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Final Report

Driver Assistive Systems for Rural Applications: A Path to Deployment

Volume 1

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16. Abstract (Limit: 200 words)

Deployment of any system is driven by market demand and system cost. Initial deployment of the Intelligent Vehicle Lab Snowplow Driver Assistive System (DAS) was limited to a 45 mile section of Minnesota Trunk Highway 7 west of I-494 and east of Hutchinson MN. To better gage demand and functionality, St. Louis and Polk Counties in Minnesota operationally tested the system during the winter of 2003-2004; Polk County also tested during the winter of 2004-2005.

Operational benefits were found to be drastically different in the two counties. Low visibility was not an issue with the St. Louis County snowplow routes, so the system offered few benefits. In contrast the topology of Polk county is flat, with almost no trees. High winds combined with few visual cues create significant low visibility conditions. Polk County was pleased with their original system, and obtained a second system and tested it operationally during the 2004-2005 winter. The experience of these two counties is documented in this volume, Volume One.

A key component of the DAS is a high accuracy digital map. With the exception of the mapping process, the present cost of the DAS is well documented. Volume Two describes a system designed to collect and process geospatial data to be used by driver assistive system, and the costs and time associated with collecting map data, and creating a map from that data. With cost data complete, counties can determine whether to acquire these systems.

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Driver Assistive Systems for Rural Applications: A Path to Deployment Volume 1

Final Report

Prepared by:

Lee Alexander

Pi-Ming Cheng

Alec Gorjestani

Bryan Newstrom

Craig Shankwitz

Walter Trach, Jr.

University of Minnesota
Department of Mechanical Engineering and ITS Institute

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Acknowledgements

A number of thanks are in order. First, this project stretched out two years beyond its original end date. This was due to a number of reasons, including a lack of snowfall, changes of personnel at the county engineer level, and the realization that the system is better suited for particular environments. Dan Warzala and Rick Kjonaas of Mn/DOT have appreciated these circumstances, and have accommodated two no-cost extension requests to help us deliver our best work.

Dave Pagel of Mn/DOT's Office of Electronic Communication provided both frequency coordination and broadcast antenna design support to this project as well as significant insight into the implementation of efficient schemes for GPS correction broadcasts. Dave's help played an important role in the success of this project.

Thanks also go to Bob Martimo and Bruce Hegrenes of St. Louis County. Bob supported a number of project changes, and also provided honest feedback in reporting that the driver assistive system offered St. Louis County little operational benefit. Bruce assisted with the relocation of the DGPS correction broadcast system from the Mn/DOT antenna farm in Duluth to the St. Louis County Truck station at 5595 Jean Duluth Road.

We also wish to thank Rich Sanders, Jerry Kovar, and Donald Juvrud of Polk County. Rich was instrumental in getting a second plow for Polk County, and we appreciate his willingness to deploy a small fleet of snowplows equipped with this driver assistive system. Jerry provided mechanical and fabrication assistance during equipment installations, and allowed us to stay late in the shop while equipment was installed on their plows. Donald Juvrud determined the roadways to map, and helped with route selection.

Finally, we would like to thank the City of Fisher for allowing us to place both a DGPS broadcast antenna on the city water tower and an equipment box on the pump house to house the DGPS broadcast equipment. Without their cooperation, we would be unable to support the operations in Polk County.

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Executive Summary

The Intelligent Vehicles Lab (IV Lab) at the University of Minnesota has developed a wide range of driver assistive systems. One such system is designed to assist a driver maintain lane position and avoid collisions under low visibility conditions. The system uses high accuracy, dual frequency, carrier phase DGPS, radar, digital maps, and a conformal, augmented graphical display to provide a driver with a virtual view of the road and obstacles ahead when atmospheric conditions would otherwise preclude driving. The graphical display is augmented with an active, tactile seat which complements the visual system by providing vibrational cues to a driver that a lane departure is imminent. (The system vibrates the right buttock if the vehicle is departing to the right, and the left buttock if departing to the left.) With funding from both the Federal Highway Administration and Mn/DOT under the Generation Zero Specialty Vehicle Operational test, this system was installed and tested on a number of vehicles, including a state patrol car, an ambulance, and four snowplows. Although the breadth of vehicles covered was quite wide, the vehicles were limited to a 45 mile section of Minnesota Trunk Highway 7, between I-494 and Hutchinson, MN. To fully judge the utility of the system, testing over a wider geographical area is required.

The primary goal of the FHWA-sponsored field operational test was deployment. However, because county highway departments are responsible for clearing a large number of lane miles in the state, deployment will require counties to assess the value of the system in terms of performance, reliability, and cost. As a means to this end, the Minnesota Local Road Research Board (LRRB) sponsored this research program, which was designed to provide this driver assistive technology to counties for their operational evaluation.

The research was separated into two components. The first component (and subject of this volume) focused on putting the technology into the hands of snowplow operators who routinely plow in low visibility conditions. These drivers are typically not shy, and they will provide honest feedback. Moreover, installing equipment at the shop and leaving its use to the drivers' discretion provides valuable insight into the utility and value of the system. A system has value only if an operator uses it.

The second research component (and the subject of Volume 2) of the project is on the creation and maintenance of digital maps used by the driver assistive system. Volume 2 addresses the issue of creating digital maps used by the driver assistive system. The motivation behind Volume 2 is that if these driver assistive systems are to be widely deployed, the end user (i.e., in this situation, the county highway department) is likely to be responsible for the creation and maintenance of the digital map. Increasingly tight federal and state rules have forced land management/Geographical Information System (GIS) to utilize increasingly sophisticated maps and databases. It is likely that a decision to deploy a driver assistive system may depend on whether a land management/GIS department is willing to create and/or maintain the accurate map. Volume 2 outlines potential processes used to create these highly accurate maps, and discusses one technique in great detail, providing methodology, results, and costs to create these maps.

As reported in this volume, a specific task was performed to recruit counties willing to participate in this project. As part of the recruitment process, counties cost-shared the cost of the equipment placed in their vehicle. St. Louis County in Northeast Minnesota, and Polk County in Northwest Minnesota elected to participate, and provided funding to purchase the equipment installed in their vehicles. To support the project, equipment was procured, and appropriate mounts, equipment boxes, and electronic hardware were fabricated and assembled by the IV Lab. To provide the county an idea of the level of effort involved with equipping a vehicle with this technology, IV Lab personnel traveled to both St. Louis County and Polk County to install the equipment. While equipment was installed, digital maps for the snowplow routes were created. Once the vehicles were built, operators were trained; with training complete, the operators were free to use the system at their discretion.

The experience of the counties was mixed, and varied by geographical areas. The St. Louis County snowplow equipped with IV Lab equipment operated out of the Jean Duluth Road truck station. On the routes the St. Louis County plow clears, the land is heavily forested, with high densities of conifers located close to the roadway. These conifers serve two purposes. First, these conifers block the wind, reducing local wind speeds. Relatively low wind speeds limit the amount of visibility loss due to blowing snow. Second, these trees are located relatively close to the road, creating a "tree canyon." Because of the abundance of these trees and their close proximity to the roadway, low visibility never became an issue with the St. Louis County plow operators. Ultimately, they decided the performance of the system failed to justify the cost, and subsequently made their system available to another county.

In complete contrast to St. Louis County is Polk County. The topology of Polk County, located in the Red River Valley, is flat. Moreover, the land is nearly completely tilled, with only few stands of trees. Essentially, no elements of the landscape act to reduce the effects of the winds. With nothing to slow the winds, whiteouts are commonplace, and can occur at any time during the winter season.

Just as topology differs between St. Louis and Polk Counties, so too did the perceived value of the Driver Assistive System. Polk County was happy with the performance of their first system, and when the second system became available, they requested that it be installed on a second Polk County Snowplow. Even though snowfall has been relatively light in the Polk County over the past two winters, snowplow operators indicate that the system operates satisfactorily, and improves their confidence in the snow removal process.

It is important to note that extensive operational testing of the system by Polk County led to a philosophical change in what data should be presented in these maps. Originally, the IV Lab focused on providing drivers with significant detail, including the location of mailboxes and other road details including turn lanes, traffic islands, guard rail, etc. Given a fixed budget for mapping, a tradeoff exists between the number of lane miles mapped and the detail provided in the map. The overwhelming consensus is that more lane miles with less detail are preferred to fewer lane miles with more detail. Snowplow operators, when faced with low visibility conditions, need to make roads passable. Clean up of the details (i.e., turn lanes, etc.) can be done when poor conditions subside, and the driver assistive system is not needed. This change in philosophy is reflected in both this volume and in Volume 2.

Chapter 1
Introduction

The Intelligent Vehicles Lab (IV Lab) at the University of Minnesota has developed a wide range of driver assistive systems, both vehicle based and infrastructure based. One such system is designed to assist a driver maintain lane position and avoid collisions during low visibility conditions. The system uses high accuracy, dual frequency, carrier phase DGPS, radar, digital maps, and a conformal, augmented graphical display to provide a driver with a virtual view of the road and obstacles ahead when atmospheric conditions would otherwise preclude driving. The graphical display is augmented with an active, tactile seat which complements the visual system by providing a driver vibrational cues to a driver that a lane departure is imminent. (The system vibrates the right buttock if the vehicle is departing to the right, and the left buttock if departing to the left.) With funding from both the Federal Highway Administration and Mn/DO under the Generation Zero Specialty Vehicle Operational test, this system was installed and tested on a number of vehicles, including a state patrol car, an ambulance, and four snowplows. Although the breadth of vehicles covered was quite wide, the vehicles were limited to a 45 mile stretch of Minnesota Trunk Highway 7, between I-494 and Hutchinson, MN.

The primary goal of the FHWA sponsored field operational test was deployment. However, because county highway departments are responsible for clearing a large number of lane miles found in the county, deployment will require counties to assess the value of the system in terms of performance, reliability, and cost. As a means to this end, the Minnesota Local Road Research Board (LRRB) sponsored this research program, which was designed to provide this driver assistive technology to counties for their operational evaluation.

The research was separated into two components. The first component (and subject of this volume) focused on putting the technology into the hands of snowplow operators who routinely plow in low visibility conditions. These drivers are typically not shy, and they will provide honest feedback. Moreover, placing equipment in at the shop and leaving its use to the drivers' discretion provides valuable insight into the utility and value of the system. A system has value only if an operator uses it.

