- Magnetic Sensing Software Process
- Database Process
- Two Radar Driver Processes
- Radar Target Sorter Process
- Encoder Process
- Display Process

The priorities were determined based on the importance of the process in maintaining the essential functions of the RoadView system. Although the display is the end-goal of the system, if the underlying processes aren't functioning, the display's information is irrelevant. Therefore, though it may seem paradoxical to give the display the lowest priority, this results in the best information being displayed.

Magnetic Sensing System Process

The Magnetic Sensing System (MSS) process determines the vehicle's current position in the roadway and the vehicle's future location based on current vehicle and roadway data. The MSS determines the vehicle's position on the roadway using data from an array of magnetometers, devices that measure magnetic field strength, as described in Chapter 6. The magnetometer array contains seven magnetometers, evenly spaced and mounted in enclosures located under the vehicle, behind the fuel tanks.



Figure 4-1: System Processes

Magnets are embedded in the highway infrastructure in the center of the lane spaced 1.2 m apart. The magnetometers sense the magnets and send signal strength information to the computer. The MSS then determines the vehicle's position relative to the magnets by analyzing the field strength of the magnet on the seven magnetometers. The magnet's location will always be between the two magnetometers with the highest strength readings. The exact location of the vehicle over the magnets can be determined with very high accuracy based on this method. Chapter 6 provides the details of the magnet signal processing algorithm.

By varying the polarity of the magnets in the roadway (North vs. South pole) the magnets can represent binary code (ones and zeros). Information can then be coded into the roadway in much the same way as computers use binary serial data streams. This data stream provides an index, which in combination with a lookup table, provides the MSS with information such as, what the upcoming road curvature changes are, where the vehicle is on the roadway (which mile marker, which exit, etc.), and other location-specific information.

The MSS then uses the roadway curvature information provided by the coding, as well as the vehicle's current information (speed, local trajectory relative to the magnetic markers, steering angle, location on roadway) to predict the vehicle's position at a future location if it were to continue on the same trajectory. The prediction information is displayed on the in-vehicle display, dramatically improving the operator's ability to keep the vehicle on the desired path. The MSS process is shown in Figure 4-2.

The vehicle's current position information should be augmented with predictive information in controlling the vehicle or providing driver assistance. Consider that driving with only current position is like cutting a hole in the floorboard and attempting to drive by staring at the ground under the vehicle—obviously a very difficult task, and highly stressful. The purpose of the prediction information is to mimic the normal information people use when driving. People look at the road ahead and use their senses to estimate where their vehicle is heading. If they see a curve ahead and realize that their current trajectory would cause the vehicle to leave the lane, they compensate accordingly. The prediction information does exactly the same thing, showing the future location of the vehicle on the display based on the road curvature and steering input. The immediate feedback to steering input allows the operator to maintain the lane position without a significant increase in stress or skill requirements. This immediate feedback can be the difference between stable and unstable behavior, as has been demonstrated extensively in the literature [31].



Figure 4-2: Magnetic Sensing Software Process Diagram

Database Process

As noted above, to allow prioritization of functions, RoadView software is split into several processes that run simultaneously. A database process was created to coordinate the processes and share information. The database can be written to and read from as needed by each process. Three processes write information to the database, one just reads from it, and two others read and write. For any database variable, only one process is allowed to write data, thus assuring synchronization and data integrity.

Data is stored in the database using named variables. Processes access information for the desired variable, or write information to it. The processes write and read data at about 10 Hz. Simultaneous read/write problems are handled automatically and more than one process can access the database at the same time. The database process, including data flow information, is shown in Figure 4-3.

Using the database dramatically improves the performance of RoadView software. The database is very robust and not prone to stalling, unlike other forms of interprocess communications, such as pipes.



Figure 4-3: Database Process Diagram

Radar Driver Processes

There are two radar driver processes, one for the left side radar and one for the right side radar. Each driver reads range, azimuth, rate, and target ID data from an Eaton VORAD radar unit (EVT-300) for each target detected and uses that data to generate collision warning information. Data is read at 10 Hz and is processed if any targets are detected. The EVT-300 model radar can detect and track up to seven targets simultaneously. Thus a maximum of fourteen targets, seven from each radar, can be detected.

The radar driver process reads in target information from the serial port and extracts the data fields. Then all target information is stored in the database for use by the Radar Target Sorter Process. The radar driver process is depicted in Figure 4-4.



Figure 4-4: Radar Driver Process Diagram

Radar Target Sorter Process

The radar target sorter process sorts all target information from the radar driver processes and selects a maximum of three targets to send to the display process.

The radar target sorter process establishes virtual lanes in front of the vehicle, assuming it to be in the center of a lane, with a lane to the left and a lane to the right. Thus, any target detected in the center lane would be a collision candidate, while targets in the left or right lane would not. A target in the right lane would be a collision candidate if the wingplow were deployed. Clearly, the opposite is true for a plow equipped with a left-side wingplow.

Targets detected by the radar are first sorted by lane, then by longitudinal distance from the vehicle. The closest target in each lane is selected and sent to the database for use by the display software. The distance to each target in feet, as preferred by the snowplow operators, is sent to the database in three variables: left target, center target, and right target. These variables represent the three corresponding lanes, as described above. Even if there are multiple targets detected in one lane, only data about one target will be sent for each lane. The radar target sorter process is depicted in Figure 4-5.

Encoder Process

The encoder process reads information from an absolute encoder connected to the vehicle's steering column. The encoder sends a turn value from 0 to 3600 for a single turn of the encoder, or 0.1 degree per encoder count. The steering wheel resolution depends on the gear ratio between the steering wheel and the encoder. For the two new RoadView snowplows (C#7228 and

C#8467), the gear ratio is 3:1, so that the encoder makes one complete turn for every three steering wheel turns, with resulting resolution of 0.3 steering wheel degrees per encoder count. For the original ASP (C#7005), the gear ratio is 2.17, with resulting resolution 0.217 steering wheel degrees per encoder count. The encoder process converts from the encoder count to the vehicle's steering wheel angle and outputs the vehicle's current steering wheel angle to the database.



Figure 4-5: Radar Target Sorter Process Diagram

The database steering wheel angle is updated regularly, and is used by the MSS to predict the vehicle's future location, a key aspect of the lateral assistance portion of the HMI. The encoder process is shown in Figure 4-6.

Display Process

The display process creates a user-interface display based on the information generated by the radar and MSS processes. As shown in Figure 4-7, the display process presents radar information in the left panel of the screen, and provides MSS-derived roadway information in the main portion of the screen. A more detailed screen layout is provided in Chapter 5.

As an example, in Figure 4-7 the radar shows two targets represented by bars or "tapes." These targets are separated by "virtual lane." Virtual lanes are predefined strips of road to the right, straight ahead and to the left of the vehicle. They do not necessarily match the road lanes. The amber colored bar represents the closest object detected to the right of the vehicle. The yellow bar represents the closest object detected straight ahead of the vehicle. According to the radar there is no object detected in the left lane at this time. The horizontal bar on the bottom represents a distance of zero feet and can be considered the vehicle's front end. Logically, the longer a bar, the closer it is to the snowplow's front end. The number under the horizontal bar represents the 10 m detection range of the Eaton VORAD radar. The tick marks to the side conveniently divide this into 75, 50 and 25 m distances. As a target approaches the color

of a bar will change from yellow (low priority) to amber (medium priority) to red (highest priority). This process implicitly provides approach rate information to the operator.







Figure 4-7: Simplified Example of the In-Vehicle Display.

The virtual lanes have been created to allow classification of potentially dangerous objects; objects in the left or right lane have to be monitored because they might change into collision object at any moment, they may pass very close to the vehicle or may hit a deployed wing plow. The middle lane objects are in the vehicles head-on trajectory and may collide with the vehicle if

not dealt with. By default these lanes are straight strips of radar-covered area directed straight before the vehicle. This causes discrepancies with the actual road lanes in cases like a road curve.

To minimize unnecessary target detection, road information is used to adjust the virtual lanes (radar's field of view) to the actual road lanes. This enhancement, called False Warning Suppression Software, greatly decreases the number of targets displayed that are in reality beside the road. It must be noted that it is reliant on magnet code and therefore will not function when the vehicle is not over magnets. Other versions independent of the magnet sensing have been investigated, and work well when the vehicle is not near a curvature transition point; however, these versions are not included in the RoadView implementation.

The right panel of the display, majority of the screen, provides lateral position and roadway geometry information. The tick marks at the top and bottom of the lane represent offsets, based on the need for up to a 0.6 m (2 ft) offset from lane centerline during normal plowing operations. The vertical curves represent the upcoming roadway curvature. The horizontal bar at the bottom of the display represents the current plow position, while the smaller horizontal bar at the top of the display predicts the vehicle position twenty meters ahead (the "predictor"). Further details of the HMI display are provided in Chapter 5. The display process diagram is shown in Figure 4-8.



Figure 4-8: Display Process Diagram

CHAPTER FIVE: EVALUATION OF OPERATOR ASSESSMENTS AND FIELD-TEST DATA

Introduction

The RoadView Human Machine Interface has been developed through an iterative design process, beginning with ASP-I, continuing through ASP-II, and concluding with RoadView. The design goals of the HMI are to allow drivers to:

- Acquire vehicle lateral information at a glance and
- Switch between normal and guidance-assisted driving at ease.

The goal of this portion of the RoadView testing was to further evaluate the current HMI and to provide suggestions for future display refinements. Prior iterations of the HMI have been tested and improved in ASP-I and ASP-II through analysis of both driver feedback and performance. This chapter will firstly describe the RoadView HMI, then discuss and compare evaluations of the current display with those from ASP-II. Then the chapter concludes with some specific recommendations for future iterations of the HMI.

Current HMI

The HMI display contains two major components, a forward collision warning system (CWS) and a lane-keeping system. The left-hand section of the HMI display contains CWS information derived from MMW radar data (Figure 5-1). Downward-moving tapes indicate the distance to each of the forward targets. Distance rather than time was used as a metric due to operator requests and the fact that distance is a more valuable metric at slow speeds. Tapes were chosen as they mimic the forward approach of obstacles. The tape changed from yellow, to orange, and then red as the target approached. The three tapes place targets in their matching lateral position (left, center, right) with respect to the plow, improving detection accuracy, and reporting the distance to the closest target in feet.

To reduce the likelihood that drivers would integrate the collision warning display with the shorter distance lateral display, a line is used to divide the sections (Figure 5-1). A major component of the lateral assistance display is the prediction feature. The marker shows the future lateral position 20 m ahead corresponding to the magnitude and direction of the steering wheel angle. When the steering wheel is turned left, the prediction marker moves left. The current lateral position of the truck is shown at the bottom of the display. The graphics represent a displayed longitudinal distance of 20 m with a 2 m width between the "curbs." Road lines are computed using an internal map database of road curvature and heading angle. The map database is indexed based on code from the roadway magnets. Drivers can steer by positioning the predictor at any desired "future" location.

The center tick marks indicate the center of the lane, while the exterior tick marks indicate 0.6 m (2 ft) offsets. Offsets are used during certain plowing formations and are often used intentionally by snowplow drivers of other agencies [16]. Under normal conditions the lateral assistance lines are white and the current and prediction markers are red. If the computer is

uncertain of its current longitudinal position on the track, but is detecting position markers (magnets), the whole lateral display turns yellow and the display depicts a straight road. This signals to the driver that the display should not be completely trusted. If the plow leaves the magnets, the road changes to gray and freezes with a yellow arrow pointing back towards the lane center. This arrow is placed over the lane boundary that is crossed. After a short time off the magnets, the lateral display blanks out. Besides color changes and the yellow arrow, no lane departure warning is issued.



Figure 5-1: HMI Characteristics

Road segment names are displayed below the lateral imagery. These are the local names (i.e. nicknames) used by the drivers for specific curves and stretches of road. Names were associated through software along with specific longitudinal locations within the magnetic marker internal map. In addition, milepost numbers are provided on the top left portion of the display.

A flat panel display with an easy to operate brightness knob, an on/off switch, contrast control buttons, and a darker black background (similar features are also suggested in [16]) is used to display the information. The display is mounted where a rear-view mirror would normally be located (Figure 5-2). The plow is not equipped with a rear-view mirror 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 the HMI is now mounted on a double ball-joint mount, allowing the drivers to easily adjust the orientation and position of the display.



Figure 5-2: HMI and Other Equipment Positioning

In addition to the HMI a forward camera is mounted on a double-ball joint. This mount allows the camera to be easily lowered into a storage position. The lens cap was left on the camera unless data collection was in progress. A driver-facing, low-light camera in the upperright quadrant of the HMI housing was typically covered with black tape. Video output can be recorded on a small, handheld digital video recorder (which was removed from the plow when data was not being collected).

For more detailed descriptions of the RoadView ASP HMI design process from a human factors and control point-of-view, see [26, 27, 33].

Summary of Human Factors Assessments

The iterative design process used in the development of the HMI involved the following information collection activities: driver surveys, on road driver performance data, and driver interviews. The breakdown of each of these information collection activities can be found in Table 5-1. The surveys used for each year (see Appendix A) contained a core set of questions with additional questions added each season. Unfortunately, as there was no snow during the Arizona (Flagstaff) 2002 testing no on-road "in plowing conditions" data was collected for the RoadView evaluations. The Arizona test period lasted six weeks at the end of which a human factors researcher went to Arizona and collected some fair-weather night-time (i.e. low visibility) driving data to further evaluate the system performance and gather feedback from the drivers. The fair-weather driving data is reported here.

	Survey	Interview	Driver Performance Data	
Arizona 99/00	\checkmark		\checkmark	
Arizona 00/01	\checkmark			
Arizona 01/02	\checkmark			
Kingvale 99/00				
Kingvale 00/01				
Kingvale 01/02				
Burney 01/02				

 Table 5-1: Summary of Human Factors Assessments

Driver Experience with RoadView

The drivers in Arizona experienced the RoadView equipped plow for a short period of time (approximately 6 weeks) during February/March each year on a plow that was transported from Kingvale (California). As Arizona typically experiences large snow accumulations during February, the system was tested at Kendrick Park during February 2000, 2001 and 2002 However, during these periods Arizona had little significant snowfall. Drivers in Kingvale experienced the system on two plows that were based at Kingvale. One of the plows at Kingvale was developed with driver feedback through ASP I and ASP II. The second plow was developed during the RoadView project. Drivers in Burney experienced the system on a third plow that was based at Burney over the 2001/2002 winter.

Arizona Driver Training

2000

A member of the PATH development team trained the team leaders by explaining the system to them on a ride along. In addition, members of the development team rode along with the team leaders to test the equipment and answer any questions that arose. The team leaders then trained other drivers on the plow. The drivers received differing levels of hands-on driver training on the plow due to operational constraints. At the end of each training session drivers were asked to complete a survey prepared by the human factors team member.

2001

As the system had radar and steering wheel encoder problems it was not operating for a number of days when it was in Arizona. No training was given to the drivers (though some of the

drivers had experienced the system the previous year). The team leaders trained drivers and at the end of each training session, drivers were asked to complete a survey on the plow. In the 2001/2002 Arizona testing it was discovered that drivers were trained to drive from the snowplow current lateral position indicator on the display instead of from the predictor position (and this is noteworthy because the system is easier to use when driving from the predictor). The drivers said that they were trained to look at this part of the display in the 2000/2001 season.

2002

Training was given by a PATH development team member to two team leaders. The team leaders then gave training to the rest of the drivers, with different drivers receiving differing amounts of hands-on training due to operational constraints. At the end of each training session drivers were asked to complete a survey. Most of the drivers were trained on both the RoadView and the ADOT-3M advanced snowplow² on the same day, experiencing one system in the morning and the other in the afternoon. On-road driver testing occurred at the end of the six week period. A summary of the on-road testing is given at the end of this chapter.

California Driver Training

A member of the PATH development team trained team leaders by explaining the system to them on a ride along. In addition, members of the development team rode along with the team leaders to test the equipment and answer any questions that arose. Team leaders then trained other team members on an as needed basis.

Survey Feedback

To provide comparison, Arizona driver responses for the 1999/2000 ASP-II evaluation have been included in the analysis. Along with the Arizona drivers' responses, California driver information has been added for the 2001/2002 year. The California data comes from three drivers experienced with driving the RoadView plow: two drivers from Burney with one season experience with the RoadView and a third driver from Kingvale with three seasons experience who participated heavily in the design of the HMI. The feedback from the Arizona drivers should be considered feedback from drivers new to the system (although some drivers had used the system over multiple years, there had been very little snow accumulation to experience the system working in the conditions that it is designed for). The feedback from the Burney drivers should be considered semi-experienced as the drivers had operated the system for one season, in some extreme weather conditions (though unfortunately the system was broken during their worst storms). The feedback from the Kingvale driver should be considered to be from an experienced RoadView driver as the driver has been working with the development team since the beginning of the project and has used the system in a wide variety of weather conditions.