In this volume of the final report, the results of the following tasks are described:

> **Task 1: Selection of partners.** The objective of this research was to put the driver assistive system in the hands of the end user to determine the value county engineers and operators place on this system. A number of counties were identified, contacted, and asked to participate. Although many counties were enthusiastic about the project, only St. Louis and Polk Counties elected to participate. Topologically, these two counties are vastly different, and this difference provided significant insight into which geographic and topological conditions are most suited to the driver assistive system described herein.
>
> This process and results are described in Chapter 2.

Task 2. Vehicle specification, design, and build. County engineers have a limited budget for experimental programs. To give the engineers their best value for money spent, features and options for the driver assistive system were described. Both St. Louis and Polk Counties elected the basic system, which uses the Head Up Display as the only driver interface. This minimized system cost, yet provided complete system functionality.

This process and results are described in Chapter 3.

Task 3. Determination of DGPS corrections. Dual frequency, carrier phase Real-Time Kinetic (RTK) differentially corrected GPS is required to provide sufficiently accurate measurements of vehicle location and heading for the driver assistive system. In 2002, two correction options were available. The first option was conventional terrestrial based corrections utilizing a single GPS base station and a radio modem to broadcast corrections. The second option was a satellite based correction which uses a series of ground-based GPS receivers to collect raw observables from orbiting GPS satellites. These observables are collected at a central location, and uploaded to a geosynchronous satellite. The geosynchronous satellite rebroadcasts the observables to earth, where they are received by a proprietary receiver.

Both options were deployed, and performance:price tradeoffs described. These results are provided in Chapter 4.

Task 4. Mapping. To provide an operational system, routes driven by the snowplows equipped with the driver assitive technology required a highly accurate geospatial database. Although the development of an efficient process to develop maps is the focus of Volume 2, operators nonetheless needed functional, accurate databases to use while evaluating the system. For both St. Louis and Polk County, routes within range of the DGPS broadcast station were mapped. Initial mapping efforts included mail boxes, guard rails, bridge abutments, etc. After operators had experience with the system, they clearly voiced their opinion that more miles and less detail were preferred.

Descriptions of the maps delivered to both St. Louis and Polk Counties are discussed in Chapter 5.

Task 5. Project support. For the duration of the project, the University provided support to the counties using this equipment. The equipment installed on the county plows proved to be remarkably reliable, with only one hardware equipment failure reported. The installation of the driver assistive systems did cause 2-way radio interference problems; however, that was corrected by moving the 2-way radio antenna from the roof of the vehicle to the side mirror mounts.

This is the focus of Chapter 6.

This volume concludes with a brief project summary, and recommendations for future work.

The second component (and the focus of Volume 2) focuses on the remaining two tasks:

- Design and implementation of geospatial database data collection hardware and software.
- Automated database generation from collected data.

Those are covered fully in Volume 2.

Chapter 2
Selection of Partners.

This project was initiated with a Center for Transportation Studies (CTS) proposal in 2000. Funding was approved by the Minnesota Local Road Research Board (LRRB) in spring of 2001, with a fixed core budget, and a cost-share requirement for counties choosing to participate. Rick Kjonaas, formerly county engineer for McLeod county, and presently Minnesota Assistant State Aid engineer, was appointed Technical Liaison for this project.

Rick Kjonaas played an active role in the recruitment of partners for this project. As McLeod County engineer, Rick promoted this project to a number of county engineers in Minnesota. Serious interest was indicated by Redwood County, Otter Tail County, St. Louis County, and Polk County. Also expressing interest was Capt. Richard Wittenberg from the Minnesota State Patrol as the patrol is responsible for US Highway 2 in Polk County.

In the first quarter of 2002, it was clear that Polk County and St. Louis Counties were the partners who had sufficient resources to support such research. Once this had been determined, vehicle options were decided, (see Chapter 3) and contracts between the University of Minnesota and each county were drafted, revised, and finally approved by October 2002. Given this late time frame, vehicles would not be ready until the winter of 2003-2004.

In terms of partners, two unexpected (but fortuitous) events had a significant impact on the project. First, two primary suites of equipment from the FHWA-Sponsored Intelligent Vehicle Initiative Generation Zero Field Operational Test (IVIFOT) became available.

1. Driver assistive equipment from the state patrol car which participated in the IVIFOT was removed at the conclusion of the test in 2003. To pass federal safety standards, much of the equipment in the patrol car was custom designed for Ford Crown Victoria vehicles. It became a relatively simple proposition to transfer equipment from one vehicle to another. (It should be noted that IV Lab Core support funding was used to pay for the State Patrol Car operating in Crookston; LRRB funds were not used.)

2. The lease for the DGPS base station in Chanhassen, MN, expired in 2004. Because the federal funding for the IVI FOT expired in 2003 and because the Mn/DOT Virtual Reference network can provide DGPS corrections for the Chanhassen area, the Chanhassen GPS base station was removed from service.

Because of the availability of this equipment, the IV Lab decided to equip the state patrol car operating out of Crookston with a driver assistive system. The City of Fisher, MN, agreed to allow GPS correction equipment necessary to support the snowplow and the state patrol car to be placed on its watertower if power costs would be reimbursed. The IV Lab agreed, and the GPS base station was installed (see Chapter 4 for more details). This base station was made operational in October 2004, and supported the second Polk County Plow as well as the state patrol vehicle.

(It should be noted that IV Lab Core support funding was used to pay for the state patrol car operating in Crookston, and for the electrical power and GPS base station installation in Fisher; LRRB funds were not in these instances, but the GPS correction signal was received by the Polk County plow.)

Once partners were determined, work on the infrastructure side of the system was begun immediately. This work focused primarily on the DGPS correction broadcast systems and the creation of the digital maps. These efforts are discussed in Chapters 4 and 5, respectively.

Chapter 3
Vehicle Specification, Design, and Build.

Vehicle Specification. For the IV Lab driver assistive system, the core technology consists of the DGPS positioning system, the radar based obstacle detection system, the geospatial database and processor, and the Head Up Display (HUD). Three options to the system are available:

- Inertial measurements which can be used to "smooth" out the image in the HUD and to improve the accuracy with which the image in the HUD follows the road during turns. The IMU adds $5500 to the cost of the system.

- DGPS correction. Two options are available; either a terrestrial-based system, or a celestial-based system. When compared to the celestial-based system, the terrestrial based system offers higher positioning accuracy and more rapid position solution convergence after the loss and reacquisition of satellite or correction signal. However, the terrestrial-based system costs considerably more than the celestial-based system. For reasons which will be explained in Chapter 4, St. Louis County chose the terrestrial-based system, and Polk County chose the celestial-based system. A terrestrial base stations costs approximately $20,000 in capital and installation costs, and between $1000 and $2000 per year to lease tower space and provide electrical power to the broadcast radio and GPS antenna. Celestial-based corrections cost approximately $1000 per year for satellite correction service.

- Driver Interface. Two options supplement the Head Up Display: a tactile seat and audible warnings. The tactile seat vibrates to indicate imminent lane departures; for instance, the right side of the seat vibrates if the vehicle is departing to the right. Audible warnings are directional "rumble strip" sounds; if the vehicle departs to the right, the right speakers in the audio system produce the simulated rumble strip sound. Neither St. Louis county nor Polk County opted for either driver interface option.

Vehicle Design. The driver assistive system design is rather flexible, and can be configured to accommodate vehicles from passenger cars to semi-tractor trailers. For snowplows, standard design practice is to place computer and electrical equipment in an enclosed metal fabrication which supports the passenger seat. Four nuts typically hold the passenger seat to the equipment box, allowing quick, easy access to the electronic and computer equipment.

The studs to which the equipment box mounts to the vehicle varies between vehicle manufacturers, and even between vehicle models. Because of this, the equipment box is typically manufactured on site, cooperatively between the county and IV Lab personnel.

The HUD consists of two components:

- the combiner, which is a partially transmissive, partially reflective, chemically tempered, coated lens manufactured to IV Lab specifications, and the
- projector, a “superbright” Liquid Crystal Display (LCD), the image of which is reflected in the combiner, allowing a virtual image to be projected approximately 30 feet in front of the vehicle in which it is installed.

An installed HUD, with combiner, projector, and supporting structure, are shown in Figure 3.1 and Figure 3.2 below. A Polk County Ford Snowplow is highlighted.

The combiner is supported by a plexiglass frame, manufactured by the Mechanical Engineering Machine Shop. The frame is supported by a “flip-up” mechanism manufactured by the Mechanical Engineering Machine Shop. Because of variations among vehicle manufacturers, and even between models, an interface between the “flip-up” mechanism and the vehicle cab is fabricated at the county truck station. IV Lab personnel design the interface on site, and county maintenance weld and machine the parts which are installed in their vehicle.

The projector is also mounted onto a standard frame. The frame is attached to the vehicle cab by a structure which is also fabricated by the county maintenance personnel based on IV Lab personnel design.

Figure 3.1. Interior view of first Crookston Plow equipped with Driver Assistive system. Combiner is shown in the “up” position.

The remaining hardware which is used by the vehicle operator is the driver's information/control panel. To minimize the "real estate" consumed by the system, and to keep project costs down, a Compaq IPAQ was used as a means for the driver to communicate with the system. The iPAQ uses a touch sensitive screen, and can be activated with gloved hands/fingers. A typical installation is shown in Figure 3.3 below.

Figure 3.2. View of HUD from passenger seat. Combiner is in "down" position.

Figure 3.3. View of driver control panel mounted on vehicle dashboard. The control panel is a Compaq iPaq running IV Lab control panel software.

The operation of the driver assistive system is straightforward; a summary of its operation is provided below. The driver control panel is shown in Figure 3.4.