²ADOT purchased a 3M (Minnesota Mining and Manufacturing Co.) advanced snowplow for evaluation. The 3M version is based on continuous magnetic marking tape.

It should be noted that since the drivers experienced the system on their local sections of road, that is, local to Flagstaff, Kingvale and Burney, they experienced the system under different operating conditions. The section of road in Arizona is six miles of a two-lane undivided highway at 7000 ft elevation, with thirteen curves of which the sharpest has a 278 m radius of curvature. At Burney the section of road consists of ten miles of undivided lanes at 4366 ft elevation, with fourteen curves , the sharpest having a 213 m radius of curvature. The Kingvale section of road is 10.9 miles, which includes two separate sections of two- to three-lane divided highway at 7239 ft elevation, with six curves and a sharpest radius of curvature of 457 m.

Table 5-2 below gives the mean amount of experience for both plow driving and RoadView driving, and number of drivers who completed the survey each year.

	Arizona 99/00		Arizona 00/01		Arizona 01/02		Burney-Kingvale 01/02	
	Mean response	# of Drivers	Mean response	# of Drivers	Mean response	# of Drivers	Mean response	# of Drivers
Experience (years)	6.43	15	8.75	20	7.8	27	13.3	3
Time on RoadView	1.8 (hours)	10	2.91 (hours)	14	1.5 (hours)	27	1.67 (seasons)	3

Table 5-2: Driver Plow Experience

Discussion of Drivers' Responses to the Survey Questions.

Drivers' responses to: "How easy is the system to use overall?"

Figure 5-3 indicates that the more experienced RoadView drivers from Kingvale and Burney after three and one seasons use (respectively) consistently (all three drivers gave the same rating) rated the system higher on the "easy-to-use" scale. This indicates that ratings increase with more experience on the system. One reason for the slight decreases in ratings from the Arizona drivers may be that in the 2000/2001 and the 2001/2002 seasons the drivers were introduced to both the ADOT-3M and the RoadView plows. In the 2001/2002 season drivers were introduced to the two plows in the same day which may have lead to the drivers feeling "information overloaded", the Arizona drivers also noted that it was hard to evaluate a system without seeing it in working conditions. In addition the Arizona drivers experience the plow for less time (as is shown in Table 5-2) in the 2001/2002 season than in other years.



Figure 5-3: Drivers' Mean and Range of Responses to: "How easy is the system to use overall?"

Drivers' responses to: "How much do you like the system overall?"

Drivers' responses to the question: "How much do you like the system overall?" remained reasonably constant as is depicted in Figure 5-4. This component is discussed in greater detail in the analysis of Figures 5-8 and 5-9. It should be noted that the drivers' responses to this question were mainly positive.



Figure 5-4: Drivers' Mean and Range of Responses to: "How much do you like the system overall?"

Drivers' responses to: "Would you like the system more if you had more experience with it?"

Figure 5.5 suggests that the Arizona drivers' responses to this question have remained consistently high over the three years indicating that they would prefer more experience with the system. The combined Burney and Kingvale responses clearly indicate that the drivers feel that one season is long enough to fully evaluate the system.



Figure 5-5: Drivers' Mean and Range of Responses to: "Would you like the system more if you had more experience with it?"





Drivers' responses to: "Please rate the system in terms of its ability to increase the efficiency of snow removal tasks."

Drivers consistently rated the system highly for "ability to increase the efficiency of snow removal".

Drivers' responses to: "How much do you like and how easy to use are the lane keeping and collision warning components?"

The ease of use questions as are shown in Figures 5-7 and 5-9 suggest that on the whole drivers find the Lane Keeping Component slightly easier to use than the Collision Warning Component. Of note was that the "longer term RoadView drivers" (Burney & Kingvale) had one of the largest ranges of responses for how much do you like the collision warning component. In discussion with the longer term drivers it became apparent that the Burney drivers (after one season of use) were dissatisfied with the collision warning system as they felt that it picked up too many false targets. In comparison the driver from Kingvale (who had been involved in the development of the system) rated this component high because he had "adapted" to the systems false alarms. The driver had determined that in certain areas he could trust the collision warning component more than in others, so had "adapted" to trust it more in certain geographical locations than others. Another reason for the higher ratings from the Kingvale driver is that the system is used on both less curves as well as less tight curves, as compared to either Burney or Arizona - situations that provide more false detections in the collision warning system.



Figure 5-7: Drivers' Mean and Range of responses to: "How easy is the collision warning component to use?"



Figure 5-8: Drivers' Mean and Range of responses to: "How much do you like the collision warning component?"

The small range of responses, overall high rating and discussion with the Burney and Kingvale drivers for the questions relating to like and ease of use for the lane keeping component (see Figures 5-9 and 5-10) suggests that with increased use drivers liked the lane-keeping component more, with one Burney driver describing this component as "flawless".



Figure 5-9: Drivers' Mean and Range of response to: "How much do you like the lane keeping component?"



Figure 5-10: Drivers' Mean and Range of responses to: "How easy is the lane keeping component to use?"



Figure 5-11: Comparison of Estimated Time for Comfort

Drivers responses to: "Amount of time they estimate it would take them to get comfortable with the system."

Figure 5-11 shows the amount of time drivers estimate it would take to become comfortable with the system each year. As can be seen in the graph the highest percentage of drivers for each year (with the exception of Arizona 2000/2001) suggests 1-3 days. The highest percentage of drivers for the Arizona 2000/2001 season felt it would take 2-6 months. The big jump in time for the Arizona 2000/2001 may be due to inadequate training being given to the drivers in 2001. It is unknown what effect repeat drivers from each year had on answers as repeat drivers were not tracked year to year. It should also be noted that where drivers used the term "storms" these were converted into one storm being one day. However, it is possible that some of the drivers interpret a storm to last more than one day.

Additional Survey Questions 2001/20002

In addition to the same core questions asked in previous years a number of additional questions were asked in the Arizona 2001/2002 and Burney-Kingvale 2001/2002 questionnaires. The first question as is shown in Table 5-3 looks at how drivers would explain the system to other drivers. The answers suggest that the drivers come away with both a positive impression and a clear understanding of the main goals of the system.

Table 5-3: Drivers' Response to: "Please describe the system and how it works the way that you would to another plow driver that has not yet seen or used the system."

"Tells you where you are at on the roadway gives mm and location in which you are at visual is go on the computer screen"

"This system show the position in lane also warns of on coming traffic, this is good in fog or white out conditions"

"Its work with sensors off hwy from 235 to 238"

"It is a lateral lane display like a video game and a forward obstacle screen. Nice set up"

"Is a (guide) on road way, to keep you on the road when visibility is low "

"The system tracks on the display front and back of truck, central line middle of lane. When the visibility poor to zero you know where you are"

"It tells you where your location is on the roadway. The white line on the road way curves."

"Lets him get good feel of the place of where he is plowing. To know the system and it would be a real good asset for a white out"

"It tells you where you are on the road"

"This system requires you to take off the road (presume eyes off the road) and watch a screen to keep you on the road and away from oncoming traffic. It takes a while but not that hard to do but you need to trust the system"

"It works good, show cars going by you and it shows edge of the lane from the middle yellow line and the edge of the road on right hand. It will help a lot, when there is white out snow storm"

"That it senses the trucks position in the lane – useful in poor conditions!"

"The system work off magnet placed in roadway – screen inside cab picks this up. The screen shows the vehicle and your steering. The objective is to drive with the screen only"

"Its pretty easy to use not complicated at all after the instructor showed me how to use it and were I to be it was easy to read"

"It work good but we (some specifics?) and get used to the truck, how it work ASP"

"Very simple, easy to use screens, keeps you on the road, for our roads it would be a great benefit due to mostly two lane roads with a lot of traffic

Note: this system was much easier to use than the 3M"

"Seems like will beneficial to everybody if you get familiar with the system"

"Try to keep truck in center"

"This system is a good concept for plowing snow, however it takes some time to know the system"

"This is so simple I would say just do it because it explains itself "

"It's a nice ASP system, for future snow storm w/ADOT"

"The system is an aid for referencing the lanes, centerline, and orienting your position on the traveled way by use of landmarks and post miles. The radar system picks up too much to distinguish obstacles that are vehicles as opposed to stationary objects."

"I would describe it as a visual aid and caution them to not rely on only the display. You must still try to see out the windshield whenever possible."

"The system is a tool to enhance safety for the traveling public, safety for plow operators, less damage to equipment. The system in layman terms is a guidance system using magnets imbedded in the roadway in certain areas with B and with B/ The truck has an onboard computer and visual screen that displays truck position over magnets or center of lane in periods of low visibility where plowing snow. Also, screen displays a radar proximity to the plow, distances are displayed as plow progresses or other vehicles move in front of plow and right, left sides to the front."

Drivers' Responses to: "Did the system ever lead you to make an inappropriate maneuver or error in judgment? (If so please describe)"

Two Arizona drivers reported that the system led them to make an inappropriate maneuver. The first driver did not give any further details as to what caused the error. The human factors researcher was able to talk with the second driver who indicated that when off the magnets he moved in the wrong direction. This driver said that after he realized he had gone the wrong way he quickly adjusted to the system. The driver said that he was more used to the ADOT-3M display, which worked differently, leading to the error. The human factors researcher looked at both the ADOT-3M display and the RoadView and could not determine any display learning that would account for this. Both systems indicate that the driver needs to move over from the side of the display that they need to move away from.

Display Usage

As was mentioned previously under the Arizona driver training section it was discovered that drivers were trained to drive from the snowplow current lateral position indication on the display in 2001. During the 2001/2002 testing the human factors researcher asked three drivers who were using the current plow position to navigate using the predictor. Afterwards, the drivers were asked about the difference. All three drivers felt that it was "easier" to drive with the predictor. One driver commented that he did not get disorientated when driving in the curves when he drove with the predictor (the predictor displays the plow position 20 meters ahead).

In addition to the Arizona drivers using the current plow position to navigate from in interviews with the California drivers it was found that one of the drivers also uses the current plow position to navigate. When the California driver was asked whether he had tried using the predictor, the driver explained that while plowing, he monitors the white line behind him in one of the mirrors (thus driving more from the current plow position than from using any form of prediction). His response taken in conjunction with the Arizona drivers also navigating from this part of the display suggests that driving with the predictor is not intuitive.

Miscellaneous Comments

Many of the comments on the systems centered on two main areas: The radar performance and the lack of magnets in the roadway. Drivers commented that it was frustrating not to be able to use the system in the worst condition areas because of a lack of magnets. Each driver had one to two areas each that they felt needed magnets more than the areas that had magnets. Drivers
commented that it was sometimes difficult to convince new drivers to use the system because it could not be used in the worst areas. With regards to the radar, drivers' comments were summed up by one driver who said "that the guidance part was flawless" but that "they didn't have much confidence in the radar". Specific comments from drivers most dissatisfied with the collision warning component included inconsistency in what/if/when objects were detected. Ongoing research and new algorithms were implemented in the 2000/2001 and the 2001/2002 seasons though these do not appear to have increased overall operator acceptance. In order to further investigate drivers' comments on the collision warning system further analysis on the warnings is given below.

Number of drivers	Comments
1	Right hand side border for width reference (an indication of road edge information) as not to hit curb, one Burney driver noted that there are a couple of places where if the plow is over the magnets and the wingplow is extended the wing would hit the embankment on the side of the road. They also mentioned that they would like to know about road signs for the same reason.
2	Move(display) to better more central location
1	"The display layout is ok as it is- get wires, cords, cleaned up on desk. The display format is fine, location is fine, maybe smaller dimension."
	"Maybe a heads up display projected on windshield fully adjustable for operator ease and unobtrusive. The cab is cramped and full of sharp edges. Cords, wire looms, can be cleaned up some on dash. Front view and controls has to stay as uncluttered as possible. Some stuff, panels, etc. impede movement on controls. Sometimes a quick reaction on plow lever is required to avoid something usually traveling out of control or on foot."
2	"Addition of a vibrating seat" (to give an indication of lane-keeping)
1	"Sound should be added"
1	"A set up where you could see the snowplow itself"
1	"Add oncoming hazard lights"
2	Amongst the Burney drivers there was some discussion over the addition of section names, one of the night drivers preferred that the name came up at the exact landmark and not be one section name to the next whereas the day driver felt that the section name changing for each section was appropriate. Opinion on this convention varied driver to driver.

Table 5-4: Drivers	' Response to:	"Questions	relating to rec	ommended	display	changes."
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Radar Analysis

To empirically determine the performance of the radar system, the forward view and the display content were recorded, while time-correlated system data was simultaneously saved to a file. In total, 46 nighttime runs (24 southbound, 22 northbound) were made with a total drive time over magnets of 3 hours and 20 minutes (approximately 4 min. 21 sec. per run). A run is defined to start when the magnet state first transitions to valid, and end when the "end magnets" message appears on the screen. As the radar system is designed to perform based on low to zerovisibility (i.e. whiteout) conditions, testing was conducted during nighttime to have conditions approximating whiteout to the extent possible, given that no snow was falling during testing. The radar software deliberately filters out targets that have a closing rate above a set threshold. Cars typically drive slower during nighttime, so that smaller error is introduced with respect to target vehicle approach speed. For the 2002 testing in Arizona wherein this data was collected, the test track is a two lane road and the wingplow was not deployed, so that warnings for the right lane were turned off and are not considered for this analysis. Note that some daylight tests were also performed—a comparable analysis including the combined daylight and nighttime test data is included in Appendix B. A summary of the analysis and performance is provided in Table 5-5, while the details of the procedure and results follow. All data analyzed in this section was recorded during 2002 Arizona testing.

Overview of the Analysis Procedure

In the description of the radar analysis, "left lane" refers to the left-most tape in the display, "center lane" is the middle tape, and "right lane" is the right tape, as discussed previously relative to the HMI. The footage was analyzed for "events" and two types were recognized: "car events" and "false events." A "car event" was counted for each object recognized as on the road. These were without exception all cars, either oncoming or passing (hence "car events"). Some car events were dismissed if they occurred at a road widening or if an oncoming car was closely trailing another. For the remaining valid car events, three different actions of the radar system were recognized:

Total driving time reviewed	200 minutes
Correct Detection Rate	73% (60 of 82 cars)
Missed Detection Rate	17% (14 of 82 cars)
Oncoming car in center lane	10% (8 of 82 cars)
Total False Events	51
Ave. Time Between False Event	235 (2 min 55 sec)
Ave. Time Between False Event w/o 235.3	600 (10 min)

 Table 5-5: Summary of Radar Performance in AZ

• Correct detection: an oncoming car is shown on screen in the left lane, or a passing car is shown on screen in the left lane and/or center lane respectively,

- No detection: a car event occurred (in the video), but no on-screen warning appeared,
- Erroneous detection: an oncoming car event occurred (in video) and was detected, but at any time the warning appeared in the center lane instead of the left lane.

A "false event" was counted every time there was a warning seen on the display without any valid corresponding target on the road ahead. Many of the false warnings were recognized to be due to a few obstacles close to the road in certain locations. It is important to know how often these false warnings occur, as provided in a table below.

General Event Rules

- Only time and evaluate footage during valid magnet time.
- Events happening during invalid magnet state are dismissed.

False Event Scoring Rules

- For every false event: 1 false warning.
- For false events happening simultaneously or near so: count as one event.

Car Event Scoring Rules

- For a passing car detected in left lane and center lane respectively: 1 correct detection.
- For a passing car detected in center lane or left lane only: 1 correct detection.
- For an oncoming car detected in left lane: 1 correct detection.
- For an oncoming car undetected: 1 missed detection.
- For an undetected oncoming car at wide road locations: dismiss event, i.e. not a valid event.
- For a closely trailing oncoming car: treat as a single event with preceding car.
- For an oncoming car appearing in center lane: 1 erroneous detection (misrepresented on screen).

Analysis Results – Car Events in AZ

In total 90 car events were counted. Table 5-6 provides location, curvature, and direction of travel, and event count for each milepost. There were significantly more oncoming cars while driving north. In general, car events are reasonably spread out over the track. Of the 90 car events, 8 were dismissed because the car was trailing another closely (so a combined single event) or passing at a road widening (so not a valid event). Of the 82 valid car events 60 were correctly detected (73%), 14 were undetected (17%) and 8 were incorrectly represented on the

screen (10%). Within the valid events, a total 29 car events occurred in curves, while 53 were on straight sections.