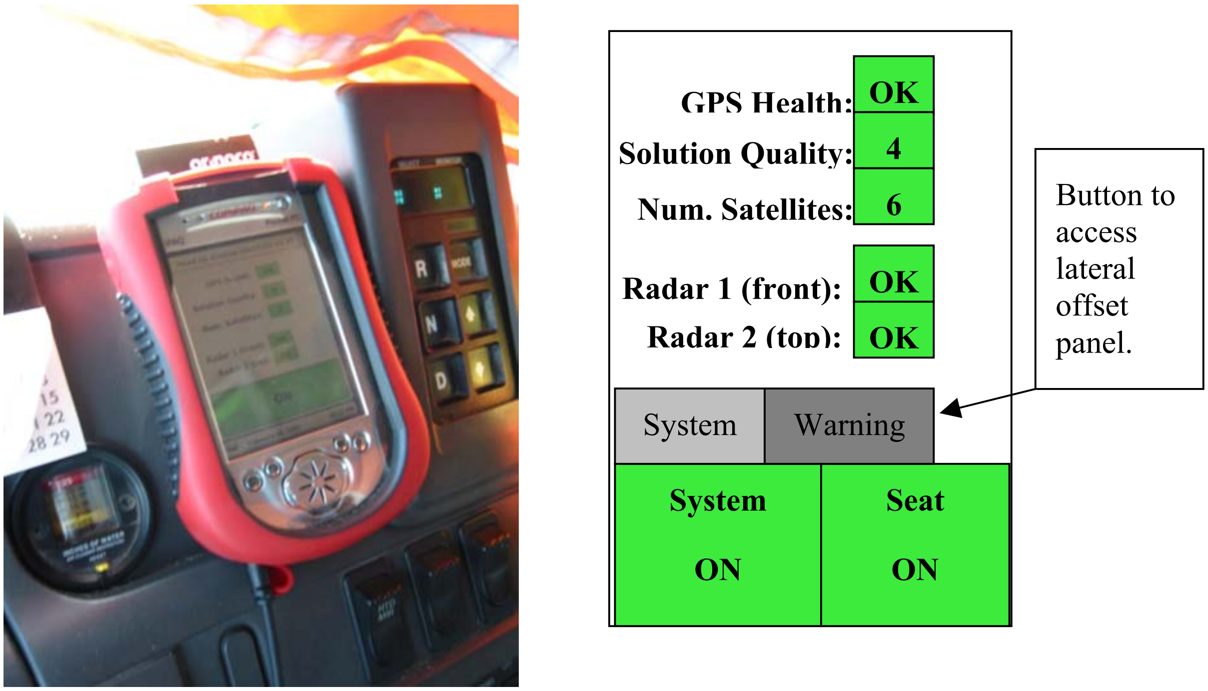

Figure 3.4. Primary display page of the iPAQ-based driver control panel for the driver assistive system. The vehicles evaluated in this project did not have active seats, so the button on the lower right of the display was a "dummy." This page provides the driver information regarding the operational status of the system. The "Warning" button activates a panel which allows operator to select desired lateral offset. (See Figure 3.5).

Driver Control Panel. The driver control panel displays the status of the GPS unit and radar units. With the driver control panel, the driver can turn the display on and off and select a desired lateral offset, allowing the operator to move the "virtual" centerline of the road. For instance, should a six foot wide shoulder require plowing, the operator can shift the virtual lane center to the right six feet; this provides a driver lane departure warnings when the virtual, not the physical, lane is to be departed.

System Status Indicators

GPS Status

GPS Health:

OK (green) – system is communicating with the GPS unit

ERROR (red) – system is receiving no data from GPS unit

Solution Quality:

Green (4) – best accuracy (5-10 centimeters), otherwise known as a "fix" solution, meaning integer ambiguities have been resolved. Lane boundary lines will be projected onto the HUD at this level of accuracy.

Yellow (5) – next best accuracy (10-20 centimeters), otherwise known as a "float" solution, meaning integer ambiguities have not been resolved. Although accuracy is decreased, lane boundary lines will be projected onto the HUD at this level of accuracy.

Red (0,1,2) – GPS not accurate enough to run system, where (0,1,2) below indicate

- 0 means GPS has no position
- 1 means uncorrected GPS solution
- 2 means corrected, but with undetermined accuracy

Num. Satellites:

The GPS units need four or more satellites to compute a 3-D (latitude, longitude, elevation) position. Maximum number of satellites the MS 750 GPS unit can track is nine. In general, the greater the number of satellites, the better the GPS position solution.

Radar Status

Green (OK) – system is communicating with the radar units

Red (Error) – system cannot communicate with the radar unit, indicating that radar targets will not be presented in the HUD.

System Control Buttons

The HUD and seat warnings can be disabled by pressing the System ON/OFF button. The button will be green when the system is enabled and red when the system is disabled. Because the iPAQ uses a touch sensitive screen, the respective system can be activated by pressing the appropriate the system buttons in the lower one-third of the display.

System Warning Button

The system also allows an operator to offset the point at which lane departure warnings occur using the driver control panel. Offsets are favored by the drivers when shoulders or turn lanes must be cleared. For instance, should a shoulder require plowing, a driver can move the center of the virtual lane from 0 to 12 feet to the right. This allows the driver to plow any distance (up to 12 feet) to the right of the physical lane centerline without triggering continuous lane departure warnings. However, should a driver deviate from the center of the virtual lane, warnings will be appropriately issued.

Figure 3.5 indicates the panel used to set the desired lateral offset. This screen is activated by pressing the "Warning" button in the middle one-third of the display, as shown in Figure 3.4. Once the screen in this figure is displayed, the operator has two means with which to adjust the lateral offset of the virtual lane center. The first option is to repeatedly tap either the "<Left" or "Right>" buttons; each tap moves the virtual lane center to the left or right twelve inches. The slider bar moves to indicate the offset selected by the driver. The second option is to move the slider bar to the left or right. The offset will be placed precisely where the driver puts it. The slider offers greater precision, but is more difficult to set precisely in a moving vehicle.

When the driver wants to return to the default (physical) lane center, the "Reset to Center" button is depressed, which zeroes any previously specified lateral offset. Likewise, to return to the main information/control panel (as highlighted in Figure 3.4), the driver taps the "System Buttons" button.

Vehicle build. For this project, three vehicles were equipped with the driver assistive system. The first vehicle built was the Polk County snowplow. This vehicle was equipped with the driver assistive system in February 2003. The St. Louis County plow was fabricated in the early fall of 2003; the second Polk County Plow was built in October, 2004. Although slight variations in mounting details were present due to cab design differences, the installed systems all appeared similar to what was shown in Figure 3.1- Figure 3.3 above.

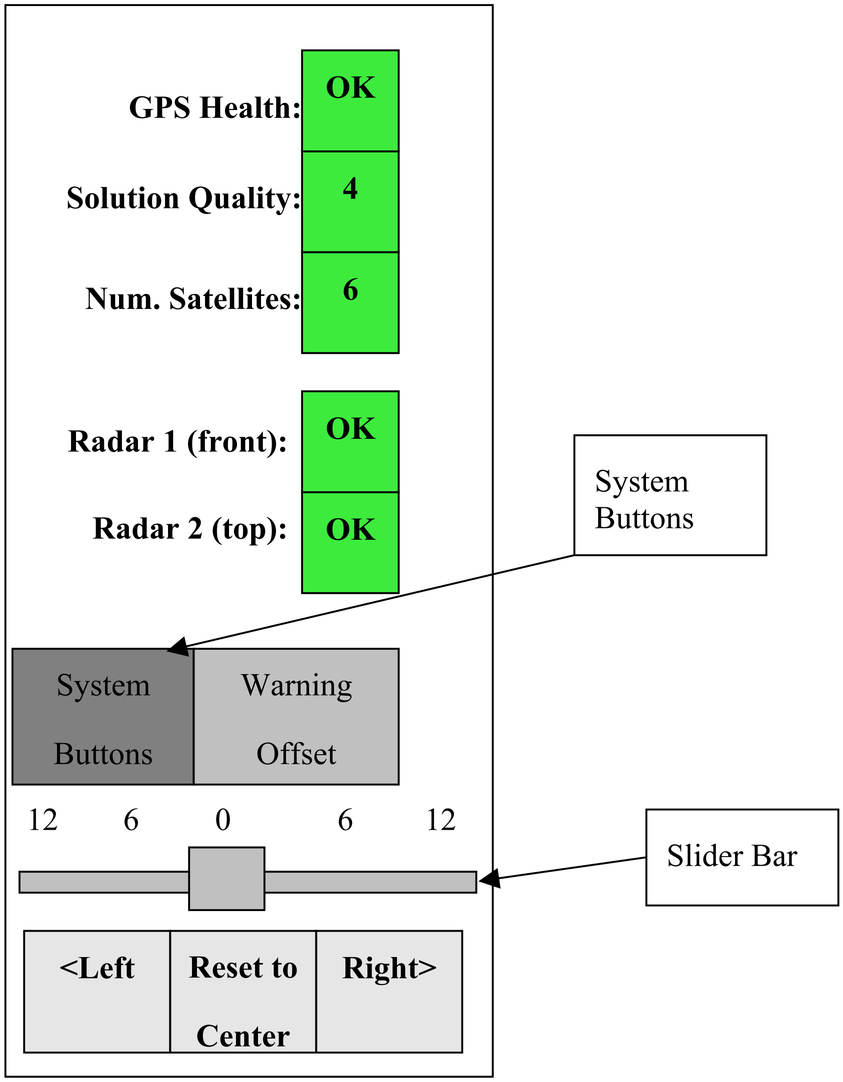

Figure 3.5. Capture of warning offset screen. This screen is accessed by pressing the "Warning Offset" button indicated in the access screen in Figure 3.4. The screen of Figure 3.4 is accessed by touching the "System Buttons" area indicated above.

Chapter 4
Determination of DGPS Corrections.

Background. The primary requirement for the Driver Assistive System is accurate (5 – 20 cm) real time positioning. Dual frequency, carrier phase Real-Time Kinetic (RTK) differentially corrected GPS is required to provide sufficiently accurate measurements of vehicle location and heading for the driver assistive system, provided that a sufficient number of GPS satellites are "in view" of the GPS antenna and that a proper differential correction is provided to the GPS receiver in a timely manner. GPS positioning can be lost should the reception of either satellite or correction signals be interrupted. In an ideal situation, both will be continuously available; in reality, both will be lost from time to time. Clearly, an optimal design will provide an operator with the greatest amount of uptime for the least cost.

In 2002, two correction options were available. The first option was conventional terrestrial-based corrections utilizing a single GPS base station and a radio modem to broadcast corrections. The second option was a celestial-based correction which use a series of ground-based GPS receivers to collect raw observables from orbiting GPS satellites. These observables are collected at a central location, and uploaded to a geosynchronous satellite. The geosynchronous satellite rebroadcasts the observables to earth, where they are received by a proprietary receiver.

Until 2002, the IV Lab only had experience with the terrestrial based system. The state of the art in 2002 would provide 5-8 cm dynamic accuracy, and recover from a loss of GPS satellite or GPS correction information in a period of 15-30 seconds. Convergence from a cold start (where the GPS receiver is power up with no *a priori* information regarding its position) takes 30 to 60 seconds. In rural areas, GPS satellite outages are primarily due to local tree stands, overhead signs, and passing under bridges. Correction outages tend to arise from long baselines (distance from receiver to rover), due to either weak broadcast signals (due to FCC licensing limitations or geographical/topological problem) or algorithmic limitations with either the base station or receiver firmware.

Celestial-based corrections were just emerging in 2002. At that time, accuracy claims of 20 cm were quoted, sufficiently accurate for a driver assistive system. However, cold start convergence depended on the status of the GPS constellation, and could take between 5-15 minutes. Moreover, loss of satellite view or loss of GPS corrections due to passing under/near trees, underpasses, etc., can cause a loss of signal, from which it may take 2-5 minutes to recover.

Clearly, the terrestrial base station offers significant performance advantages to the celestial base system, not only in terms of absolute accuracy, but in the time it takes to recover from a loss of satellite or correction signal. However, the celestial-based system offers considerable cost savings. In 2002, establishing a terrestrial base station was a relatively expensive proposition. The cost to establish a base approached \$20,000; approximately \$15,000 for a base station GPS receiver, \$1500 for a Radio Frequency Modem, \$700 for a base station broadcast antenna, and approximately \$2000 for a tower contractor to install and test the antenna, and \$800 for power supplies and cables. Moreover, the roving vehicle requires its own RF Modem, adding approximately $2000 to the vehicle cost. This cost, coupled with a $15,000 base price for the in-vehicle GPS receiver represents a significant investment for the end user.

In contrast to the terrestrial-based system, the celestial-based correction offers substantial cost savings. NavCom, a wholly owned subsidiary of John Deere, in 2003 offered a celestially-corrected DGPS receiver for the precision agriculture market. Retail price in 2003 was approximately $12,000; the celestial correction service retailed for approximately $1500 per year.

Extenuating circumstances were ultimately responsible for the choice of GPS corrections for both St. Louis County and Polk County. In early 1998, the Office of Land Management for St. Louis County initiated a program to provide dual frequency, carrier phase corrections throughout St. Louis county to support surveying and foresting applications. Unfortunately, that program was terminated because of problems with establishing a wireless communication network upon which GPS corrections could be broadcast. This left St. Louis County with seven GPS receivers, which if modified slightly, would provide corrections necessary to support a driver assistive system operating in St. Louis County. The availability of a GPS base station receiver and antenna, combined with the geography and topology of St. Louis County, made terrestrial corrections the obvious choice.

On the contrary, in 2002, Polk County did not have access to a GPS receiver which could provide sufficiently accurate positioning capability for a snowplow equipped with the driver assistive system. Moreover, Polk County wanted to limit its buy-in costs for the program. The availability of the NavCom system was appealing as the costs to establish a GPS base station far exceeded the cost to purchase the GPS correction service. Moreover, the topology of Polk County is flat, with few overpasses and other landmarks to block satellite broadcasts from either GPS or the Geosynchronous satellite providing NavCom Starfire corrections. Polk County is primarily an agricultural area, so the NavCom target market was also represented in Polk County.

In 2003, the IV Lab negotiated University of Minnesota pricing for a NavCom Starfire 2050 GPS system. NavCom offered the Starfire 2050M receiver and one year correction service at a 50% discount from retail pricing. Polk County was made aware of the risks associated with acquiring untested equipment, but the benefit:risk ratio was sufficiently high to justify the purchase.

Implementation. Significant effort went into implementing the GPS corrections in both St. Louis and Polk County. Technical risk for St. Louis County was much lower than that for Polk County; however, personnel and route changes in St. Louis County created other issues which had to be overcome.

1. **St. Louis County**. When St. Louis County was first approached to participate in this project, Dick Hansen was the county cngineer. One of St. Louis County's more difficult highway maintenance zones is Old Highway 61 which runs adjacent to Lake Superior. In addition to heavy lake effect snows, Highway 61 suffers from frequent fog and ice conditions. Under Dick Hansen's guidance, Old Highway 61 and roads in close proximity to it were to be covered by the GPS corrections, and mapped to support operational testing of the driver assistive device.

Working under this premise, the IV Lab worked with St. Louis County and Mn/DOT to identify a site from which GPS corrections could be broadcast. In June 2002, Mn/DOT agreed to provide antenna space on one of its towers on its "antenna farm" located in Duluth, MN. A directional antenna would provide DGPS coverage along Highway 61 north of Duluth along the north shore of Lake Superior.

With agreement on a GPS correction broadcast site, the following four tasks were completed to bring the base station on-line:

- The St. Louis County Novatel RT-2 GPS was sent to Novatel to be updated to a ProPack 2, its highest performance model using the Millenium GPS engine

- A broadcast frequency had to be identified, coordinated, and licensed. Because of the proximity of Duluth to Canada (i.e., north of "Line A"), frequency coordination was done in cooperation with the Canadian FCC. Dave Pagel from Mn/DOT's Office of Electronic Communication performed these three duties for the IV Lab.

- GPS broadcast and reception equipment designed to operate on the Duluth frequency was selected and procured.

- Northern States Tower service was selected and contracted to perform the installation of the GPS broadcast equipment at the antenna farm site.

By November 2002, the DGPS base station was operational on the antenna farm in Duluth. The system was found to perform well for the original area to be mapped (along Old Highway 61 north of Duluth, and surrounding areas).

However, in December 2002, Dick Hansen retired as county engineer for St. Louis County; Marcus Hall replaced Dick Hansen. With the change in management, maintenance priorities and distribution of resources changed. With the new administration, the decision was made to provide driver assistance north of Duluth on maintenance routes originating from the Jean Duluth Truck Station (JDTS) at 5595 Jean Duluth Road. The routes originating from the JDTS put the baseline from the Duluth antenna farm from12 to 20 miles. Although it was unlikely to work, an attempt was made at using that base station for corrections to support operations out of the JDTS. A number of tests were performed in January 2003; these tests showed that although the antenna farm base station could provide "fix" solutions, coverage was spotty, and relatively unreliable.

Because of the difficulties with the long baselines, a decision was made to move the GPS base station from the antenna farm to the JDTS. Final approval to move the base station was given by St. Louis County on 18 August 2003; once approval was given, the FCC frequency coordination process was repeated (with both US and Canadian involvement), and Northern States Tower was again tasked with moving the base station. FCC approval was granted on 29 October 2003; the base station was brought online in mid-November 2003. Subsequent testing showed very good performance; loss of GPS "fix" solutions were primarily due to loss of GPS satellite signal due to conifers located close to the roadways near the JDTS. The quality of the base station corrections was high. Once the JDTS base station was brought on-line, the corrections were used to facilitate mapping of relevant snowplow routes. Mapping is discussed further in Chapter 5 below.

2. **Polk County.** A two-step process was used to provide corrections to the vehicles in Polk County. First, the quality of the NavCom Starfire correction had to be verified. This verification process was undertaken at the Mn/ROAD pavment research facility in Albertville, MN, and is documented in [1]. The Starfire performed well, although it did take a considerable amount of time to converge to a solution from both a cold start and from a loss of GPS or Geosynchronous correction satellite lock. The performance of the Startfire receiver was also sensitive to the number of satellites seen by the receiver. In general, it took approximately 15 minutes to converge to a solution of 20 cm accuracy from a cold start; it takes, on average, approximately 5 minutes to recover from a loss of GPS or correction signal.

   From [1], accuracy results for the NavCom SF2050 receiver are provided in Table 4-1 and Table 4-2 below. Although accuracy fails to reach the level of the MS 750, it is sufficient for driver assistive systems. The results below are based on data collected one hour from a cold start; this allowed the system to converge to its best possible positioning accuracy.

Table 4.1. Position error for NavCom SF-2050M.

SPEED, MPH	Number Of Measurements	Mean error, cm	Standard Deviation, cm	Average Latency ,mSec
10	119	14.3	2.3	53.0
20	41	13.0	6.1	55.1
30	24	22.0	15.9	60.0

Table 4.2. LATERAL and LONGITUDINAL error for for NavCom SF-2050M.

Speed MPH	Lat Mean error, cm	Lat Std Dev, cm	Long Mean error, cm	Long Std Dev, cm
10	-7.9	3.4	-11.6	1.7
20	-9.9	5.2	-4.8	7.7
30	-4.1	26.0	-3.6	6.8

One difficulty with the Starfire system is that self-reported accuracy estimates are difficult to interpret. As a comparison, the Trimble MS 750 receiver used by the IV Lab issues as part of its position message an estimate of its position accuracy. This information is described in Chapter 2, where a "fix" (solution quality 4) solution accuracy is typically from 5 to 10 centimeters, a "float" (solution quality 5) is 10-20 centimeters, and solution qualities of 0, 1, and 2 are insufficient for the driver assistive system application.

Review of the StarFire System operation manual and extensive testing on Highway 7 (using an MS 750 as a reference GPS system) led to the development of an interpreter which would provide an analogue of the Trimble 0-5 quality index. This interpreter allowed an operator of a vehicle equipped with a StarFire GPS receiver to use a Trimble-equipped machine without any additional training. This feature proved beneficial because Polk County received a Trimble-based DAS in October, 2004.

In October 2004, under IV Lab core support funding, a DGPS base station was brought on-line in Fisher, MN. This base station provided high accuracy GPS corrections to two vehicles: the Minnesota State Patrol car, and the second Polk County snowplow. This installation was unique in the sense that the GPS equipment was mounted on the outside of a building instead of inside where environmental conditions are typically less severe. In Northwest Minnesota, ambient temperatures of –29 degrees Celcius (-20 degrees Fahrenheit) are not uncommon. The winter of 2004-2005 was unseasonably cold, yet the GPS base station in Fisher operated without flaw.

Because this installation is somewhat unusual, it is shown in Figure 4-1. A detail of the installation, to show its compactness, is shown in Figure 4-2.

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Figure 4-1. Installation of GPS base station equipment on Fisher, MN, pump house. Power to the system is provided through the conduit pushed through the pump house wall. Fisher is paid a flat fee of $150 per year to cover the expense of providing power to the system.