Section	Mile-post	Road Curvature	all cars	North	South
	235.0	straight	2	2	0
	235.1	straight	1	0	1
Hart Prairie Curve	235.2	Right/Straight	1	1	0
	235.3	Left/Straight/Right	3	2	1
	235.4	Left/Right	1	1	0
	235.5	Straight/Right	3	3	0
Kendrick Park	235.6	straight	2	1	1
	235.7	straight	6	3	3
	235.8	straight	4	4	0
	235.9	straight	4	4	0
	236.0	straight	8	5	3
	236.1	straight	2	0	2
	236.2	straight	4	2	2
	236.3	straight	1	0	1
	236.4	straight	4	0	4
	236.5	straight	8	4	4
	236.6	straight	4	1	3
The Dip	236.7	straight	4	4	0
	236.8	Left/Straight	3	2	1
Dirty Jacks	236.9	straight	2	2	0
	237.0	straight	0	0	0
	237.1	straight	2	1	1
	237.2	straight	3	1	2
	237.3	straight	1	0	1
The Back Side	237.4	Straight/Right	4	2	2
	237.5	Left/Straight/Right	2	1	1
	237.6		5	3	2
	237.7	Straight/Right	2	2	0
	237.8	Left/Straight/Right	2	1	1
	237.9	Left/Straight	2	1	1
	238.0	straight	0	0	0
		Total	90	53	37

Table 5-6: Summary of Car Event Locations, including AZ section names

An unknown portion of the 14 undetected vehicles had closing rate above the threshold set within the radar software. As noted above, the radar software filters and removes warnings for oncoming vehicles above a threshold closing rate, based on the ADOT operator preferences. Some of these 14 vehicles passed in a curve, which will generally also reduce the time the car moves through the radar's field of view, and can lead to a missed detection. This is one area where further refinements can be made in the system.

Six of the eight erroneous detections were detected correctly in the left lane but also showed in the center lane at some point. Two showed only in the center lane on screen. Six out of eight errors took place between mileposts 237.5 and 237.8. Table 5-7 provides a detailed breakdown and classification of the event types for each milepost for northbound and southbound runs.

Analysis Results – False Warning Events in AZ

During the total test time (3 hours and 20 min.) a total of 51 false warning events were counted (one false warning every 235 sec., or every 3 min. 55 sec.). Most false warnings appear to be caused by a few roadside infrastructure elements that are incorrectly detected as obstacles. Variations in vehicle heading and lane position may explain why these obstacles sometimes are detected. Again, all site-specific issues noted here are related to the 2002 AZ test results.

- An obstacle at milepost 235.3 northbound appears 16 times out of 22 runs (73%). In 11 of these runs this false warning shows up more than once.
- The guardrail at milepost 237.5-7 southbound appears 4 times out of 24 runs (16%).
- The guardrail at milepost 237.5-7 northbound appears 4 times out of 22 runs (18%).
- "The Dip" at milepost 236.8 has an abrupt change of road inclination, which is detected by the radar in some cases. It shows on the display 3 times northbound (14%) and once southbound (4%), or 9% for all runs.
- A false event (cause unknown) at 235.9 northbound appears 3 times out of 22 runs (14%).
- A false event (cause unknown) at 235.5 southbound appears 4 times out of 24 runs (17%).

Only one false warning took place at an unexpected location. Comments from the California drivers suggest that the regular picking up of, for example, a road sign and guardrail are less problematic if they occur consistently, as with experience a driver can screen those out where known signs always trigger the system. Of greater concern are those false detections that occur in lower numbers as these can lead to operator distrust in the system. Warnings that don't show consistently on every run will still seem random. Only the warning at milepost 235.3 northbound is consistent enough (73%) to be recognized by the driver. If these consistent warnings are omitted, the average time between false warnings increases to 10 minutes.

It is noteworthy that most "false event" warnings only appear briefly, are typically beyond 50 meters (i.e. yellow tape, so not an imminent threat), and don't move. Software revisions can reduce the occurrence rate in these conditions, and this is an area for future improvements based on the current analysis.

Section	MP	Road Curvature	corre	ct car	misse	ed car	error	eous	dism	issed
			Ν	S	Ν	S	Ν	S	Ν	S
	235	straight	2							
	1	straight				1				
Hart	2	right/straight							1	
Prairie	3	left/straight/right		1					2	
Curve	4	left/right			1					
Curve	5	straight/right	1						2	
Kendrick	6	straight	1							1
Park	7	straight	3	2		1				
	8	straight	3				1			
	9	straight	3		1					
	236	straight	4	3	1					
	1	straight		2						
	2	straight		2	2					
	3	straight		1						
	4	straight		4						
	5	straight	4	4						
	6	straight	1	3						
The Dip	7	straight	3				1			
1	8	left/straight	2			1				
Dirty	9	straight	1		1					
Jacks	237	straight								
	1	straight		1					1	
	2	straight	1	1						1
	3	straight		1						
The	4	straight/right	2	1		1				
Back	5	left/straight/right	1					1		
Side	6				2	1	1	1		
5100	7	straight/right					2			
	8	left/straight/right				1	1			
	9	left/straight	1	1						
	238	straight								
Totals		33	27	8	6	6	2	6	2	
Totals North and South		North and South	6	0	1	4	8	3	8	8

Section	MP	Road Curvature	false event	
			Ν	S
	235	straight		
	1	straight		
Hart	2	right/straight		
Prairie	3	left/straight/right	31	1
Curve	4	left/right		1
	5	straight/right		
Kendrick	6	straight		
Park	7	straight		
	8	straight		
	9	straight	3	
	236	straight		
	1	straight		
	2	straight		
	3	straight		1
	4	straight		
	5	straight		1
	6	straight		
The Dip	7	straight	3	
	8	left/straight	1	1
Dirty	9	straight		
Jacks	237	straight		
	1	straight		
	2	straight		
	3	straight		
The	4	straight/right		
Back	5	left/straight/right	1	4
Side	6			
2100	7	straight/right	3	
	8	left/straight/right		
	9	left/straight		
	238	straight		
	42	9		
	5	1		

 Table 5-8: False Warning Events by Location, including AZ section names

Radar Analysis Summary and Conclusions

• There were a total of 11 car events between mileposts 237.5 and 237.8. Only one was correctly detected. Four passed undetected and six yielded an erroneous detection. This section of road has several alternating curves and inclination changes. Since most erroneous detections took place here, it is clear that there are issues with the masking of the radar for such road geometries. The high number of missed cars may significantly improve under whiteout conditions—with tight curves the radar coverage of the road is limited, which is mostly problematic with faster traffic.

- Of the noted false events, almost all were caused by certain roadside objects. There are software revisions which may improve the false warning suppression in these cases. The radar field-of-view is adjusted dynamically based on road curvature, but this masking could be enhanced to anticipate irregularities, given a database of known problem areas. In addition, it is possible to determine whether the object is stationary and suppress those that are not in the roadway; however, some caution is in order when, for example, the wingplow is in use near the roadway edge. Results indicate some errors may be caused by heading; software revision to incorporate estimated vehicle heading to more precisely calculate the radar field-of-view is an area for future improvement.
- All 9 passing cars were correctly detected. Only one did not appear in the center lane as well as in the left lane. The essentially perfect detection of passing cars (as opposed to the less-than-perfect detection for oncoming cars) indicates that speed is an important factor in the radar performance. The radar results improve at slower speeds, indicating that the system should perform better in actual whiteout conditions.

The overall correct detection rate of approximately 73% is improved from previous year's testing, but still leaves room for further improvements in the radar system. In addition, the time between false events is reasonable, but again indicates some systems improvements should be pursued. The empirical data provides a solid basis for targeted improvements in the system software. With these improvements, and with the system operating in its intended conditions (i.e. whiteout), empirical results will be improved, and it is reasonable to anticipate that the subjective survey results would also be significantly better. Ultimately, the perceptions and views of the snowplow operators are the key metric for this and any other driver assistive technologies, so that the improvements identified herein should be addressed before further deployment and testing of the system.

Arizona Field Testing 2001/2002

In February and March 2002 a human factors field test of the advanced snowplow system was conducted on a six-mile round-trip closed loop test track on US 180 north of Flagstaff, near Kendrick Park, Arizona. The goals of the field test were as follows: to evaluate the effectiveness of the advanced snowplow system, to determine in what ways the system changes snowplow driver behaviors and to investigate what recommended changes to the driver vehicle interface can be made. Due to a lack of snow, all sessions were conducted in clear weather conditions, on dry roads, and with the plow blade lifted, during dedicated and intensive night testing, to best match low visibility conditions.

Three Arizona DOT snowplow operators participated in field testing over a three day period. The three operators completed both HMI aided and unaided runs to allow for comparisons of driver data. A human factors researcher "rode-along" on each run to collect observational data, to communicate tasks to the driver, and to collect driver feedback. The three drivers included a team leader who had conducted the training of the other drivers on the ASP system for the three prior years (driver 1), an experienced team leader who gave training and worked on the ADOT-3M plow (driver 2) and an inexperienced RoadView driver who had seen the system working on a ride-along but had not driven the system (driver 3). Given the differing levels of experience for each of the three drivers, their results are given separately below. Most of the testing was down

either in the late afternoons or in the evenings until about 11 pm. The testing was scheduled to accommodate the operators other normal operational tasks and often occurred after they had already completed a full workday.

The drivers were all given trial no-data collection runs so that they could become accustomed to the plow as it was different from the plow used by ADOT. The drivers generally felt comfortable with the plow after having driven to the test site and completed one round trip over the magnets. If they did not drive to the test site, they felt comfortable after one or two round trips over the magnets.

After the drivers reported feeling comfortable with the plow, they were asked to complete one round trip over the magnets where normal driving data was collected. Since the testing was performed on a public road, we were unable to simulate any whiteout conditions. To simulate normal system use the drivers were asked to complete a number runs looking at the display as their primary navigation tool. The number of runs completed by each driver varied according to the length of time each driver was available, and if the drivers reported any discomfort, the testing was stopped. Two of the drivers reported sore necks as a result of constant looking at the display. Both drivers however felt that the display location would not cause any problems in whiteout conditions since they would only need to look at it for short periods of time, instead of during the whole trip, which we were asking them to do. A human factors researcher was present for all runs to monitor both driver feedback and behavior, as well as to ensure that the drivers were aware of any oncoming traffic or road hazards.

The drivers also completed "Information search" runs where they were asked at random times to look at the display and report to the researcher how off center from the markers they were, as well as whether the display reported any on-coming traffic. The requests were generally made once or twice per curve and once or twice per straight section. Again, the number of actual trials in these conditions was dependent on how long the driver was available at the time of testing.

It should be noted here that because a majority of the testing was conducted at night with clear weather, and little traffic, the drivers felt that for safety reasons they needed to "keep their speed up" so that they did not present a road hazard for the generally faster moving traffic.

Data was analyzed for the last part of each run. The analysis of data looked at mean vehicle lateral displacement (LD), mean speed, vehicle and number of steering wheel standard deviations.

Driver	Experience	Normal runs	Aided runs	Information Search Runs
Driver 1	RoadView Team Leader	1	6	3
Driver 2	ADOT-3M plow team leader	1	3	3
Driver 3	Inexperienced user	1	2	4

Table 5-9: Summary of Testing Conditions

Aided Driving

Analysis of the first driver (the RoadView team leader) shows that in doing the aided runs the driver initially slowed down and became more accurate, then as the trials progressed his speed increased to slightly above the normal run while the mean LD approaching that of the non-aided run. This suggests that the driver was able to drive slightly more accurately at about the same speed.



Figure 5-12: Driver 1 –Normal Versus Aided Runs

Analysis of the second driver (the ADOT-3M team leader) in the distracted run versus the aided conditions show a drop in speed with an accompanying drop in LD. The fast speed and high LD in the normal condition may in part be due to the driver not wanting to present a road hazard. For this driver run 1 was completed looking at the current plow position whereas runs 2 and 3 were completed looking at the predictor, and show a decrease in LD.



Figure 5-13: Driver 2 - Normal Versus Aided Runs

Driver number 3 performed two trials under the display condition, but, reported having a sore neck in the second trial so results are not reported for this section.

Information Search Task

The data shown in Figure 5-13 show an initial drop in speed and an increase in LD when performing this task, on subsequent runs the driver very quickly increase his speed and with a corresponding decrease in mean LD. This suggests that the driver after an initial trial of learning the task did not suffer from the added burden of doing quick information searches.

Mean Speed vs Run Plot (Driver 1-Information Search)Mean FLD vs Run Plot (Driver 1-Information Search)



Figure 5-14: Driver 1 – Normal vs. Information Search Runs

Driver two showed a drop in speed over the first two trials then an increase in speed and LD for the third trial.



Figure 5-15: Driver 2 - Normal vs. Information Search Runs

Driver three showed an initial increase in speed and then a gradual decrease in speed and LD deviation.



Figure 5-16: Driver 3 - Normal vs. Information Search Runs

In addition to analyzing the mean speed and LD, we looked at the steering wheel angle standard deviations versus different curve radii. Higher steering wheel angel standard deviation generally corresponds with a more difficult driving task. Figures 5-17 through 5-19 indicate driving performance for the three drivers on the separate graphs. Of note here is that no clear pattern emerges from any of these three conditions (normal, aided or information search) experienced by the three drivers being substantially or consistently easier than the others.



Driver 1 Steering Wheel Angle Std. Dev. versus Curve Radius

Figure 5-17: Driver 1 - Steering Wheel Angle Standard Deviation vs. Curve Radius



Figure 5-18: Driver 2 - Steering Wheel Angle Standard Deviation vs. Curve Radius



Driver 3 Steering Wheel Angle Std. Dev. versus Curve Radius

Figure 5-19: Driver 3 - Steering Wheel Angle Standard Deviation vs. Curve Radius

Overall, the findings suggest that drivers were able to quickly transition between obtaining relevant information from the display and performing their normal driving tasks. Drivers' performance also improved under the display-only condition compared to the normal driving conditions.

Overall HMI Conclusions

The findings from the lateral-assistance portion of the display suggest that even with limited instruction, the system is easy to learn and that drivers can easily transition between navigating from normal driving to guidance assisted driving. However, given that a number of drivers were driving from the current plow position in the future, drivers should be trained to use both the predictor and the plow current position while navigating so that they can experience the difference in difficulty and determine which method is most beneficial. Further studies could investigate performance differences experienced when using either method. If there is always an advantage of using the predictor then a fixed plow display (in which only the predictor would move) should be further investigated to prevent any future confusion. In addition, a one-page card should be made that explains how the system works and what the different display conditions mean. This card could be left in the plow and used by experienced RoadView drivers when training new drivers or it could be given directly to new drivers to help them better learn

the system. Such a card would also standardize the training and ensure that all drivers receive information about the way that the system works and what it is designed for.

Driver comments suggest that they would like the option of mounting the display either on the dash or on the rear-view mirror position. Additional information that should be added to the display is right-side border information (particularly in places where the road is too narrow to accommodate the plow), and a display telling a driver their distance from a specific section name on the road. Driver feedback also suggests the need for drivers to be involved in determining geographical areas of priority should future magnet installation occur. Driver feedback also suggests that the drivers would like more magnets installed.

The drivers' qualitative comments with regards to the collision warning system suggest further work to decrease the number of false and missed detections whilst increasing the numbers of correct detections. Any advances in this area will enhance driver trust and use of the system. Specific causes and remedies for these false and missed detections have been identified, and implementation of these remedies is being considered for future phase efforts.

This study further validates the finding from ASP-I and II that suggests that a simple, lowfidelity display reminiscent of early video games increases the effectiveness of the system and its acceptance among drivers. The original decision to use a "low-tech" image during ASP-I was based on computational concerns and a desire for simplicity. The drivers responded enthusiastically to this type of display, and field measurements demonstrated that high performance can be achieved without complex graphics or custom hardware. This finding has direct ramifications on future commercialization or deployment.

Feedback from the drivers suggests that under whiteout conditions, the display would allow snowplows to operate under situations where it would normally be unsafe to plow. The results in this report and in those for ASP-I and II suggest that the HMI meets the design goals of allowing drivers to acquire vehicle lateral information at a glance and to switch between normal and guidance-assisted driving at ease.