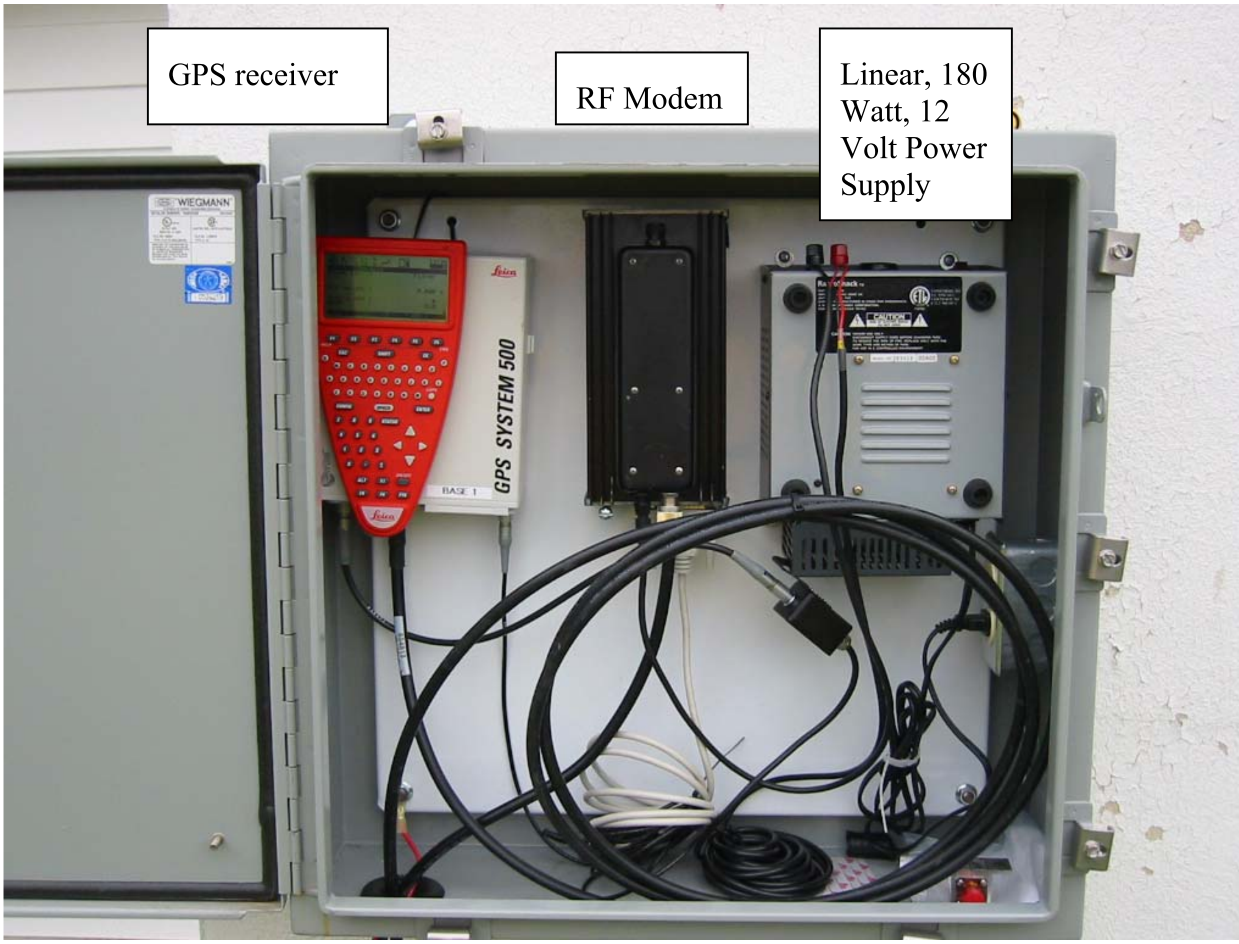

Figure 4-2. Detail of GPS equipment cabinet mounted on Fisher pump house. System has provided reliable operation in temperatures below –29 degrees Celcius (-20 degrees Fahrenheit).

Chapter 5
Mapping.

This chapter describes the maps provided to St. Louis and Polk counties to support their use and evaluation of the driver assistive systems provided to them; however, it does not provide the technical details of the system used to develop those maps. The development of the technology to collect road boundary data is the subject of Volume 2 of this two-volume report.

Feedback from drivers using the DAS motivated a significant change in geospatial database philosophy. When this project was proposed in 2001, the philosophy of the IV Lab (and snowplow operators who were asked their opinion, but had never used the system under operational conditions) was that as much of the geospatial landscape as possible should be included in the database. The database should locate signs, mailboxes, guardrails, turn lanes, and elements of intersections (traffic islands, traffic control devices, etc.) so that drivers can clear close to these elements, but not strike them.

The IV Lab is capable of providing this level of detail. However, a tradeoff exists between the level of detail and the per mile cost to build the map. Because the Driver Assistive System had not been used operationally at the time this project was proposed, it was assumed that the maps provided to the counties would include a high level of detail, including mailbox locations, all guard rails, etc. Given this level of detail, the project budget, and the range of DGPS corrections in 2001, each county was provided 22 miles of mapped roads. Additional road miles could be added by each county at a cost of $250/mile.

The IVIFOT and feedback provided by snowplow operators indicated that the accuracy of the lane boundaries is of key importance, but the level of detail provided initially was excessive. County snow removal operations are different than those of Mn/DOT; the "bare pavement 24 hours after a snowfall" policy of Mn/DOT is not followed by the counties. The understanding between the county highway maintenance department and the local public is that the county will keep roads passable during periods of heavy snowfall. Once the storm clears, county crews will perform cleanup operations.

Given this philosophy, county maintenance supervisors and snowplow operators clearly favored less database detail and more miles of lane boundary information. More miles of lane boundary information allows county crews to make more roads open to residents sooner, and enables drivers to make it back to the maintenance shop should conditions worsen while out on their routes. Making roads passable is the highest priority; clean-up can occur when conditions permit.

Interestingly, this "more miles, fewer details" philosophy is also well aligned with other safety applications, notably lane departure warnings. This is fortuitous in the sense that digital maps created for either snowplowing operations or lane departure warnings can be used for the other application without any modification.

Operator feedback has played an important role in the development of the process used to collect road boundary data, and has in fact simplified the process considerably, making the process substantially faster and less expensive. The analysis in Volume 2 indicates that roads can be mapped to 20 cm (8 inch) accuracy for a price of approximately $10 per mile. In October 2004, nearly 150 miles of road boundaries were mapped in a period of two days for the routes covered by the State Patrol and the second Polk County plow. Those maps contained only lane boundary data, two guard rails (where the guard rail was very close to the driveable road surface), and turn lanes on US Highway 2 (as requested specifically by the trooper, who often has to change travel directions to respond to incidents on Highway 2 during poor weather/visibility conditions).

In the following, the roads mapped by the IV Lab to support snowplow operations are presented.

St. Louis County. St. Louis County provided an initial area to be mapped; however, with the change in management, the roads along the north shore of Lake Superior were never mapped. Instead, roads to the west of the Jean Duluth Truck station were mapped, based on input from Bob Martimo, Maintenance Supervisor at the JDTS. The routes to be mapped are shown in Figure 5.1 below. The actual map produced by the IV Lab is shown in Figure 5.2. Two key differences exist between the requested and the actual map requested. First, in Figure 5.1, the green circles indicate where GPS satellite signal reception was blocked because of the dense forest growth close to the roadway. Without GPS, a map could not be made; even if a map were created, the snowplow would be unable to receive GPS signals, thereby making the DAS inoperable in those locations. Second, the mapped area covers County Road 4 considerably further North than was originally requested. This additional mapping was performed on behalf of the snowplow operator, who requested it. Highway 4 eventually leaves heavy forest, and passes between two lakes. High winds blowing over these lakes create localized low visibility conditions; the driver felt the DAS would be useful in this area.

It is important to note that the geospatial database in St. Louis County included all guard rails, intersection detail, and 376 mail boxes found along the 24 mile route.

Polk County. Two mapping efforts were undertaken in Polk County. The initial mapping effort, performed in 2003, focused on County Highway 11 east of Crookston. The 24 miles of road which were mapped also included all mail boxes, guard rails, and intersection detail are shown in Figure 5.3 as provided by Donald Juvrud, maintenance supervisor for Polk County. These roads were maintained during the winter of 2003-2004 by the vehicle equipped with the NavCom StarFire DGPS receiver. The graphical representation of this route using map data collected by the IV Lab is shown in Figure 5.4.

With the delivery of the state patrol vehicle to Lt. Theis and a second snowplow for Polk County for the winter of 2004-2005, the Polk County database was significantly expanded. The state patrol was asked to prioritize the routes it would like to be included in the additional mapping. The state patrol indicated the routes shown in Figure 5.5. Moreover, Polk County drove the route that the snowplow operator assigned to the second vehicle is responsible for maintaining. The performance of the GPS systems in both vehicles covered not only all of the state patrol routes, but also the entire route of the Polk County snowplow (See Figure 5.6.) In all, approximately 150 miles of geospatial data were added to the previous Polk County geospatial database, bringing the road miles mapped to 175 (or the lane miles mapped to approximately 350).