CHAPTER SIX: MAGNETIC SENSING SYSTEM

Introduction

The development of a reliable and accurate lateral referencing system is crucial to the success of the lateral guidance system of the snowplow. PATH has proposed and developed a lateral referencing and sensing system that is based on the magnetic markers embedded in the road center to provide the lateral position and road geometric information [45]. The snowplow steering guidance system based on such technology provides the driver with the following two fundamental pieces of information that support steering control: the vehicle position with respect to the roadway, and the current and future road geometry. Furthermore, the high accuracy of the lateral referencing system offers sufficient resolution enabling the calculation of other vital information for the stability of human steering control [29].

Under previous snowplow projects (ASP-I and ASP-II), different configurations of magnetic sensing systems were tested and evaluated for their proficiency in making lateral displacement measurements. Two arrays of magnetometers, one located behind the front wheels and the other at the rear of the truck, were used to simultaneously obtain front and rear lateral offset measurements under ASP-I. Those measurements were then used to derive vehicle information such as heading angle for the predictor calculation. During ASP-II, it was found that the front magnetometer array is sufficient for such calculations as long as the noise of the position measurement is small enough to allow a mathematical observer to estimate the vehicle-heading angle. By eliminating the rear magnetometer array, significant cost reduction as well as reliability improvement of the snowplow guidance system is achieved. In this chapter, the background of the magnetometer signal processing will be reviewed first, followed by discussions of the lessons learned from the snowplow signal processing experience.

Extensive development and experiments have been performed on magnetic marker-based lateral sensing systems for many PATH vehicles equipped with automated steering control [32]. The vast knowledge available about this lateral sensing technique was one of the primary reasons that this technology was first chosen to support the steering guidance system. Other positive characteristics of this lateral sensing technique include good accuracy (better than one centimeter), high reliability, insensitivity to weather conditions, and support for binary coding. The requirement of modifying the infrastructure (installing magnets) and the inherent "lookdown" nature (the sensor measures the lateral displacement at locations within the vehicle physical boundaries, versus look-ahead ability) of the sensing system [10] are two known limitations of this technology. Although the associated application software for this sensing system can be quite involved, the principle is straightforward. Magnetic markers are installed under the roadway delineating the center of each lane; other magnet installation configurations can be supported as appropriate for different applications. Magnetometers mounted under the vehicle sense the strength of the magnetic field as the vehicle passes over each magnet. Onboard signal processing software calculates the relative displacement from the vehicle to the magnet based on the magnetic strength and the knowledge of the magnetic characteristics of the marker. This computation is designed to be insensitive to the vehicle bouncing (e.g., heave and pitch) and the ever-present natural and man-made magnetic noises. Furthermore, the road geometric

information can be encoded as a sequence of bits, with each bit corresponding to a magnet [9]. The polarity of each magnet represents either 1 (one) or 0 (zero) in the code. In addition to the lateral displacement measurement and road geometry preview information, other vehicle measurements such as yaw rate, lateral acceleration, and steering wheel angle may also be used to improve the performance of such a lateral guidance system [6, 29].

The following sections review the background information on both the magnetic marker concept and the development of a reliable magnetometer sensor signal-processing algorithm. The last section discusses some lessons from the RoadView experience.

Magnetic Marker Model

A representative mathematical model of the magnetic marker provides a base for understanding many important issues regarding the design of a reliable signal-processing algorithm. Among these issues, the key problems that determine the effectiveness of any algorithm are how to reliably detect the magnets, how to correctly identify the earth field, how to remove the effect of vehicle bounce, and how to desensitize the noise disturbance effects. PATH researchers have chosen to model the markers as magnetic dipoles for analysis. Aside from its relative simplicity and compactness, extensive testing at the Richmond Field Station reveals a strong correlation between model prediction and empirical measurements [45].

Under the dipole assumption, the magnetic field, $\vec{B}(x, y, z)$, at some location, $\vec{P}(x, y, z)$, can be given by

$$\vec{B} = \frac{\mu_0 M}{4\pi r^5} \left(3xz\vec{i} + 3yz\vec{j} + (2z^2 - x^2 - y^2)\vec{k} \right)$$
(6-1)

where $r = \sqrt{x^2 + y^2 + z^2}$, μ_0 is the permeability of free space, and *M* is the magnetic moment of the magnetic marker. Also note that the coordinate system ($\vec{P} = x\vec{i} + y\vec{j} + z\vec{k}$) is chosen so that $x\vec{i}$ corresponds to the direction of vehicle travel, $y\vec{j}$ the lateral deviation, and $z\vec{k}$ the height, relative to the marker's center.

Equation (6-1) shows that, at any given longitudinal location x, in particular at x=0, i.e. immediately over the magnet, there exists a one-to-one mapping from the magnetic field $\vec{B}(0, y, z)$ to the sensor location (0, y, z). Therefore, it is theoretically plausible to invert this mapping to obtain the lateral deviation as well as the sensor height at the sensor location just as the vehicle passes over each magnet (x=0). The method of inverting this mapping can be analytical, numerical, or experimental. One crucial determining factor for designing a real-time algorithm of the inverse mapping is the tradeoff between the algorithm's effectiveness in handling noise and the algorithm's complexity.

Noise Effects

Four major noise sources are usually present in the magnetic signal measurements in a typical vehicle operational environment: earth field, local magnetic field distortion, vehicle internal electromagnetic field, and electrical noise.

The most frequent external disturbance is the ever-present earth's permanent magnetic field, which is usually on the order of 0.5 Gauss. The value of the earth field measured by the magnetometers on the vehicle depends on the location of the vehicle on earth as well as the altitude and orientation of the vehicle. Although the earth magnetic field usually changes slowly, sharp turns and severe braking can quickly change the field measurements along the vehicle axes.

The most serious noise problems are caused by local anomalies due to the presence of roadway structural supports, reinforcing rebar, and the ferrous components in the vehicle or under the roadway. Underground power lines are another source of such local field distortion. Rebar or structural support usually creates a sharp change in the background magnetic field and sometimes is difficult to identify. Most signal processing algorithms will have some difficulty recovering from such sharp distortions. The ferrous components in the vehicle, on the other hand, can be isolated as long as their locations are fixed with respect to the magnetometers, or are located at a significant distance from the sensors.

A third source of noise comes from the alternating electric fields generated by various motors operating in the vehicle. These motors may include alternator, fan, electric pump, compressor and other actuators. However, their effects vary according to the motor rotational speed and distance from the magnetometers. The higher the motor rpm or the farther it is placed away from the magnetometers, the less the resultant noise. Sometimes modest changes in sensor placement can alter the size of such disturbances.

The last common noise source arises from the electronic noise in the measurement signal itself. Such noise can be created by the voltage fluctuations in the electrical grounding or from the power source. It can also be a result of poor wiring insulation against electromagnetic disturbances. Usually, the longer the wire, the higher such noise. Although low-pass filtering can reduce the magnitude of such disturbances, noticeable degradation of the magnetic sensor signal process algorithm occurs when such noise level exceeds 0.04 Gauss. Digital transmission of magnetic field measurements or a local embedded processor are two possible approaches that could significantly reduce such noise. AHMCT is currently developing a system along these lines [4].

Magnetic Sensing Algorithm

One of the important attributes of the lateral sensing system is its reliability. Currently, there exist several algorithms designed to detect the relative position between the marker and sensor (magnetometer), as well as to read the code embedded within a sequence of these markers. Three magnetic marker detection and mapping algorithms have been experimented with by PATH [45]. The first is called the "peak-mapping" method that utilizes a single magnetometer to estimate the marker's relative lateral position when the sensor is passing over the magnet. The second algorithm is the "vector ratio" method that requires a pair of magnetometers to sample the field at two locations. It returns a sequence of lateral estimates in a neighborhood surrounding, but not including the peak. The third is the "differential peak-mapping" algorithm that compares the magnetic field measurements at two observation points to eliminate the common-mode contributions and reconstructs a functional relationship between the differential sensor readings and the lateral position using knowledge of the sensor geometry. The "peak-mapping" algorithm

was selected for the snowplow project because it has proven effective over a wide range of speeds and has been widely applied in many experimental applications conducted by PATH.

Under the assumption that the vehicle lateral speed is significantly smaller than its longitudinal speed, it is obvious that the largest vertical field B_z occurs at the point when the sensor is just passing over the magnetic marker, i.e. as x=0. This point is called the "peak" because it corresponds to the location where the magnetic field achieves its maximum strength during the sensor's trajectory over the magnetic marker in question. What is noteworthy here is that the three-dimensional mapping of Equation (6-1) can be reduced to a two-dimensional mapping using the constraint relationship x=0.

Two basic methods can be used to detect peaks: the variance method (using B_z) and the switching method (using B_x). The variance method computes the instantaneous variance of the vertical field $\sigma_z(t_k)$ as

$$\sigma_z(t_k) = \sum_{i=k-N}^k \left(B_z(t_i) - \overline{B}_z(t_k) \right)^2, \tag{6-2}$$

where $\overline{B}(t_k)$ is the running average of the last N samples, i.e.,

$$\overline{B}_{z}(t_{k}) = \frac{1}{N} \sum_{i=k-N}^{k} B_{z}(t_{i}) .$$
(6-3)

Using this variance, the peak and the valley of the vertical field can be identified using the following relationship

if
$$|B_z(t_k) - \hat{B}_{zEarth}| > HIGH_threshold \& \sigma_z(t_k) < \varepsilon => \text{Peak detected},$$
 (6-4)

if
$$|B_z(t_k) - \hat{B}_{zEarth}| < LOW_threshold \& \sigma_z(t_k) < \varepsilon \implies$$
 Valley detected. (6-5)

Here, ε is a small value to be empirically selected. Equation (6-5) suggests that the marker is far enough away from the sensor so that the field from the magnetic marker is negligible. Thus the vertical and horizontal earth field estimates (B_{zEarth}, B_{yEarth}) can be updated based on the sensor measurements at the valley. It should be noted that the earth estimates play a very important role in the accurate computation of the lateral deviation.

To improve the reliability of the peak detection process, the switching method utilizes the sign-change property of the longitudinal field (B_x) at peak, both to provide candidates for peaks and to double-check any detected peak.

Once the peak is detected, the marker's magnetic field is computed as

$$B_{zMagnet} = B_z(t_m) - \hat{B}_{zEarth}, \text{ and } B_{yMagnet} = B_y(t_m) - \hat{B}_{yEarth}.$$
(6-6)

By setting x=0 in Equation (6-1), the slope function between the vertical and horizontal field of \vec{B}_{Magnet} can be expressed as

$$\frac{B_{zMagnet}}{B_{yMagnet}} = \frac{2z^2 - y^2}{3yz} \equiv \varphi(y, z) \,. \tag{6-7}$$

It is known from calculus that the curve (B_z, B_y) form a field if $\varphi(y, z)$ is single-valued, or that partial derivatives of $\varphi(y, z)$ do not vanish. Since

$$\frac{\partial^2 \varphi(y,z)}{\partial y \partial z} = \frac{y^2 - 2z^2}{3y^2 z^2} \neq 0, \text{ as long as } y \neq \sqrt{2}z, \qquad (6-8)$$

under the restriction that $y \in \{y_{\min}, y_{\max}\}$ and $z \in \{z_{\min}, z_{\max}\}$, with $z_{\min} > 0$ and $y_{\max} < \sqrt{2}z_{\min}$, the curve $\{B_{yMagnet}, B_{zMagnet}\}$ does form a field. Therefore, the inverse mapping from $\{B_{yMagnet}, B_{zMagnet}\}$ to $\{y, z\}$ does exist for most of our application where z_{\min} is usually greater than 15 cm (5.9 in) and y_{\max} is less than 20 cm (7.9 in).

Magnetic field maps were produced from readings from each magnetometer on all three snowplows and used for analysis. In the current snowplow environment, the magnetic field maps can deviate quite significantly from the theoretical prediction from Equation (6-1) because of the massive amount of ferrous material from the plow blade structural support located in the vicinity of the magnetometers. The magnetic field maps can also be different among various snowplow platforms. Numerical mapping created by empirical data gathering (calibration) was used to create the associated inverse maps. Figures 6-1, 6-2 and 6-3 show the magnetic tables for the snowplows used in the RoadView project: C#7228, C#8467 and C#7005. The figures consist of tables of the seven magnetometers starting from the right side of the snowplow to the left, designated as follows: right-right, right, center-right, center, center-left, left and left-left. Each table was obtained from two sets of calibration data, one at a lower sensor height (usually at around 18–20 cm (7-8 in.) from the magnetometer to the magnet) and the other at a higher sensor height (28–30 cm, (11-12 in.) from the magnetometer to the magnet). Each half-circle in the table consists of vertical and horizontal fields of the marker that are collected at 2-cm interval of lateral displacement. In order to obtain better protection against the environment, magnetometers are installed behind the front tires for all the RoadView snowplows. The magnetometers on snowplows C#7228 and C#8467 are installed further behind the front wheel in such a way that most of the blade support structure is located above the magnetometers. The magnetic tables on these two plows are therefore somewhat symmetric as can be seen in Figures 6-1 and 6-2. On the other hand, Figure 6-3 shows the very nonsymmetrical field characteristics due to the fact that some of the magnetometers are next to the plow blade support structure in the C#7005 snowplow. Furthermore, the snowplow sensor array for C#7005 was installed with a 2.5 cm (1 in.) height offset between the right-right and left-left magnetometers. Therefore, one can observe in Figure 6-3 that the field strength reduces from right to left. One advantage of the peak mapping method is its robustness against height variations. One can observe in Figures 6-1 to 6-3 that movement in the z axis only changes the coordinates along the radial lines with constant y [45].







Figure 6-2: Snowplow (#8467) Magnetic Tables



Figure 6-3: Snowplow (#7005) Magnetic Tables

Signal Processing Algorithm

Magnetometer signal processing for the "peak-mapping" method involves three procedures: peak detection, earth field removal and lateral displacement table look-up (see Figure 6-4 for block diagram of signal processing algorithm). Although it is straightforward in principle, it becomes complicated when the reliability of the process is the major concern. Many parameters in the lateral sensing signal processing software need to be tuned in order to provide consistent lateral displacement information regardless of vehicle speeds, orientations, operating lateral offsets and vehicle body motions. Debugging can become very time consuming when failure conditions cannot be recreated. To improve the reliability of the lateral sensing system with the magnetic road markers, PATH has developed a "reconstructive" software system for the lateral sensing signal processing data as usual, stores all sensor data in memory and later dumps the data into a file. That data can be post-processed on a desktop computer, so that erroneous situations can be recreated in a lab environment and debugged with ease.

Parameter tuning of the signal processing algorithm presents a difficult trade-off between signal noise rejection, measurement accuracy and the robustness against variations of magnet depth.

One difficult problem encountered during the tuning of the signal processing parameters was to desensitize the sensing software against the inconsistency of magnet installation. The magnets were installed at various depths ranging from 1.3 to 2.5 cm (0.5-1.0 in) below the surface of the

road. Since precise installation specifications were not developed during the RoadView project, and some installers did not maintain a uniform standard in the installation process, there are locations where the magnets are installed deeper than 5 cm (2 in.). Furthermore, because of certain sealant problems, some of the magnets that were installed early on have shown some degradation as a result of losing the top magnet. The magnetic strength of such magnets thus has more variation than what was anticipated. The data suggests that a reduction of (30-40%) strength has occurred in some magnets. This reduction in strength results in more than a 50% reduction in the variance calculation. The problem is greatest when the magnet is right between two magnetometers, and is less apparent when the magnet is just beneath a magnetometer.

To make matters worse, electrical noise in the RoadView magnetic channels is not very consistent. In some situations, the electrical noise is borderline acceptable. In others sharp, pulse-like electrical noise has been found to be coming from the switched DC-DC power supply and inverter leaking into the sensor signal from the ground. In the borderline cases, these noise spikes are just within 40 mV (corresponding to 20 mG), which limits the software's ability to reliably detect low-strength magnets. In order to achieve high lateral position accuracy, the analog magnetic signal must be much larger than the noise value to maintain a high signal-to-noise ratio (SNR). Reducing such electrical noise becomes an important issue in order to improve the SNR under either external magnetic noise or to raise the magnetometer array up. Reconstructive runs provide the ability to carefully tune the balance between the above trade-offs. However, occasionally some magnets miss detection. These scenarios, although not common, require some modifications in the guidance software to maintain the performance consistency.



Figure 6-4: "Peak-Mapping" Magnetometer Signal Processing Block Diagram

Magnet Installation

This section describes two issues related to the magnet installation: the draft installation specifications and the results of a comparison of magnet installation accuracy at the three sites used by the RoadView project. Throughout this section, may of the specifications are labeled as "TBD", or To Be Determined. The intent of this designation is that all values provided are the

current best known values, but subject to refinement. Thus, the specification is designated as draft.

The draft installation specification consists of the magnet requirements and the installation accuracy requirements. The magnet requirements address magnetic strength and magnet physical properties. The physical properties involve the size and shape of the individual magnets and how they are stacked together to form a single marker, as well as the operating temperature range and life cycle of the magnets. The physical properties are not discussed in this section. Two kinds of lateral accuracy relate to the magnet installation: absolute accuracy and smoothness accuracy. Other accuracy requirements include longitudinal tolerance, perpendicular tolerance and depth tolerance.

The absolute accuracy specifies the tolerance to the exact magnet location when there is an accuracy performance requirement with respect to some "fixed" coordinates. Such fixed coordinates may be the relative distance to the guardrail or the distance to the center of the lane. Conventional wisdom calls for the measurement accuracy (installation tolerance plus sensor precision) to be at least 1/10 of the performance accuracy. (For example, a 5 cm (2 in.) performance accuracy requires a 0.5 cm (0.2 in.) measurement accuracy.) When the smoothness accuracy is satisfied, the absolute accuracy can be relaxed to about 1/4-1/5 of the performance accuracy.

The smoothness accuracy relates to the smoothness of the magnet lines and curves. It is an important factor that determines both the smoothness of the steering action (and consequently the actuator's life for automated steering control), and the attainable control accuracy. In general, the smoothness accuracy is more important than the absolute accuracy in cases where "steering guidance" is the fundamental mode of operation. The absolute accuracy is crucial when the accuracy of the "automated steering control" is of major concern, such as in the case of a snow blower automated steering control along a guardrail.

One specific method that determines the smoothness accuracy is based on the three-magnet "center-offset". The center-offset of a magnet (x_i of magnet #i) is defined as the distance from the magnet to the line delineated by the two adjacent magnets (#i-1 and #i+1) subtracting the curvature contribution ($x^2/(2R)$), where x is the spacing between two consecutive magnets, and R is the road curvature. On a typical highway, the lateral offset from curvature for a radius more than 300 m is less than 0.25 cm (for x<1.2 m). One way to generically define the smoothness accuracy is to bound the center offset of all magnets in question as follows:

$$|x_i| < b \text{ cm}$$

 $|x_i| + |x_{i+1}| < 1.5b \text{ cm}$
 $|x_{i-1}| + |x_i| + |x_{i+1}| < 1.75b \text{ cm}$

The following section describes an example of the draft magnet installation requirements:

Strength of Magnetic Field

(1) The magnetic field measured at Point A (Figure 6-5) shall be greater than 850 milligauss.

(2) The magnetic field measured at Point B (Figure 6-5) shall be greater than 500 milligauss.



Figure 6-5: Magnetic Field Strength Requirements

Size and Shape

Magnets shall be cylindrical with a diameter between 20.3 mm and 38.1 mm.

Magnet Configuration

Magnets may be stacked together until the field strength requirement is met, to a maximum height, which is to be determined in future testing. The value is expected to be based on the road structure, magnet mechanical strength, and the shape of the field; however, proper determination may require detailed theoretical and empirical study.

Operating Temperatures

The magnets shall maintain greater than 90% of the magnetic field strength as defined above at temperatures between -35° C (TBD) and 100° C (TBD). Thermally caused changes of magnetization shall be reversible between 100° C and 210° C.

Lateral Position Accuracy

There are two types of lateral (perpendicular to centerline) accuracy required for magnet placement: position accuracy and smoothness accuracy. Lateral position accuracy specifies the tolerance of the magnet location relative to the reference line. Lateral position tolerance is ± 15 (TBD) mm. Smoothness accuracy specifies the tolerance of a series of magnet locations relative to adjacent magnets. Smoothness accuracy (Figure 6-6) is defined as:

For a single magnet:

$$|X_A| \le 15 \text{ (TBD) mm}$$

For a series of magnets:

$$|X_{A}| + |X_{B}| + |X_{C}| \le 30 \text{ (TBD) mm}$$

Smoothness accuracy is determined by visual inspection of the hole location marks to see if they form a smooth line or curve. If there are questionable magnet location marks, the following procedure will be used (see Figure 6-6).

For a single questionable magnet location:

$$|X_A| \le 15$$
 (TBD) mm.

For multiple magnet locations:

- (1) Measure the offset from the chord between three adjacent magnets (X_A, X_B, X_C)
- (2) The sum of the offsets should be less than 30 mm (TBD)

$$|X_A| + |X_B| + |X_C| \le 30 \text{ mm (TBD)}$$

(3) Re-mark locations that exceed required smoothness accuracy



Figure 6-6: Smoothness Accuracy Requirements

Longitudinal Position Accuracy

Magnets shall be placed to within ± 100 mm (TBD) longitudinally (parallel to centerline) of the designated location. The longitudinal accuracy may be relaxed to suit for particular roadway limitations.

Vertical Position Accuracy

The top of the magnet stack shall be between 10 mm to 15 mm (TBD) below the surface of the road.

Holes

Holes drilled or punched into the processed subgrade shall be perpendicular to the surface and shall be sized to permit snug installation of the stacked magnets. The diameter of the hole shall be less than diameter of the magnet plus H/12, where H is the height of the stacked magnets.

The following section describes the magnet installation comparisons of the three sites where the RoadView snowplows field tests were conducted: in Arizona, Shasta and Tahoe.

<u>Arizona</u>

The highway is US-180 north of Flagstaff, Arizona. The chosen section is a 2-lane highway at 7000 ft elevation, with thirteen curves and a sharpest curve of 278 m radius of curvature.

Six miles of magnets were installed in asphalt by the ADOT snowplow operators themselves. The northbound section is three miles long (4020 magnets) and the southbound section three miles (4017 magnets). The magnet installation was conducted in two phases: the first four miles (magnet #1 to #5334) were installed in 1998, and then the remaining two miles (magnet #5335 to #8037) in 2000.

Figure 6-7 shows data taken in February 2002 with snowplow C#7005 for the whole track length (4000 magnets) on the northbound and southbound sections. The magnets should be ideally placed at 1.2 meter spacing. The longitudinal distance standard deviation is 3.35 cm.



Figure 6-7: Longitudinal Distance between Magnets at US 180, AZ

<u>Shasta</u>

The highway is SR-299 west of Burney, CA. The chosen section is a two-lane highway at 4366 ft elevation, with fourteen curves and a sharpest curve of 213 m radius of curvature.

Ten miles of magnets were installed in asphalt in 2001 by a private contractor. The eastbound section is five miles long (6706 magnets) and the westbound section five miles (6706 magnets). The first seven hundred holes were drilled too wide and too deep because the contractor was given specifications for another type of magnet. That problem was discovered and resolved after the first day of drilling.

Figure 6-8 shows data taken in December 2001 with snowplow C#8467 for the whole track length (6700 magnets) on the eastbound and westbound sections. The longitudinal distance standard deviation is 3.15 cm.



Figure 6-8: Longitudinal Distance between Magnets at SR-299, CA

<u>Tahoe</u>

The highway is I-80 west of Truckee, CA. The chosen section is a two to three-lane divided highway at 7239 ft elevation, with six curves and a sharpest curve of 457 m radius of curvature.

The first magnet installation involved 3.9 miles of magnets on the westbound section after Donner Summit. These magnets were installed in asphalt in 1998 by the Caltrans snowplow operators themselves.

Then more magnets were installed in concrete by a private contractor. The eastbound section is 3.3 miles long (4405 magnets) and the westbound section 3.3 miles (4365 magnets). The magnet installation was conducted in two phases: the eastbound magnets were installed in 2000, and then westbound ones in 2001.

Figure 6-9 shows data taken in December 2001 with snowplow C#7005 for the whole track length on the new eastbound and westbound sections. The longitudinal distance standard deviation is 4.9 cm, which is significantly worse than the other sites. This situation is due in part to the fact that the magnets had to be moved around the grooves in the concrete so that they did not fall too close to the grooves.

Other collected data showed a big variation in magnetic field strength, which indicates that some magnets were buried too deep. This is especially true for the eastbound section, which was the first section done by the new contractor. The signal processing had to be significantly tuned to detect all the magnets. Still, some of the magnets are so deep that they can never be detected. Because of this problem, codes #201, #203 and #207 in the eastbound section can never be read.



Figure 6-9: Longitudinal Distance between Magnets at I-80, CA

Magnet Coding

PATH has used several different coding schemes to code information into the magnetic markers using the north and south pole orientations of the magnets as zeros and ones of a binary code. Two types of coding schemes (and combinations of them) have been installed in various test tracks: generic coding with road information embedded in the code, and milepost-style coding with a corresponding map database linked by decoder software. Limitations have been observed for all the current implementations. The RoadView project employs two different milepost-style coding schemes: a 16-bit code on the old sections and a 19-bit code on the new sections. The new code length was chosen so that the maximum number of codes would span the maximum length of the highway to be outfitted with magnets for snowplow operation. In order to minimize the number of codes, and to quickly identify the appropriate travel direction, the default polarity was chosen to be opposite on each section. Once the software knows the direction of travel, the same code number can thus be used on each section.

Arizona

US-180 is one of the first highways to be used for the RoadView project, and thus is installed with the 16-bit code. There are 48 codes total, 24 for the northbound and 24 for the southbound. Each code is spaced at 204 meters. Codes #1 to #47 (even) on the northbound section and codes #49 to #63 (even) on the southbound sections were installed in 1998. Codes #0 to #30 (odd) on the southbound sections were installed in 2000. The default polarity is "1".

Shasta

SR-299 is installed with the new 19-bit code. There are 90 codes total, 45 for the eastbound and 45 for the westbound. Each code is spaced at 180 meters. Codes #265 to #309 were installed on the eastbound section, and codes #309 to #265 were installed on the westbound section. The default polarity is opposite on each section: it is "0" on the eastbound and "1" on the westbound.

Tahoe

I-80 is the only highway that is installed with the two coding schemes, which greatly complicates the decoder software that has to be able to read both types of code.

The first section installed in 1998 has the 16-bit code. There are 30 codes, each spaced at 204 meters, from code #3 to #61 even. Code #1 was installed in the maintenance yard. The default polarity is "1".

The new sections installed in 2000 and 2001 have the new 19-bit code. There are 44 codes total, 22 for the eastbound and 22 for the westbound. Each code is spaced at 204 meters. Codes #199 to #220 were installed on the eastbound section, and codes #220 to #199 were installed on the westbound section. The default polarity is opposite on each section: it is "0" on the eastbound and "1" on the westbound

With the increase of opportunity in applying the magnetic sensing technology to various pilot projects throughout the state, an optimum/standardized coding strategy for magnets (which can be implemented statewide or nationwide) is in urgent demand and needs to be investigated. The development of the coding scheme may involve the characterization and prioritization of required roadway information, tradeoff analysis and evaluation with respect to possible integration with other technologies (such as GPS). Any coding proposition should include the discussion of the tradeoffs among the following factors: code length, error correction ability (with respect to missing or misread magnets), information redundancy, installation and maintenance simplicity, national standard/local specificity, short-term applications/long-term integration.

Link between Magnet Sensing and HMI

This section describes the link from the magnetic sensing signal processing algorithm to the human machine interface display.

Guidance information is crucial for performing the tasks associated with driving. The information that a driver can use is limited to the recognition and perception of what can be seen and felt. Such information includes forward knowledge for speed control and lateral information for steering control. When the driver does not have a clear view of what is in front of the vehicle, the ability to carry out driving tasks in a safe manner is diminished. From a control-engineering viewpoint, the driver steering function presents itself in the form of a closed-loop control problem. The driver acquires vehicle and road information using his perception; the brain processes these data and directs the hands to steer in order to follow the desired trajectory; and various human "sensors" report back the vehicle response with respect to the desired trajectory

and thus complete the control loop. Multiple senses are used to support steering functions. By fusing various pieces of perception information together, human intelligence derives complex and adaptive control strategies to perform the steering function. However, as soon as the driver switches to using the steering guidance system, application of perception may not occur in the same manner as in the unassisted steering mode. That is, the steering guidance system may not be able to supply the same information as is perceived in the normal driving environment, especially when the vehicle position is obtained through "look-down" lateral sensors [29, 32] as is the case of the magnetic sensing system. With practice the driver is likely to learn to adapt to the new system, but it is undesirable if such a system requires intensive training, or if the use of such a device demands constant driver concentration.

In observing human steering behavior, one may suggest that an "ideal" steering guidance system would allow the driver to steer using minimal vision demand during non-safety-critical situations (although it may not be "recommended"). To approach this goal, a "good" steering guidance system should allow the driver not only to maintain the desired vehicle lateral position without excessive steering oscillation, but also to steer through the present curve without deliberate eye-tracking of any component of the guidance display [29, 31]. Furthermore, variation in the steering performance due to individual drivers' characteristic difference should also be minimized. The two essential performance requirements defined in [29, 33] for the Caltrans snowplow steering guidance system are to allow different drivers to:

- (1) acquire the vehicle lateral information at a glance, and
- (2) switch between normal and guidance-assisted driving at ease.

Since the snowplow driver cannot afford to stare at the display for any extensive length of time, the statements "at a glance" and "at ease" represent crucial design criteria for the display design. In the snowplow steering guidance case, a "predictive" display law that satisfies the above requirements is proposed in [7]. The design process consists of the following three major steps:

- (1) model the human steering characteristics as a variable time lag with variable gain,
- (2) design a control law that stabilizes the driver-in-the-loop steering control problem and satisfies the lane tracking performance with sufficient gain and phase margins, and
- (3) allocate the "dynamic" portion of the control law into the display law and present the information to the driver in an intuitive and direct manner.

To alleviate the above problems, a driver display with predictive function was developed. A major component of this lateral assistance display is the prediction feature (see Figure 6-10). This marker shows the future lateral position 20 m ahead corresponding to the magnitude and direction of the steering wheel angle, δ . When the steering wheel is turned to the left, the prediction marker moves left. The current lateral position of the vehicle, y_0 , is shown at the bottom of the display. The graphic represents a displayed distance of 20 m with a 2 m width between the "curbs." Road lines are computed using an internal map database of road curvature and heading angle, θ . A driver can steer by positioning the predictor at any desired "future"

location. The internal dynamics governed by the prediction control law then steer the vehicle to the predicted position. More details on the development of this display and sensing system can be found in [27, 29].



Figure 6-10: The Lane Positioning Assistance Display

The calculation of the lateral position of the prediction marker, y_p , can be described using:

$$y_p = ay_0 + bd\theta + cY(d,\delta), \qquad (6-9)$$

where a, b and c are coefficients that describe the gain on each term and d is the look-ahead distance. As a typical example, one can choose the numbers for a, b and c to be equal to one. In such case, y_p becomes the "true" predicted position of the vehicle. The first and second terms in the right hand side of Equation (6-9) represent the components in y_p that are contributed by the current vehicle location, and the vehicle heading angle, respectively. The last term, $Y(d, \delta)$, is the vehicle displacement at d meters ahead of the vehicle if the driver maintains the current steering angle δ . Note that there is no direct sensor providing vehicle heading. Instead, heading angle is output from an estimator, based on the lateral measurement history (moving window), road curvature, steering angle, and a dynamic model of the snowplow. Under normal vehicle operating conditions, Equation (6-9) can be approximated into Equation (6-10).

$$y_p = ay_0 + bd\theta + c\frac{d^2}{2}G_v(s)\delta, \qquad (6-10)$$

where $G_{\nu}(s)$ is the dynamic factor between steering angle and vehicle traveling curvature. See [29] for a more detailed derivation of the above equations.

CHAPTER SEVEN: COLLISION WARNING SYSTEM

In general, a Collision Warning System (CWS) will be capable of detecting and warning the driver of potential hazardous conditions near the forward, side, and rear regions of a vehicle. In the past, much of the research in developing collision warning systems has focused on systems for highway driving in passenger vehicles [2, 7, 17, 28, 37, 39, 41, 44]. In these works, the CWS typically only looks at the lane directly ahead of the driver and either generates an audible warning or activates automated throttle and/or brake control.

Multiple radars have also been used, for example, in a system developed by Veridian Engineering [13]. This system is, however, aimed intersection collision warning, and is not well-suited for highway applications. The systems developed in Minnesota [8, 18] and earlier research at AHMCT [34, 42, 43] address multiple lanes. The Minnesota system detects obstacles in the forward and rear lanes. The system developed at AHMCT displays forward obstacles in each of three lanes, that is, the left, center and right lanes (assuming a three-lane highway). This lane configuration is designed to facilitate snowplow operations on a three-lane highway with a lead CWS-equipped plow in the center lane. However, early versions did not accurately detect and display obstacles in curved sections of the roadway. Thorne *et al* [34] did investigate fixed-curvature situations but did not address changes in curvature. This chapter presents a solution to this problem.