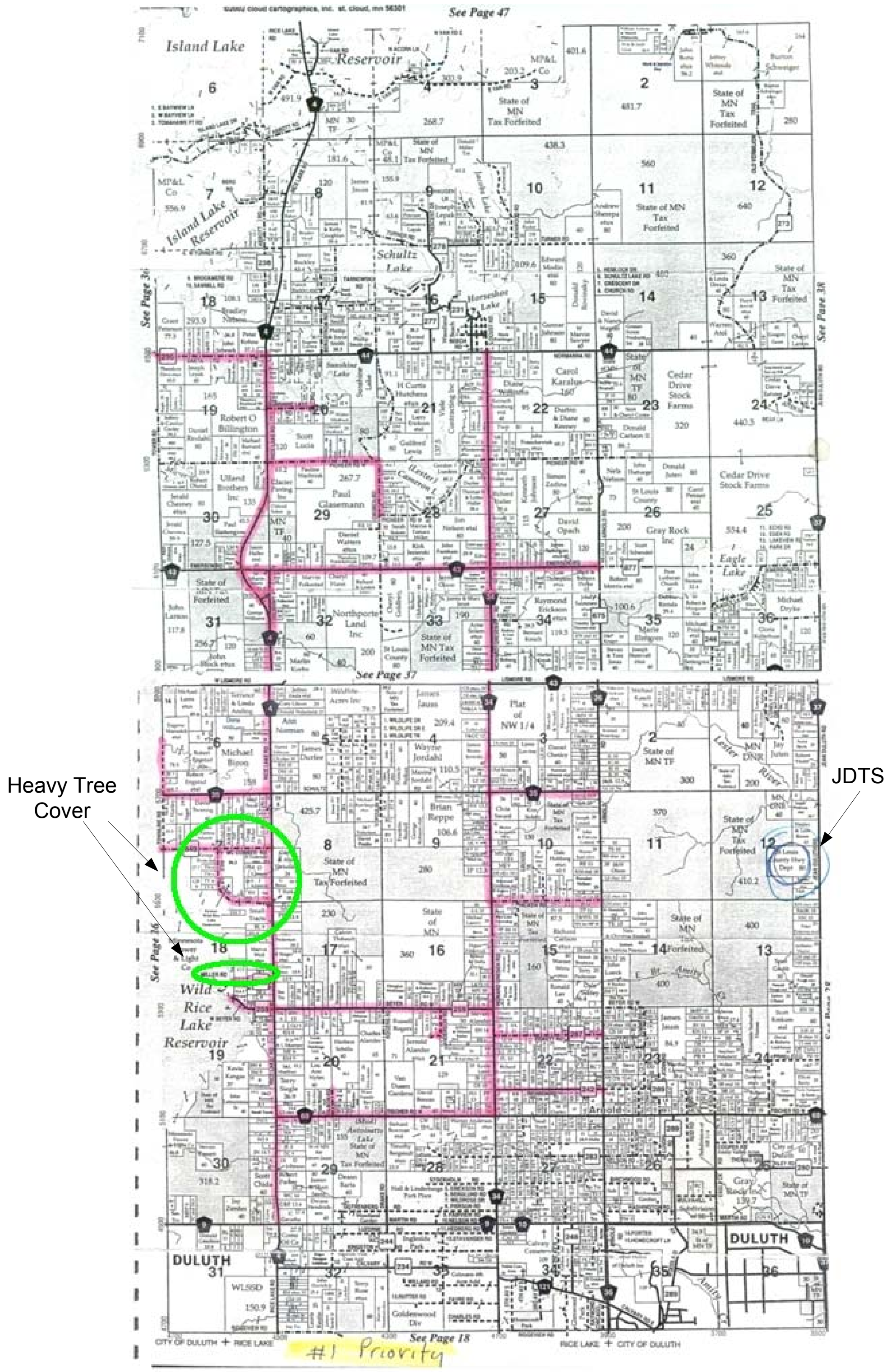

Figure 5.1. Snowplow route for St. Louis County. Truck Station from which snowplow operated is circled in blue. Green circles indicate where heavy tree cover blocked GPS satellite reception, making mapping and system operation difficult.

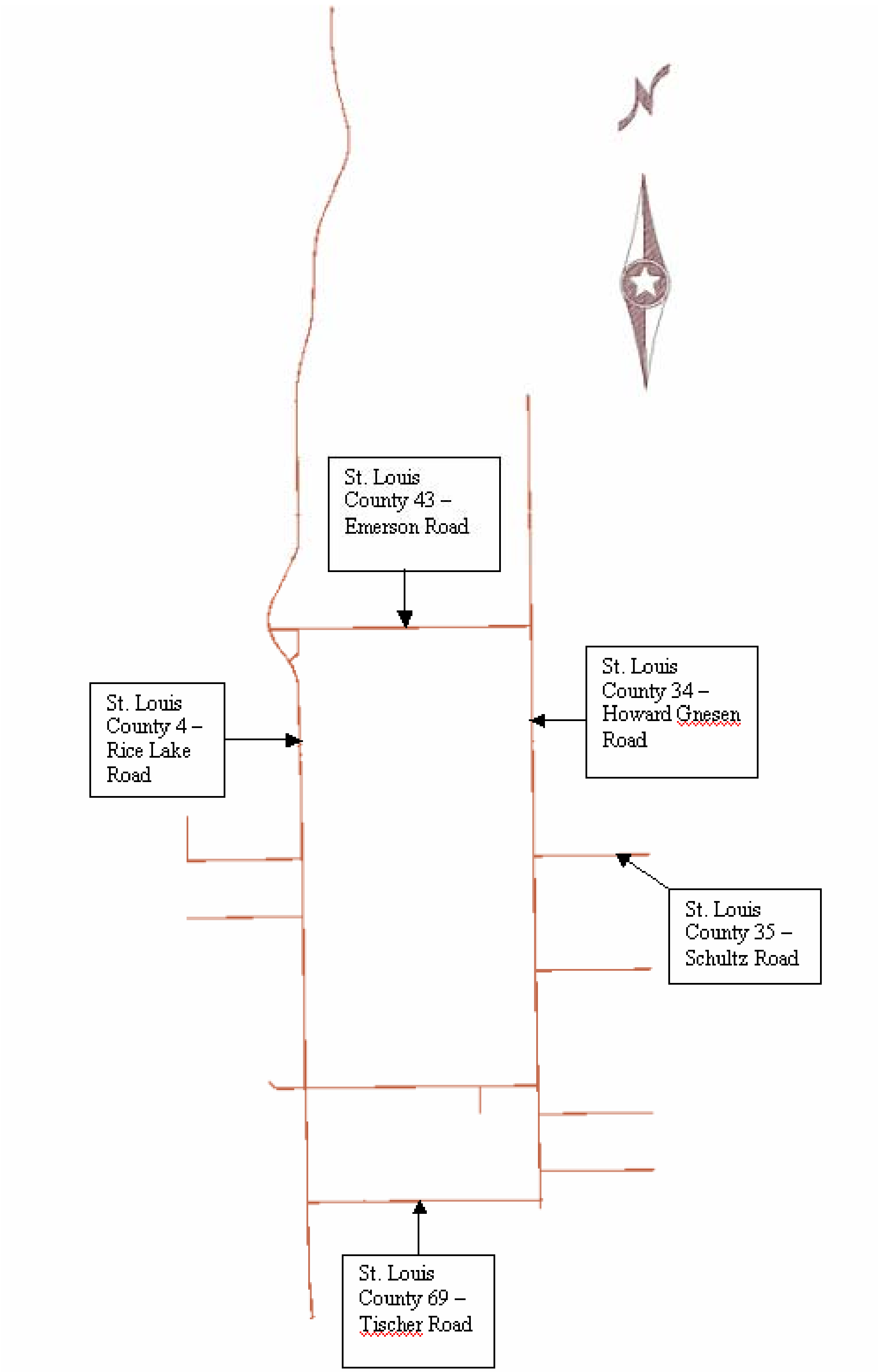

Figure 5.2. Representation of roadways mapped for St. Louis County.

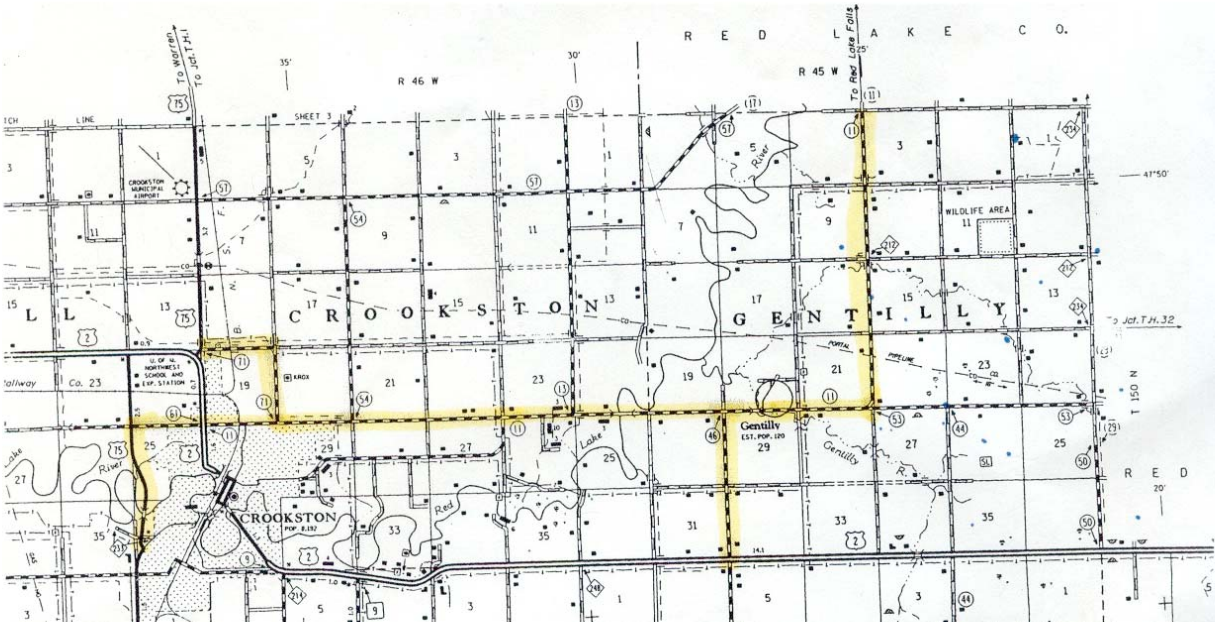

Figure 5.3. Roads to be mapped for the first Polk County Snowplow. Map provided by Polk County Highway Department.