In a collision warning system, information flows among the various system modules, that is, from the sensing systems (which might include a Forward Collision Warning system and a Side Collision Warning system), to the Collision Warning Processing Module, and eventually to the Driver-Vehicle Interface (a.k.a. HMI), which provides warning cues to the driver. In addition to the sensing systems input, the Collision Warning Processing Module also receives information about the host vehicle's states (yaw rate and vehicle speed) from on-board sensors, which are combined to determine the vehicle's position relative to the lane, as well as to calculate the vehicle's projected path. The Collision Warning Processing Module combines the information from the active sensing systems (i.e. target tracking sensors) and passive sensors (i.e. on-board sensors used in tracking the host vehicle) in order to accomplish object detection, target tracking, in-path target identification, and threat assessment. If the detected target is assessed as being a potential hazard to the host vehicle, then warning cues will be provided to the driver in the form of visual, auditory and/or tactile cues. An advanced system may include vision (optical or infrared). Figure 7-1 conceptually illustrates the envisioned architecture for such a system [36].



Figure 7-1: for a Collision Warning System Conceptual Architecture [36]

Millimeter Wave Radar

Automotive millimeter-wave (MMW) radar sensors are rapidly moving from a research and development technology to a consumer commodity. The rapid progress in RF (radio frequency) technology, the explosion of processing speed, and decreasing prices of mm-wave components make radar more and more interesting as a consumer product. For monitoring the car's motion and surroundings (especially in the direction of motion), radar systems have been investigated and tested on vehicles since the early 1970s by the major car companies, and many research institutions. Radar makes possible new automotive features that increase the driver safety and convenience. The exact measurement of distance and relative velocity of objects in front, beside, or behind the car makes possible systems that improve the driver's ability to perceive objects while driving in poor visibility conditions or objects hidden in the blind spot during lane changes, or even stationary objects during parking maneuvers. Forward-looking radar has been extensively tested for obstacle warning and autonomous adaptive cruise control [7, 17, 28]. Millimeter-wave automotive radar is expected to be a key technology improving driving safety in the 21st century. Over a period of more than two decades, a large number of radar-based sensors have been developed for ground-speed, acceleration or drift measurements, for road condition recognition, for pre-crash condition detection, and for use as a parking aid.

Since 1992, a relatively simple forward looking radar using a single beam has been built by VORAD Safety System Inc. [5]; a version of this system was installed in 1700 Greyhound overland buses [38]. The accident rate at that time was reduced by about 25%, resulting in the lowest accident rate in Greyhound's history. Most other radar sensors have been developed for adaptive cruise control and require several beams for angular resolution of the azimuth. This may
be achieved by using different techniques such as mechanical beam scanning, electronic beam switching, electronic scanning via a frequency sweep, or mono-pulse techniques.

Characteristics of Millimeter Wave Radar

Millimeter waves offer several advantages over microwaves for radar applications in collision warning systems used in snowplows. Advantages include decreased antenna size, increased angular resolution, bandwidth availability, range resolution and Doppler sensitivity. Additionally, there is a greater immunity to interference, along with an increased immunity to unwanted detection.

Antenna

The antenna diameter required at MMW frequencies is smaller than the diameter required at lower microwave frequencies. This is a key advantage of MMW over microwave systems. For a given physical antenna size, the beam-width is smaller and the gain is higher. This characteristic is important in applications where the size and weight of the hardware are constrained, such as for automotive range finding sensors for longitudinal control. Comparison of X-band (9 GHz) and W-band (95 GHz) frequencies shows that the antenna diameter required at the latter millimeter wave frequency is less than the diameter required at the lower microwave frequency by a factor of ten. This is evident from the data in Table 7-1.

Angular Resolution

Angular resolution for the same antenna diameter is increased for the MMW radar. This results from the smaller antenna beam-width. Narrow beam-width is of paramount importance since it provides a distinct target outline from the competing "clutter patch" around the target. The beam-width of a diffraction-limited antenna is given by [23]

$$\theta = \frac{\kappa \times \lambda}{D},\tag{7-1}$$

where θ is the half power (3 dB) beam-width in the plane corresponding to dimension D, which for a circular aperture would be the diameter, and λ is the wavelength. The scalar κ may be in the range from 0.9 to 1.4 rad (52 – 80 degrees) depending on the amplitude taper across the aperture, which frequently is chosen to reduce sidelobe levels to a desired value. A typical empirical rule of thumb uses a mid-range value, e.g. $\kappa = 1.13$ rad (65 degrees) [23]. With this value, for example, a circular aperture antenna having a diameter of 15 cm has a half power beam-width of 5.4 degrees at a frequency of 24.125 GHz but has a beam-width of 1.4 degree at a frequency of 94 GHz. Values calculated from above equation are shown in Table 7-1.

Antenna Diameter (cm)	Beam-width (Degrees)					
	10 GHz	35 GHz	94 GHz	140 GHz		
10.0	19.5	5.57	2.07	1.39		
50.0	3.90	1.11	0.41	0.28		
60.0	3.25	0.93	0.35	0.23		
76.0	2.57	0.73	0.27	0.18		

Table 7-1: Beam-Wid	lth for Antenna	Diameter vs.	Frequency
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Beam-width (Degrees)	Antenna Diameters (cm)				
(2 • 8 • • • • •)	10 GHz	35 GHz	94 GHz	140 GHz	
0.25	780	223	83	56	
0.5	390	111	41	28	
1.5	130	37	14	9.3	
6.0	33	9.3	3.5	2.3	

Bandwidth

Bandwidth availability for radar target signature processing in MMW radar is increased relative to microwave radar.

Range Resolution

The range resolution in MMW radar is increased. This characteristic of any radar is proportional to the bandwidth over which it is transmitted. On a percentage basis a given quantity of frequency coverage corresponds to a much greater bandwidth at MMW than at microwaves.

One percent bandwidth at 100 GHz is 1 GHz. This exceptionally wide bandwidth permits increased range resolution of MMW radars. And so there is an advantage, by a factor of ten or more, when compared to microwave radar. One of the constraints suffered by earlier automotive radar systems was that narrow frequency allocations within which they had to work that inevitably limited their range resolution.

Doppler Sensitivity

Doppler sensitivity is increased at millimeter wavelengths relative to microwaves. The amount of frequency shift is given by:

$$f_d = \frac{2V_r \cos \gamma}{\lambda} = \frac{2V_r f \cos \gamma}{c}, \qquad (7-2)$$

where f is the operating frequency, V_r is the relative target velocity, γ is the angle between the target heading and the line of sight of the radar, and c is the velocity of propagation.

Interference

Immunity to interference in MMW radar is increased. This results from the very small antenna beam-width of MMW radar and the accompanying high antenna gains. Increased atmospheric attenuation of MMW contributes to interference immunity and can be used to advantage in automotive radar applications.

Unwanted Detection

Immunity to unwanted detection is increased. This is another benefit of high antenna gains and increased atmospheric attenuation of MMW radar relative to microwave radar.

Other Advantages

Smaller and lighter components are two significant advantages that occur from the shorter operating range envisioned for the MMW radar applications over microwave systems. Other advantages include reduced sensitivity to smoke, clouds, rain, and haze. Note that all of these advantages favor the use of MMW radar for automotive applications.

False Warning Suppression Algorithm

Snow removal equipment and other vehicles are adversely effected by whiteout conditions. Two of the more important characteristics of whiteout are very poor visibility and reduced traction on the roadway. As a result, these vehicles are very vulnerable to collision with other vehicles or roadside objects. Eliminating, or at least reducing, such conditions will reduce financial losses due to collisions and lessen the stress on people who must drive in these difficult conditions. Collision warning systems are thus being developed to provide visual and auditory warnings of near collision circumstances, giving the operator adequate time to avert a collision. These systems must have sensors able to detect other moving vehicles on the road, and determine which ones pose a threat of collision. These same systems must also be able to detect fixed roadside objects such as signs, guardrails, trees, etc. Most importantly, such a system must produce a very minimal amount of false warnings, or they will be of little use to the operator.

Collision Warning System's Requirements

Snowplows operate at speeds up to 50 kph (31 mph) in California. With a tire-to-road friction coefficient of 0.1, corresponding to rubber on glare ice [40], the maximum plow deceleration is 0.1 g. In addition to such deceleration, we also have to assume a one second delay between any warning on the HMI and actual braking by an alert operator. At maximum snowplow speed of 56 kph (35 mph), the total distance traveled with the maximum deceleration is 105 m (344 ft). Commercially available sensors in use today have a range of 120 m (394 ft). Such a range is considered adequate, as alert and experienced snowplow operators will also engage the front snowplow blade immediately in case of an emergency to increase deceleration of the vehicle. Therefore, these numbers are conservative.

In addition to range, these sensors need to be able to track multiple vehicles on the road, some of which will be going the same direction as the snowplow, and others that may be stalled or approaching from the opposite direction. In all these circumstances, the closing rate of objects is critical in determining which pose a threat of collision. To further reduce false warnings from roadway and roadside infrastructures, especially when cornering, a radar system is needed that provides data on the lateral position (azimuth angle) of objects, as well as their range and closing rate.

Available Technologies

Several available sensing technologies have been tested for suitability in hostile, stormy roadway environments. These are acoustic, vision, and radar. Acoustic systems have proven unreliable for heavy snow removal vehicles operating in highly vibratory conditions. Vision systems, including lasers and image processing, are sensitive to weather and therefore they are not well-suited for snowy conditions. At this point only radar is sufficiently advanced in development and has been proven mechanically sound enough to be used on snowplows. Millimeter-wave radar systems that operate at 24.725 GHz, corresponding to a wavelength of 1.2 cm, can recognize targets that are approximately one meter square or larger. With these considerations, a pair of EVT-300 radar sensors was selected to be the collision warning system on the snowplow.

Eaton VORAD Radar (EVT-300) Specifications

The specifications for the EVT-300 radar system are as follows [5]:

- Target data: This includes accurate range, velocity and azimuth on up to twenty vehicles or objects within a range of 100 m.
- Doppler radar: Allows radar to determine relative speeds of other vehicles. In combination with vehicle speed data from the engine data bus, it determines the absolute speeds of vehicles ahead.
- Boresite correction: The system continually monitors and analyzes vehicle or object azimuth data to automatically correct up to +/-3 degrees of antenna misalignment.

- Curved road: The combination of yaw rate and object azimuth angle provides collision warning on curved road (note that the overall RoadView CWS addresses this issue in a different manner, discussed below, with the benefit of predicted curve geometry)
- Closing rate: 0.4-160 kph
- Operating range: 1-150 m
- Host vehicle speed: 0.8-192 kph
- Power requirement: 12-24 VDC, 20 Watt
- Temperature range:-40 to +185 degree (F)
- Frequency: 24.725 GHz.



Figure 7-2: Dual EVT-300 Radar Coverage

Original (ASP-II) Algorithm

Under ASP-II, further development of the CWS focused on assigning obstacles to their actual lane using a new radar system, the Eaton VORAD EVT-300, and dealing with current curvature to reduce false warnings. This sensor tracks up to seven targets, providing target ID number, closing rate, range, signal quality, and azimuth angle. By using azimuth angle information both the longitudinal and lateral positions of the obstacles can be obtained. The maximum horizontal beam width of the EVT-300 is 14 degrees. With a single center-mounted antenna, targets in adjacent lanes can be detected at a minimum distance of 14.9 m (48.9 ft) in front of the vehicle and the minimum full coverage of the three-lane road is 44.7 m (147 ft). Therefore targets in adjacent lane would disappear from the HMI once they were closer than 14.9 m. These blind spots were not acceptable in snowplow operating conditions. Selecting from a variety of geometric configurations with two radar sensors, these blind spots were reduced. Figure 7-2 is a diagram of two radar beams projected forward from a snowplow. The two sensors are mounted to the front of the vehicle with each being 0.36 m (1.2 ft) from the centerline of the vehicle,

angled 4 degrees out, and 2 degrees down. With this configuration, there are a front blind spot of 6.9 m (23 ft), and adjacent lane blind spot of 7.4 m (24 ft), and the three-lane full coverage area is 26 m (85 ft). The forward blind spot is not critical because theoretically objects having a width greater than 0.74 m (2.4 ft) are observable down to 0.0 m separation distance. Obviously, this configuration introduces a coverage overlap, with a large area covered by both radars. This is easily rectified in the software. Since each radar antenna detects up to seven targets, the software addresses a maximum of fourteen targets.

An algorithm was developed which used a series of sorting routines to separate the fourteen targets detected by the two sensors into lanes 1, 2, and 3 (as shown in Figure 7-2). The algorithm then selects the closest target in each lane and displays those targets as a bar moving down the corresponding lane on the HMI. The three bars on the HMI correspond to the left, center, and right lanes. This approach allows the operator to observe the driving patterns of vehicles in adjacent lanes in a poor visibility environment. Figure 7-3 shows the HMI, which was used in the RoadView system. Note that the concept of a lane is situation-dependent. For the three-lane testbed on I-80, for example, the lanes do correspond to the left, direct ahead, and right lanes with respect to the snowplow. For rural sites such as Arizona and Burney, the "left" lane corresponds to oncoming traffic, and the "right" lane corresponds to the shoulder. The software includes site-specific parameters to adjust for these differences and to provide the appropriate behavior for the given location. The two operating scenarios are sufficiently different to justify distinct CWS behavior, based on interviews with snowplow operators.



Figure 7-3: RoadView HMI Charactristics

The ASP-II False Warning Suppression System (FWSS) reduced false warnings on straight stretches of road and in curves. To determine whether the vehicle is on a straight or a curved road the software used gyroscope and steering wheel encoder data to determine the truck's present path. The truck's calculated path is what defines the roadway for the software. The software then proceeds to eliminate false warnings for the selected roadway geometry. For these algorithms any radius greater than 10,000 meters is considered a straight road. The details of this algorithm are presented here for reference; however, this system has been superseded by a more advanced algorithm used in the RoadView CWS, as discussed later in this chapter.

On a straight road, on the basis of three lanes, each being 3.6 m (10.8 ft) wide, any obstacle outside of the lanes is eliminated by the software, and so out-of-lane obstacles are not seen on the HMI. For a curved section of road a more complex algorithm is necessary to make a similar determination. By using data from the gyroscope, Hall-effect speed sensor and steering wheel encoder, the algorithm can calculate a virtual curve origin and the snowplow's distance from that origin (i.e. the curve radius) as

$$R_{v} = \frac{V}{\omega}.$$
(7-3)

This defines the radius of curvature of a virtual roadway relative to the truck's reference frame. Here, speed V can be obtained in a number of ways, and yaw rate ω can be obtained from a gyro. Additionally, magnetometer data gives an accurate lateral location of the snowplow in the lane. Next, each target's Cartesian coordinates are translated to the new origin and converted to polar coordinates, giving the obstacle's radius from the origin and angle along the virtual curve. Then, based on the road curvature direction (left or right), the distance of obstacles from the centerline of the snowplow can be identified, and once again, any obstacle outside of the lanes are eliminated by the software, so that out-of-lane obstacles are not seen on the HMI.

This approach works well if the obstacle and the snowplow are both on a straight road or both on a curve. The problem with this existing algorithm becomes apparent during transitioning from one type of road to another, that is, from a straight road to a curved road, a curved road to a straight road, or a curved road to another curved road with different radius. In these circumstances the operator can receive false warnings (false positives) or missed warnings (false negatives) from the system. This is especially true in mountainous roads with high curvature. Therefore, a new algorithm was developed to eliminate these transitional false warnings by using the magnets in the road as a source of accurate roadway geometry, including prediction of upcoming curvature changes.

The RoadView FWSS Algorithm

A new set of algorithms was developed to more thoroughly prevent false alarms along all types of roadway. The previous algorithm works well in areas of fixed curvature, but performance is poor for areas near curvature transitions, where it was not able to recognize where obstacles were located in relation to those curves. The new FWSS has access to detailed current and upcoming roadway geometry, which allows it to accurately determine whether obstacles are in the path of the snowplow, as well as whether they are on or off the highway.

A Rural Field Test of the RoadView System

Once it is determined that a curvature change exists within the one hundred meter range of the radar (based on decoding of magnet data to obtain curvature, as detailed in Chapter 6), the new FWSS begins a threat assessment. The following discussion illustrates how the algorithm addresses each situation. The three scenarios to be solved for are listed here. In each case, the system will determine which lane the target is in for corresponding representation in the HMI, or will note that the target is actually off of the road and that no target information needs to be presented on the HMI.