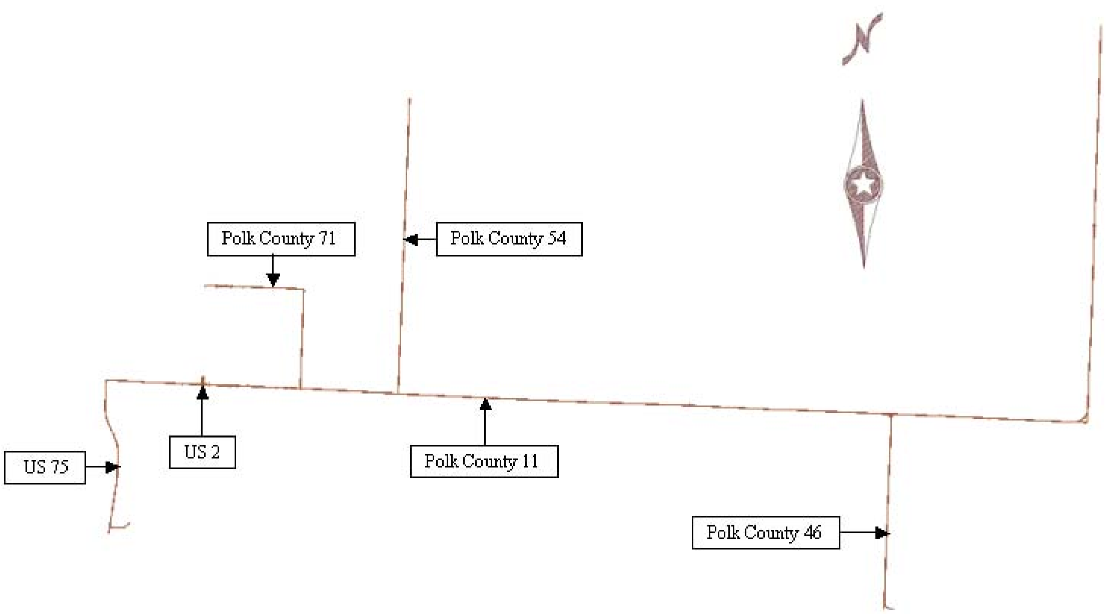

Figure 5.4. As-mapped snowplow route for Polk County used during the winter of 2003-2004.

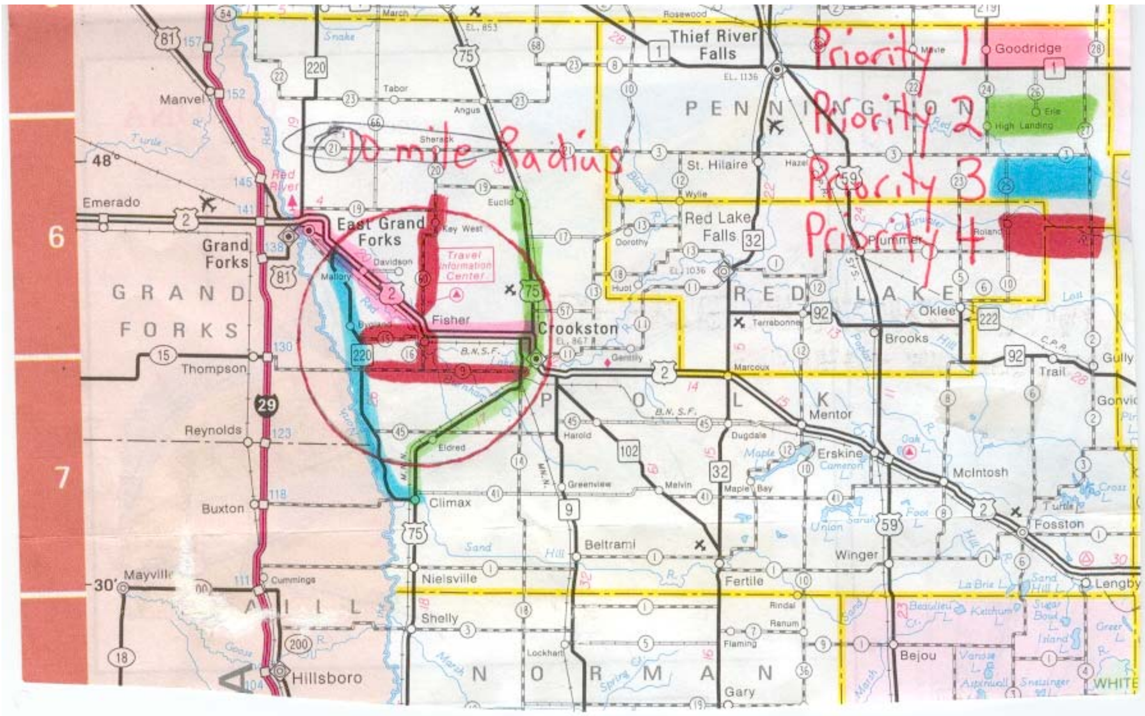

Figure 5.5. Routes requested for mapping by the state patrol. The operational range of the DGPS base station was assumed to be 10 miles, based on estimated RF signal propagation, and DGPS receiver performance capabilities. In reality, the systems installed in Polk County reliably provide "fix" solutions at baselines of 15 miles.

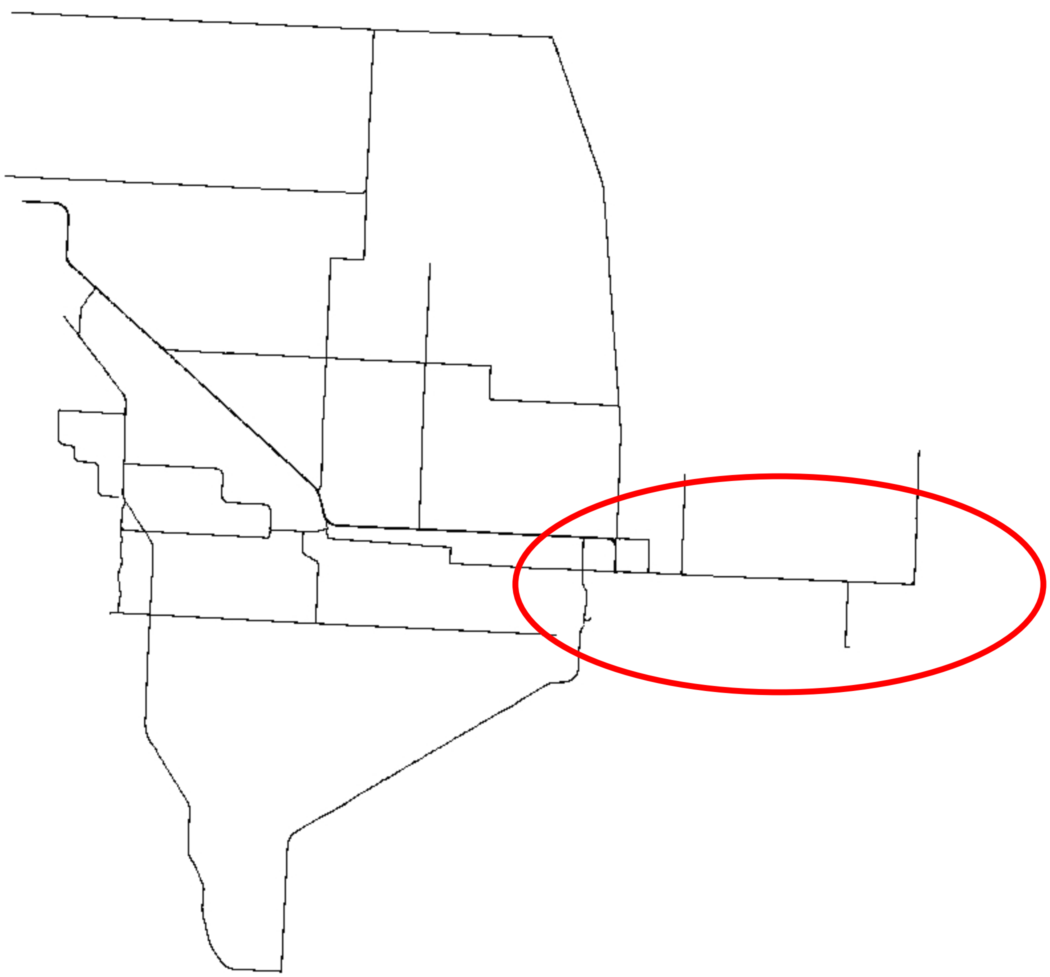

Figure 5.6. Representation of all roads mapped in Polk County, MN, as of October, 2004. Road encircled were mapped in 2003 to support the original deployment in Polk County.

It is important to note that the additional 150 miles included in the updated geospatial database provide primarily lane boundary information, with only two sections of guardrail (in locations where the guardrail is located close to the lane boundary) and the turn lanes on US Highway 2 added to the lane boundary information. Intersections are represented simply as the crossroads of two mapped roads. Both the patrol and Polk County wanted as many miles as possible mapped, and were satisfied with the tradeoff of detail for additional miles.

Chapter 6
Project Support

The deployment of these driver assistive systems in St. Louis and Polk Counties is analogous to a Beta version of an electronic product: sufficiently developed to function as conceived, but likely not sufficiently reliable or thoroughly evolved to be ready for production. At this level of development, it was very likely that the equipment provided to both St. Louis and Polk counties would suffer from component failures, software bugs, or behavior/consequences unforeseen during the development process.

As it turned out, the systems were quite reliable. The philosophy of the IV Lab was to allow the counties to make the contact should a problem arise. This allowed the operators to use the system when they felt it was needed, not because they needed to appease the developers. If the system were truly useful, the operators would use it.

Only a few problems surfaced during the evaluation period. On the state patrol car, the antenna radome cracked, allowing moisture to enter the antenna cavity where the active circuitry resides. This resulted in a circuit board failure, and a replacement was required. The repair, including a replacement board and labor, cost approximately $1000. Trimble has redesigned the radome to reduce cracking failures.

The Polk County plow suffered one failure. The combiners are mounted in a Plexiglas frame. Included in the DAS is a combiner cleaning kit. Acetone is included in the kit as a drying agent for the combiner. Unfortunately, acetone cracks Plexiglas. Based on bad advice given to Polk County by the IV Lab, they cleaned their combiner with the acetone. It caused cracking, and rendered their system inoperative. Polk County contacted the IV Lab, and a new combiner, frame, and mount was sent second-day delivery. Polk County returned the old combiner, which was fitted with a new frame.

In all, the systems proved reliable. Their utility is described in the next chapter.

Chapter 7
Conclusions and Recommendations

Conclusions. IV Lab driver assistive systems were operationally tested in St. Louis and Polk Counties in Minnesota. These two counties exhibit completely different geography, topology, and ground cover; St. Louis county is heavily forested, primarily with conifers, and offers slight to medium changes in elevation. Polk County is essentially flat, with few trees or other means with which to slow winds. These vastly different conditions had a direct influence on how these systems were received.

The St. Louis County snowplow equipped with IV Lab equipment operated out of the Jean Duluth Road truck station. On the routes the St. Louis county plow clears, the land is heavily forested, with high densities of conifers located close to the roadway. These conifers serve two purposes. First, these conifers block the wind, reducing local wind speeds. Relatively low wind speeds limit the amount of visibility loss due to blowing snow. Second, these trees are located relatively close to the road, creating a "tree canyon." Because of the abundance of these trees and their close proximity to the roadway, low visibility never became an issue with the St. Louis County plow operators. Ultimately, they decided the performance of the system failed to justify the cost, and subsequently made their system available to another county.

Although it was disappointing that St. Louis County decided not to keep the technology (especially after the effort was put forth to install two GPS base stations), their fair assessment of the technology provided important information regarding where these systems should be deployed. Clearly, the market for this system in heavily forested areas with tree canyons is small, at best.

In complete contrast to St. Louis County is Polk County. The topology of Polk County, located in the Red River Valley, is flat. Moreover, the land is nearly completely tilled, with only few stands of trees. Essentially, no elements of the landscape act to reduce the effects of the winds. With nothing to slow the winds, whiteouts are commonplace, and can occur at any time during the winter season.

Just as topology differs between St. Louis and Polk Counties, so too did the perceived value of the Driver Assistive System. Polk County was happy with the performance of their first system, and when a second system became available, they requested that it be installed on a second Polk County snowplow. Even though snowfall has been relatively light in the Polk County over the past two winters, snowplow operators indicate that the system operates satisfactorily, and improves their confidence in the snow removal process. Even with the light snowfall amounts, conversations with Jerry Kovar of Polk County indicate that the drivers did use the system on occasion, and it provided the operator information which helped maintain proper lane position.

Operator feedback from Polk County also provided a philosophical change in how digital maps were used (and therefore, created). Snowplow operators, when faced with conditions which require the use of the DAS, have as a priority, making the road passable. Having fewer details and more mapped miles allows the snowplow operator to open more roads quickly. Cleanup operations, which would require more detail from the geospatial database, can wait until the weather clears and visibility improves. If caught out in a quickly moving storm, the drivers want to be able to make it back to the truck station. Fortunately, this desire for more lane miles and less detail is consistent with other applications, including rural lane departure warning systems.

With respect to terrestrial-based and celestial-based GPS corrections, three primary differences in performance between the two systems have been noted.

1. The Trimble system converges to an accurate initial solution from a cold star in less than sixty seconds, whereas the NavCom system may take up to 20 minutes to converge.

2. The Trimble recovers from a loss of satellite or correction lock in 7 to 30 seconds, whereas the NavCom system may take 3-5 minutes to recover from a similar satellite or correction lock loss.

3. The Trimble, by virtue of its higher accuracy, provides a much more stable view in the HUD than does the NavCom. Vehicle heading is estimated by projecting ahead from past position measurements. The variance in the Trimble solution is small, resulting in small estimates of vehicle heading. Heading errors are manifest by lateral (side to side) variations in the image projected onto the HUD; these heading errors are proportional to the distance ahead the image is projected, and are therefore amplified in the far field. A 20 centimeter error in lateral position will lead to a 20 centimeter error in the near field, but can lead to multiple meter error at a virtual distance of 30 meters. Figure 7.1 below indicates how small position errors lead to disproportionate heading errors.

Although the NavCom offers a significant cost savings for a single vehicle, larger fleets may justify the price of a base station which will provide improved performance. Moreover, if the GPS base station is used by survey crews, road construction crews, and land management personnel, the cost of the equipment can be leveraged heavily, producing only a small incremental cost for the snowplows equipped with the system.

Recommendations. Because the systems are paid for and have been proven reliable, the IV Lab recommends that Polk County and the state patrol continue to use the DAS. Because system reliability is quite good, the effort expended by the IV Lab to continue to support these systems is minimal. Unless roads in the Crookston area are reconstructed, the existing geospatial database should continue to serve both Polk County and the Minnesota State Patrol.

The performance of the celestial-based system is the one component ready for improved performance. In the fall of 2004, the IV Lab procured the latest firmware for the StarFire receiver when it renewed its subscription for the StarFire correction service. However, even with the upgrade, the performance of the StarFire system did not approach the terrestrial-based system in terms of accuracy, time to converge from a cold start, and time to recover from a loss of satellite or correction lock.

Although the Starfire GPS receiver is designed to use StarFire corrections, the system is also designed to accept terrestrial-based corrections, including the CMR message which is presently broadcast from the GPS base station in Fisher. If Polk County is willing, the IV Lab can provide, on a long term loan basis, an RF Modem which will allow the Polk County plow to use corrections from the Fisher base station. This should significantly improve the performance of the DAS installed in the first Polk County plow, with no additional cost to the county.

A second recommendation is to determine an alternative location for the base station operating in Fisher, MN. The City of Fisher intends to take their water tower out of service, and move to an aquifer-based water system. The Fisher GPS base station has been an optimal location because it lies half-way between Crookson and East Grand Forks, providing GPS coverage along US Highway 2 and much of Polk county west of Crookston to the North Dakota border. Loss of GPS corrections in Fisher would be detrimental to system deployment.

However, three options exist. First, adjacent to the Fisher water tower is a grain elevator, the elevation of which is nearly as high as the Fisher water tower. It would be a relatively simple task to move the base equipment from the water tower to the grain elevator. This, however, would have to be coordinated by Polk County. Price and availability would depend on the grain elevator operator.

The second option is to lease space on a commercial antenna near Fisher. Although likely expensive, it keeps the base station near its present location, and would act to maintain the present level of service provided by the Fisher water tower. Again, use of this type of facility would have to be negotiated by Polk County.

The third option is to use the existing antenna tower operated by Polk County. However, this antenna is located in Crookston near the Highway Department building. Although attractive from a installation, cost, and maintenance perspective, the Crookston location will likely not serve Polk County as far west as it is presently served, to the detriment of the state patrol who patrol from Crookston west to East Grand Forks.

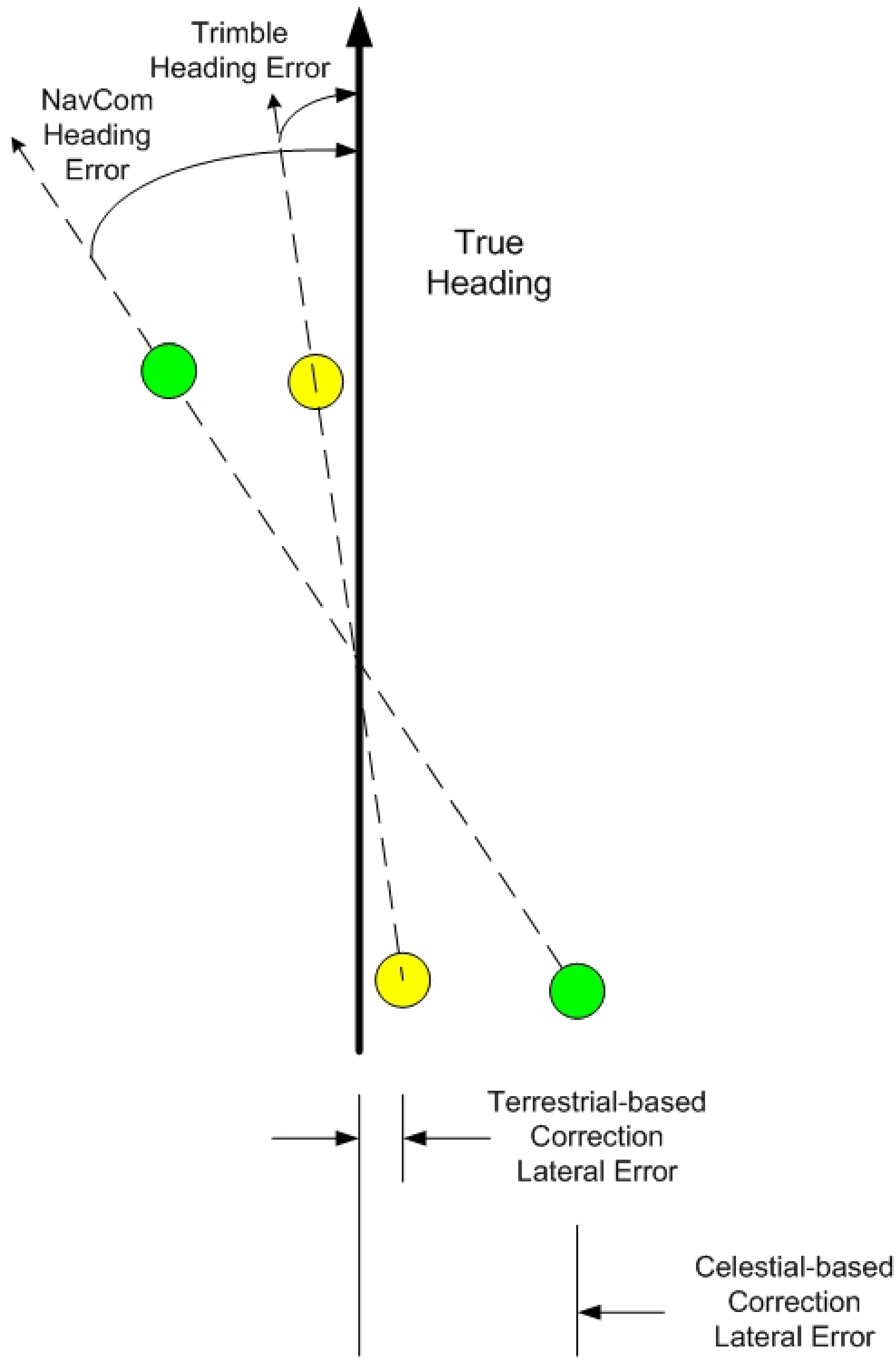

Figure 7.1. Illustration of heading errors. Small error in lateral position can lead to large errors in estimated heading. The more variance associated with positioning measurements, the greater the perceived oscillation (or jumpiness) of the image projected in the HUD.

References

[1]. M. Sergi, B. Newstrom, A. Gorjestani, C. Shankwitz and M. Donath, "Dynamic Evaluation of High Accuracy Differential GPS," Proceedings of the Institute of Navigation (ION) National Technical Meeting, Anaheim, CA, January, 2003.