1) When the snowplow is on a straight section and a curve comes into view, are detected objects located in the curved lanes?

2) When the snowplow is on a curved section and a straightaway comes into view, are detected objects located in the straight lanes?

3) When the snowplow is on a curved section and a new curve comes into view, are detected objects located in the new curved lanes?

While the discussion throughout this report has referenced snowplows and targets in relation to the left, center and right lanes, the following discussion will reference snowplows and targets in relation to the centerline of the roadway. This is because the software uses the centerline to accomplish the analysis. Therefore, the illustrations in this section show a centerline and the right and left edges of the roadway.

Case 1: Snowplow on Straight Section, Approaching a Curve

Figure 7-4 is an illustration of a plow on a straight road that is about to encounter a curved section of road within its one hundred meter field of vision. The variables used in Figure 7-4 are defined as follows:

R_1	Radius of the current curve.
1	reading of the current currey,

 R_2 Radius of the next curve,

 d_{bc} Distance from the snowplow to the beginning of the upcoming curve, and

 d_{cc} Distance from the snowplow to the center of the next curve.

The software retrieves the values for R_1 , R_2 and d_{bc} from the system database (for straight sections, $R_i = \infty$, corresponding to zero curvature). Note that in all cases the software handles left and right curves properly through appropriate use of signs, and much of this extra detail will not be included in the description herein.



Figure 7-4: Snowplow Approaching a Curve

In Figures 7-4 and 7-5, B is the distance from the snowplow to the center of the next curve at the point when the distance from the snowplow to the beginning of the next curve is equal to 100 m.

If $d_{bc} > 100$ m, then any targets found are in the area of the straight roadway and can be calculated by existing algorithm. Otherwise, for $d_{bc} < 100$, two different situations can exist. Targets can still be on the straight roadway (before the beginning of the curve) or they can be in the upcoming curve. When it has been determined that a target is present beyond the end of the

straight road section, the FWSS calculates whether the target is on or off the new section of road. A quick approximate check (valid for small azimuth angle α , which will always be the case for the radar data) is given by

$$D_t > d_{bc}, \tag{7-4}$$

for which case the target is in the area of the upcoming curve. Figure 7-5 is an illustration of a target that is in the new curve while the plow is still on the straightaway. The additional variables used in Figure 7-5 are

D_t	Distance from the plow to the target (radar range from sensor),
α	Azimuth angle to target (from radar sensor),
d_x	Distance between the curve's center and the target,
x_{lane}	Lateral distance between snowplow and target from lane centerline, and
Y _{lane}	Longitudinal distance between snowplow and target along the lane centerline.

Note that the azimuth α is the angle made by the intersection of the centerline of the vehicle and a straight line (with range D_t) drawn from the plow to a target. All angles are in radians. To continue,

$$d_{cc} = \sqrt{d_{bc}^2 + R_2^2}$$
, and (7-5)

$$b = \alpha + \cos^{-1} \left(\frac{d_{bc}}{d_{cc}} \right). \tag{7-6}$$

Then,

$$d_x = \sqrt{D_t^2 + d_{cc}^2 - 2D_t d_{cc} \cos(b)}$$
(7-7)

$$a_{T} = \cos^{-1} \left(\frac{d_{cc}^{2} + d_{x}^{2} - D_{t}^{2}}{2d_{cc}d_{x}} \right)$$
(7-8)

$$a_2 = a_T - \sin^{-1} \left(\frac{d_{bc}}{d_{cc}} \right) \tag{7-9}$$

Finally, the true lane position of the target is given by:

$$\boldsymbol{X}_{lane} = \boldsymbol{d}_{\boldsymbol{x}} - \boldsymbol{R}_{2} \tag{7-10}$$

$$y_{lane} = d_{bc} + R_2 a_2 \tag{7-11}$$





Figure 7-5 is a visual presentation that is intended to aid in understanding the algorithm. A comparison of the target's coordinates (x_{lane}, y_{lane}) to the mathematically defined three lanes provides the final determination for whether an object is in a lane or not. When the FWSS has determined that an object is in one of the lanes the information is displayed on the HMI.

Case 2: Snowplow in a Curve, Approaching a Straight Section

The second scenario begins when $R_1 < \infty$, i.e. for any non-zero curvature. This simple statement means the snowplow is in a curve and one of three possible situations exists. First, both the snowplow and target are in the curve, in which case the target is evaluated by the original algorithm [34]. Second, the snowplow is in the curve and the target is out of the curve, but on a straight section of road (corresponding to the case in this section), or third, the snowplow is in the curve and the target is out of the curve, but in the next curve (corresponding to Case 3, discussed in the next section). These latter two cases are evaluated by the FWSS. The data needed to determine the current scenario is found in the roadway geometry database.

This next analysis of target location uses some of the previous variables with some additions. In Figure 7-6 the variables R_1 , D_t and d_x are again important components along with the following new variables:

 d_{ec} : Arc segment distance between the plow and the end of the current curve, from the roadway geometry database.

Then,

$$c_1 = \frac{d_{ec}}{R_1},$$
 (7-12)

$$c_T = \cos^{-1} \left(\frac{R_1^2 + d_x^2 - D_t^2}{2d_x R_1} \right), \tag{7-13}$$

and
$$c_2 = c_T - c_1$$
. (7-14)

For this second scenario d_x is divided into two pieces at the centerline. These segments are:

$$d_{x1} = \left(\frac{R_1}{\cos(c_2)}\right) \tag{7-15}$$

and
$$d_{x^2} = d_x - d_{x^1}$$
. (7-16)

Finally, the true lane position of the target is given by:

$$X_{lane} = d_{x2} \cos(c_2),$$
 (7-17)

$$y_{lane} = d_{ec} + d_x \sin(c_2)$$
. (7-18)



Figure 7-6: Snowplow in a Curved Section and Target in a Straight Section

Once again a comparison of the target's coordinates (x_{lane}, y_{lane}) to the mathematically defined three lanes answers the question, is the object in a lane or not? If the object is in a lane it will be displayed on the HMI, and just as important, false warnings have been suppressed.

Case 3: Snowplow in a Curve, Approaching another Curve

Finally, consider the third scenario addressed by the FWSS, that is, when the snowplow is in a curve and the target is out of the curve, but in the next curve. Looking at Figure 7-7, many of the previous variables are useful components of this third analysis. Once again we have R_1 , R_2 , D_t , d_x , and the angles c_2 and c_T . The following are additional variables:

 d'_x Distance between the center of the second curve and the target, and

 c_3 Angle between the beginning of the second curve R_2 and d'_x .

with values given by

$$d'_{x} = \sqrt{d_{x}^{2} + (R_{1} + R_{2})^{2} - 2d_{x}(R_{1} + R_{2})\cos(c_{2})}, \qquad (7-19)$$

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and
$$c_3 = \cos^{-1} \left(\frac{d_x'^2 + (R_1 + R_2)^2 - d_x^2}{2d_x'(R_1 + R_2)} \right).$$
 (7-20)

Finally, the true lane position of the target is given by:

$$\boldsymbol{x}_{lane} = \boldsymbol{R}_2 - \boldsymbol{d}_x^{\prime},\tag{7-21}$$

$$y_{lane} = R_1 c_1 + R_2 c_3. \tag{7-22}$$



Figure 7-7: Snowplow in a Curve and Target in Another Curve

Again, the software determines a target's location (x_{lane}, y_{lane}) with respect to known roadway geometry, and in turn, ascertains whether the target is on the roadway or not. An object found to be in a lane is displayed on the HMI.

Simulation

The evaluation of obstacle detection without the False Warning Suppression Software was completed in previous research at the AHMCT Research Center. The previous algorithm was only applicable to straight roadways and was not capable of handling the integration of curves following straight sections of roadway. The new algorithm was successfully simulated for several curve configurations using AutoCAD and C++ programming software.

The new algorithm needs the following information as input:

- Distance D_t from the snowplow to the obstacle, which comes from the radar,
- Azimuth angle α , which comes from the radar,
- Radius R_1 of the current curve, which comes from the database, and can be retrieved from either the GPS or by indexing information provided in the database by using coded magnets and GIS,
- Radius R_2 of the upcoming curve, which comes from the database (again, various methods of indexing the database can be used),
- and Distance d_{bc} to the change in curvature, which comes from the database (yet again, once more various methods can be used).

With this information the algorithm checks the exact positions of the obstacle and the host vehicle, and also, decides if the obstacle is in the road or not. As these simulations demonstrate the program finds the actual x_{lane} which is the lateral distance between the obstacle and the center of the road, and y_{lane} which is the longitudinal distance (arc length along the road) from the obstacle to the host vehicle. x_{lane} is used to determine whether or not an object is in a lane. If an object is found to be in a lane then the coordinates (x_{lane}, y_{lane}) are the values used to determine the target's placement on the LCD screen.

An AutoCAD simulation was run in which the snowplow is moving through a curve and a target is detected in the area of the straightaway beyond the end of the initial curve. Figure 7-8 illustrates this scenario. Dimensions for some of the variables are visible in Figure 7-8 including x_{lane} . Here, $x_{lane} = 6.63$ is meters, so that the target is outside of the three lanes.



Figure 7-8: Simulation for Snowplow in Curve and Target in Straight Section

An additional simulation was run for the scenario in which a plow is in one curve and a target is in the area of a curve beyond the initial curve. Figure 7-9 is an illustration of this scenario in which the variable x_{lane} can be seen. Here $x_{lane} = 0$, which means the obstacle is right in the middle of the road. The formulas for this scenario are not presented in the previous discussion, but are a straightforward extension of the two-curve case.



Figure 7-9: Simulation for Snowplow in Curve and Target in another Curve, with Intervening Straight Section

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In this chapter we have explained how both the CWS and the FWSS function. Additionally, we have shown that the FWSS determines more accurately whether objects are on or off the road in situations where there are complex sets of roadway geometry; hence the FWSS significantly reduces false warnings related to roadway transitions.

CHAPTER EIGHT: CONCLUSIONS AND FUTURE RESEARCH

Conclusions

The RoadView Advanced Snowplows were deployed to the Caltrans maintenance fleet in December, 2000. Caltrans operators used the vehicles on a regular basis through the winters of 2000-2002, sometimes continually for several days straight during periods of intense storm activity. Caltrans testing occurred at both the AWMT site at Kingvale on Interstate 80, and at the RWMT site on State Route 299 at Burney. Additional testing occurred in our partner state, Arizona, on US 180 near Flagstaff over the two winters. Research engineers continued to analyze and improve the performance of the system, as well performing minor preventive and responsive maintenance on the system, throughout the season's testing. In addition to instrumenting the two new RoadView vehicles, AHMCT updated the original Advanced Snowplow (ASP) vehicle to the latest system hardware and software, so that the three vehicles matched to the extent possible. Data regarding operator use of the system was collected during ride-alongs by the research team. Detailed operator surveys were also performed. Analysis of this data was presented in Chapter 5; results are positive.

Qualitatively, the survey results presented in Chapter 5 indicate operators are in general comfortable with the RoadView system. Specifically, the fraction of drivers indicating that achieving comfort would take less than three days shifted from about half to about three quarters. With respect to the Collision Warning System specifically, the presence of extraneous warnings on high-curvature rural roads yielded a lower qualitative operator survey response. Specific causes for extraneous warnings have been identified via quantitative analysis of video and recorded data, and remedies are being considered for follow-on research. Quantitatively, the Collision Warning System provided 73% correct detection, which represents a significant improvement from earlier phase research, but does leave room for improvement.

It is clear that the RoadView HMI has the potential to be quite beneficial to driver safety and confidence. Quantitative and qualitative findings suggest that, even with limited instruction, the interface is intuitive and easy to learn. Most drivers were observed to reach a stable level of performance after driving the RoadView for one run or less. Anecdotal comments and experimenter observations also suggested that the display could easily be used either for reference or as a primary driving mechanism.

Based upon analyses of objective data, the system appears to allow drivers to more consistently maintain a stable position near the lane center. Small drops in performance for speed and steering wheel standard deviation while the system was on do not appear to have substantial functional relevance even though there were statistically significant differences. As such, driving with the system appears to be quantifiably similar, if not slightly better, than unaided driving. In addition, note that the comparisons between "display on" and "display off" were made under less than whiteout conditions. Under whiteout conditions, the display will allow plowing operation to continue in situations where it would not be safe to plow without such a device; this was the primary motivation and goal of the RoadView ASP development.

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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 during ASP-I was based on computational concerns and a desire for simplicity. However, drivers responded well to the display and field measurements showed good performance can be achieved without computationally intensive graphics or custom hardware, a feature that has direct ramifications on commercialization and deployment.

The experience gained during the Phase I and II studies was invaluable for RoadView efforts. During Phase I, the research team developed a better understanding of the true nature of the harsh operating conditions the system must overcome. In addition, the team gained far better understanding of the entire snow removal operation, based on time spent at the test site; this learning process continued through ASP-II, under which the hardware and software were substantially improved with respect to ruggedness and robustness. The ASP-I experience allowed the research team to develop the second-generation system (ASP-II), advance the robustness of the hardware, enhance and further validate the HMI. These experiences led to a more mature design and implementation for the RoadView vehicles, and enhanced the field-testing process.

The results of the RoadView field-test study demonstrate the safety and efficiency that can be obtained through judicious application of Intelligent Vehicle technologies for a maintenance vehicle operating in a harsh and hazardous environment. Under whiteout conditions, the system eases the workload of the snowplow operator, while simultaneously enhancing the safety and efficiency of the operation. This concept is applicable across the Special Vehicle category (maintenance, police, fire, and emergency medical), where operators must perform their duties in all conditions in order to ensure public safety and availability of facilities. Appropriate care must be taken in extending results from snowplow-based work into other vehicle types, particularly with respect to intended use and human factors issues. In addition, there are concerns regarding the impact of embedded roadway references on infrastructure cost, maintenance, and lifetime; however, AHMCT is investigating alternative approaches which may eliminate the need for the embedded elements. With respect to the overall concept and application, RoadView appears applicable across all vehicle platforms, including light vehicles, commercial vehicles, and transit vehicles, under the appropriate operating conditions. In particular, a RoadView-based system appears promising to assist emergency response vehicles in low visibility conditions, including dense fog.

Based on the results for RoadView testing, as well as strong interest from several State DOTs, the system concept as embodied in the RoadView research prototype is a viable launching point for future commercialization. The AHMCT center is investigating methods to transition the system from a research prototype to a state that is ready for a private entity to adopt and provide as a commercial product. With the field-testing and operator feedback from the current project, there is a clear interest in the system, and a general positive view of the concept of driver assistance as well as the specific implementation within the RoadView framework. In addition, the cost benefit analysis and needs assessment of the supplemental report by WTI also lend weight to future development and commercialization of the RoadView system. From a technical feasibility standpoint, the concept of driver assistance for snowplow operators has been proven as effective in terms of enhancing safety, and desirable from the operator's point of view. In addition, the technology has been shown to be field-ready through four winter's testing in some of the harshest snow environments in the lower 48 United States. Clearly, RoadView is

still in some aspects a research prototype, and further improvements are needed in terms of manufacturability, additional robustness, packaging, cost, etc. However, the research team is committed to continued efforts to enhance the state of the system, and to work with commercial entities to ensure that this valuable addition to the winter maintenance arsenal is transitioned smoothly from a research prototype to a commercially available system.

Future Research and Development

At this stage in the program development, the magnet guidance based RoadView system is mature from a research standpoint. The system as embodied in the RoadView prototype vehicles is now ready for transition to detailed commercialization; however, there are a number of open questions that can be pursued in future research and development.

The RoadView CWS is in general quite effective for forward collision warning on rural roads. Some improvements are needed with respect to false warnings, but this can be achieved through incremental changes in the system, rather than a major revision in the concept or implementation. Additional safety improvements could be made by adding rear collision warning, i.e. for impact from a vehicle behind the snowplow, as this is a primary mode of snowplow-related accidents; however, actual alarm and alert methods for this approach must be determined. Recent work by Minnesota researchers in this area focuses on providing warning to the driver of the vehicle behind the plow, using a high-intensity strobe; these efforts hold great promise. Additional modes of providing operator alerts (audible, other visual means, haptic, tactile, etc.) should be investigated in detail to determine the appropriate mix of alerts in the context of the noisy and high-distraction snowplow operating environment.

As part of the commercialization process, improvements can be made in the in-vehicle sensing systems. Significant steps have been made in this regard by AHMCT, with the development of an Intelligent Sensing Architecture, currently targeted for sensing of discrete magnetic markers, i.e. as a replacement for the existing sensing system in RoadView. This intelligent system provides numerous advantages over the existing technology. All data transmission is digital, so that electronic noise is eliminated and cabling requirements are vastly reduced. The resulting system is more robust and maintainable, while simultaneously being an order of magnitude cheaper. Sensing algorithm modifications can be made so that the system can provide key information over a wide range of speed, all the way down to zero velocity, thus facilitating use in other operations, such as low-speed bus docking. The signal processing algorithm can be extended to support both discrete and continuous magnetic reference marker systems. In addition, the processing unit can be extended to encompass other aspects of the invehicle system, ultimately leading to a "black box" that could be easily retrofitted in an existing vehicle, e.g. in the snowplow cab, allowing a commercial entity to develop a feasible aftermarket kit. Lab and preliminary vehicle tests for this system have been performed and the design and algorithms have now been confirmed [4]. Research and development on this sensing system continues at AHMCT, and early versions of the system are currently being considered for commercialization.

Other areas of research may include vehicle and environment modeling, and further integration of vehicle tracking and process data into GIS management solutions. Vehicle and environmental modeling can improve the overall driver assistance and control, as well as

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providing sensing and control solutions for special-case high-danger situations, such as ice-pack induced accidents. In addition, the driver assistance system can log data that is useful for snow and ice management. Integration of this information into a comprehensive GIS database could enhance the DOT's ability to more effectively keep roadways clear. In addition, real-time knowledge of plowing activities could be integrated into the broader traveler information system, which could prove very useful to the traveling public.

In addition to the lateral vehicle automation being developed by PATH for the ARP, AHMCT plans to investigate application of driver assistance systems for rotary plows for normal blower operations as well as road opening. Such operation will include use of embedded discrete magnets where appropriate, but will make increased use of GPS and Inertial Measurement technologies, particularly for road opening operations wherein magnets will not be appropriate.

The RoadView ASP program has applied discrete magnetic marker based lateral sensing and forward collision warning to provide driver assistance, thus keeping the driver in the loop and allowing deployment of these technologies on public roadways in mixed traffic in a safe manner. The technologies employed in RoadView clearly evolved from earlier full vehicle control work by PATH, such as that performed under the NAHSC program [25]. Thus, application of these technologies for full automation in appropriate winter maintenance tasks is a reasonable next step. One such project, scheduled for completion early in 2004, is the "Development of the Advanced Rotary Plow (ARP) for Snow Removal Operations," a pooled fund study, led by Caltrans, with participation by the Alaska DOT. This project includes full lateral control, along with forward obstacle detection for objects located beneath the snow. Application of precision lateral control for the blower will reduce or eliminate contact with the guardrail, while also improving the repeatability and accuracy of the work performed. Collision hazards are introduced by the presence of natural objects, such as large rocks and debris, as well as abandoned vehicles. Obstacle detection technology will provide added safety, as well as reduced DOT liability, repair costs, and downtime.

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APPENDIX A: ROADVIEW AND ASP EVALUATION QUESTIONNAIRES

RoadView Advanced Snowplow Evaluation Questionnaire

Arizona February 2002

We would like to ask you some questions regarding your opinion of the driver assist system. We will not be recording your identity and this information will not be associated with you or be used as a means of evaluating your performance. We are only interested in evaluating the system. We may share this information with Caltrans/Arizona DOT.

Your participation is voluntary. You are free to refuse to take part. You may refuse to answer any question and may stop taking part in the study at any time. Whether or not you participate in this research will have no bearing on you standing in your job.

Background information:

How long have you been driving snowplows?

Please rate your level of expertise (1 being novice and 5 being an expert)?

Approximately how many hours of service have you accumulated in the automated snowplow?

General Assessment:

1. Please describe the system and how it works the way that you would to another plow driver that has not yet seen or used the system.

How easy is the system to use overall?	(very easy) 1 2 3 4 5 (not easy)
How much do you like the system overall?	(a lot) 1 2 3 4 5 (not at all)
If you had more time to practice with the system, would you like it more?	(yes) 1 2 3 4 5 (no)
Do you think that they system is beneficial in terms of increasing your safety?	(yes) 1 2 3 4 5 (not at all)
Rate the system in terms of increasing the efficiency of your snow removal tasks	(helpful) 1 2 3 4 5 (not helpful)

For the following questions, please rate how well the system performs:

- 2. How long do you think you would need to become comfortable with this system?
- 3. Under what conditions was the system most helpful? (Daylight vs. darkness? Low visibility vs. high visibility? Snow accumulations of what depth? Roadway geometry or alignment features?)
- 4. Did the system ever lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

Driver Assistance Functions:

For each component Collision Indication, Lane Keeping:



Collision IndicationLane KeepingHow easy is this component to use?How easy is this component to use?(very easy) 1 2 3 4 5 (not easy)(very easy) 1 2 3 4 5 (not easy)How much do you like this component?How much do you like this component?(a lot) 1 2 3 4 5 (not at all)(a lot) 1 2 3 4 5 (not at all)Comments:Comments:

Suggested Changes:

- 5. If you could add one feature what would it be & why?_____
- 6. If you could remove one feature/display method what would it be & why?
- 7. Please draw on the back of this sheet what you feel would be an ideal display?
- 8. Please list any other comments/suggestions regarding the different ways of presenting the information_____

Advanced Snowplow Evaluation Questionnaire

RoadView 2000/2001

We would like to ask you some questions regarding your opinion of the driver assist system. We will not be recording your identity and this information will not associated with you or be used as a means of evaluating your performance. We are only interested in evaluating the system. We may share this with Caltrans/Arizona DOT.

Your participation is voluntary. You are free to refuse to take part. You may refuse to answer any question and may stop taking part in the study at any time. Whether or not you participate in this research will have no bearing on your standing in your job.

How long have you been driving snowplows?						
How much time have y	you lo	gged	on the C	CA Ad	vanced S	Snowplow?
Did you experience thi	is syst	em las	st winte	r?	Yes	No (If "No" skip to Question 2)
For the following ques	For the following questions, please circle the <u>number</u> of your choice:					your choice:
1) Is the system better	than l	ast yea	ar?			
(Not at all)	1	2	3	4	5	(A lot)
2) How easy is the system to use overall?						
(Not easy at all)	1	2	3	4	5	(Very easy)
3) How much do you like the system overall?						
(Not at all)	1	2	3	4	5	(A lot)

4) If you had more time to practice with the system, would you like it more?

(No) 1 2 3 4 5 (Yes)

5) Please rate the potential of the system to improve your safety:

(Not at all) 1 2 3 4 5 (A lot)

6) Please rate the potential of the system to improve your efficiency:

(Not at all) 1 2 3 4 5 (A lot)

Please answer the questions on the back/next page.

For each *component* (Collision Warning, Lane Keeping):



Collision Warning	Lane Keeping			
How easy is this component to use?	How easy is this component to use?			
(Not easy at all) 1 2 3 4	5 (Very easy) (Not easy at all)			
1 2 3 4 5 (Very easy)				
How much do you like this component?	How much do you like this component?			
(Not at all) 1 2 3 4 5 (A lot)	(Not at all) 1 2 3 4 5 (A lot)			
Comments:	Comments:			

How long do you think you would need to become comfortable with this system?

Please draw or describe what you feel would be an ideal display:

Are you a trainer/team leader for a magnetic snowplow? (circle each) CA ASP

ADOT-3M
Advanced Snowplow Evaluation Questionnaire

ASP2 - 1999/2000

We would like to ask you some questions regarding your opinion of the driver assist system. We will not be recording your identity and this information will not associated with you or be used as a means of evaluating your performance. We are only interested in evaluating the system. We may share this with Caltrans/Arizona DOT.

Your participation is voluntary. You are free to refuse to take part. You may refuse to answer any question and may stop taking part in the study at any time. Whether or not you participate in this research will have no bearing on your standing in your job.

How long have you been driving snowplows?						
How much time have you logged on the Advanced Snowplow?						
Did you experience thi	s syst	em las	st winter	?	Yes	No (If "No" skip to Question 2)
For the following questions, please circle the <u>number</u> of your choice:						
1) Is the system better than last year?						
(Not at all)	1	2	3	4	5	(A lot)
2) How easy is the system to use overall?						
(Not easy at all)	1	2	3	4	5	(Very easy)

A Rural Field Test of the RoadView System

3)	3) How much do you like the system overall?							
	(Not at all)	1	2	3	4	5	(A lot)	
4)	If you had more time	e to p	ractice	with the	e systen	n, woul	d you like it mor	e?
	(No)	1	2	3	4	5	(Yes)	
5)	5) Please rate the potential of the system to improve your safety:							
	(Not at all)	1	2	3	4	5	(A lot)	
6) Please rate the potential of the system to improve your efficiency:								
	(Not at all)	1	2	3	4	5	(A lot)	

Please answer the questions on the back/next page.

For each *component* (Collision Warning, Lane Keeping):



Collision Warning	Lane Keeping			
How easy is this component to use?	How easy is this component to use?			
(Not easy at all) 1 2 3 4	5 (Very easy) (Not easy at all)			
1 2 3 4 5 (Very easy)				
How much do you like this component?	How much do you like this component?			
(Not at all) 1 2 3 4 5 (A lot)	(Not at all) 1 2 3 4 5 (A lot)			
Comments:	Comments:			

How long do you think you would need to become comfortable with this system?

A Rural Field Test of the RoadView System

Please draw or describe what you feel would be an ideal display:

APPENDIX B: ALTERNATIVE RADAR EVALUATION INCLUDING DAYLIGHT TEST RESULTS

As noted in Chapter 5, the radar system is designed to perform based on low to zero-visibility (i.e. whiteout) conditions. Empirical test data for the RoadView contract period was not available under these conditions. However, detailed data was gathered during testing in Arizona in 2002. Data was collected during the day and at night. No snow was falling during this testing.

As night conditions more accurately reflect the target operating regime of the RoadView radar collision warning system, the results presented in Chapter 5 exclude the daylight data. For completeness, and to provide an alternative view of the radar testing, the complete results and analysis for the full and combined data set is provided here. Daylight performance is, as expected, inferior to night performance and other low-visibility performance. In addition, there were much more events during daylight testing hours, so that the poor daylight results have a higher weighting in the combined results. With these caveats, the combined data and analysis are presented here.

Radar Analysis

A baseline was needed in order to discuss the radar's effectiveness, and so 4 hours, 52 minutes, 38 seconds of video taken in clear weather on clear roads in Arizona was analyzed to determine how many warnings constitutes "too many" warnings. The video was a combination of information from three different drivers with a combined total of 33 runs in the northbound direction and 34 runs in the southbound direction. The video data was synchronized with the plow system data to determine when warnings were issued. The radar data was broken down into three categories; missed detections, correct detections and false detections. Within these categories the geographical location, road curvature and where applicable the radar tape affected (left, center or right) was recorded. A detection was counted if the signal was for more than 1 second.

A missed detection was defined as either a car going in the opposite direction that is not detected, or a car cutting in front of the plow that is not detected. A false detection was defined as any time that a warning was issued but no threat was noted by the researcher. A correct detection was determined where a warning was issued to indicate the presence of another vehicle (or object) that could present a potential threat to the plow. Where a car passed and cut in and was picked up by either the right or the center radar it was counted as a correct detection, if it was picked up by both radars, the left first and then the right it was counted as two correct detections. In cases where it was only picked up by center radar, the "miss" by the left radar was not counted. In addition when multiple cars were encountered they were counted as one event, this was done as we were not able to determine which vehicle was being picked up. No warnings from the right radar were observed during the video footage. No vehicles were encountered stopped in the forward path of the snowplow and no parked cars or objects (other than road signs) were present on the shoulder of the road during the testing. The right radar did not appear to detect objects when the vehicle was turning around at the end of each run in an area that forced the driver to make a very tight 3 point turn whilst surrounded by trees.

As can be seen in the table below there were 72 missed detections, 119 correct detections and 68 false detections. This gives a total of 187 warnings issued, which when averaged out equals one warning every 1.34 minutes. 63.6% of the warnings are correct leaving 36.4% of the warnings false.

Total driving time reviewed	4 hours 52 minutes 38 seconds
Total warnings issued	187
Average warning rate	1 every 1:34 minutes
(total warnings/driving time)	
Correct Detection Rate	63.6%
False Detection Rate	36.4%
Oncoming car in other lane Miss Detection Rate (by left radar)	53.4%
Total Miss Detections	72
Total Correct Detections	119
Total False Detections	68

Table B-1: Summary of Radar Detection Rates

Table B-2: Summary of where Detections Occurred

Section Name	Miss Detection	Correct Detection	False Detection
Kendrick Park	29	80	4
The Dip	10	7	8
Dirty Jacks	4	5	0
The Back Side	17	22	17
Hart Prairie Curve	12	5	39
Total	72	119	68

Missed Detections

71 of the 72 missed detections were for oncoming cars in the other lane. The remaining missed detection was a car cutting in at a fast rate. A comparison was made between the 71 undetected oncoming cars to the number of cars detected in the oncoming lane by the left

radar (62 cars). Comparison of these numbers suggests that the system missed slightly more cars than it detected.

The high speed of both the plow and the other cars (due to the good weather and traffic conditions) may have been a factor in the high rate of missed detections as at lower speeds it could be expected that more cars would be detected. As there was no cars parked in the lane that the plow was in or off to the side of the road correct and miss detection rates could not be calculated for these situations.

Note that the road curvatures noted below are from the drivers point of view as reviewed from the video footage when the missed detections occur. As can be seen in the table below the highest number of missed detections occurred when the plow was driving on straight sections. This may be a result of there being relatively more miles of straight sections than of curved.

Section Name	Road Curvature	Number of Missed Detections
Kendrick Park	Straight	29
The Dip	Straight	10
Dirty Jacks	Straight	4
The Back Side	Left	6
	Straight	9
	Right	2
Hart Prairie Curve	Left	2
	Straight	9
	Right	1
Total		72

Table B-3: Summary of Missed Detections

Correct Detection

The correct detections were broken down into different "events" in Table B-4 below. As can be seen from the Correct Detection Table the largest number of detections occurred on straight sections of road. As was mentioned in the missed detections section, this is possibly a result of there being more miles of straight sections than of curved it is more likely that vehicles will pass the plow on straight sections. Note that the road curvatures noted below are from the drivers' point of view when the missed detections occur

Description	Radar	Road Curvature	Number of Correct Detections
Oncoming car in other lane	Left	Left	2
		Straight	44
		Right	4
Oncoming car in other lane	Center	Left	3
		Straight	1
		Right	5
Car passing and cutting in	Left	Left	2
		Straight	15
Car passing and cutting in	Center	Straight	24
2 oncoming cars in other lane	Left	Straight	10
		Right	1
2 oncoming cars in other lane	Center	Straight	1
2 cars passing and cutting in	Left	Straight	3
2 cars passing and cutting in	Center	Straight	2
4 oncoming cars in other lane	Center	Straight	1
3 cars passing and cutting in	Center	Straight	1
Total			119

Table B-4: Summary of Correct Detections

False Detections

The number of false detections was a concern for the drivers. As can be seen in the table below there are two points where most of the false detections occurred, milepost marker 235.3 and 237.5. The researcher noted on the drive along that at the 235.3 marker there is a road sign that appeared to be picked up and at MP237.5 the system on occasion appeared to be picking up a guardrail. Comments from the California drivers suggest that the picking up of the road sign and the guardrail are less problematic if they occur consistently as with experience a driver can screen those out where known signs always trigger the system. Of greater concern are those false detections that occur in lower numbers as these can lead to operator distrust in the system. Operator distrust of the system will eventually lead to operators not using the system.

Note that the road curvatures noted below are from the drivers' point of view when the missed detections occur

Section name	Milepost	Road curvature	Number of False Detections
Kendrick Park	235.7	Straight	1
	235.8	Straight	1
	236.1	Straight	1
	236.3	Straight	1
The Dip	236.7	Straight	2
	236.8	Straight	5
	237.0	Left/Straight	1
The Back Side	237.4	Straight/Right	1
	237.5	Left/Straight/Right	9
	237.7	Straight/Right	2
	237.8	Left/Straight/Right	4
	237.9	Left/Straight	1
Hart Prairie Curve	235.2	Right/Straight	1
	235.3	Left/Straight/Right	34
	235.4	Left/Right	3
	235.5	Straight/Right	1
Total			68

Table B-5: Summary of False Detections