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16. Abstract (Limit: 200 words)

This report documents the evaluation efforts undertaken by the Minnesota Team. To complement the work undertaken by the independent government evaluator, Battelle, the Minnesota evaluation team focused on two specific areas of the evaluation: human factors and benefit-cost analyses. Human factors issues include driver acceptance, reduction in driver fatigue, the effectiveness of the driver interface, and the measurable changes in driver performance.

The Driver Assistive System (DAS), which is under evaluation for the US DOT Specialty Vehicle Generation Zero Field Operational Test, is designed to provide a driver a means to maintain desired lane position and avoid collisions with obstacles during periods of very low visibility. This program is motivated by the fact that specialty vehicles often must operate under inclement weather conditions and associated low visibility situations. The DAS improves safety for the specialty vehicle operator by providing the necessary cues for lane keeping and collision avoidance normally unavailable during poor visibility conditions. The DAS may also improve safety conditions for the general public by facilitating all-weather emergency services, and in the case of snowplows, opening roads and keeping them passable in heavy weather for other emergency vehicles and the general motoring public.

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Intelligent Vehicle Initiative
Specialty Vehicle Field Operational Test

Final Report

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EXECUTIVE SUMMARY

PROJECT OVERVIEW

The Driver Assistive System (DAS), under evaluation for the US DOT Specialty Vehicle Generation Zero Field Operational Test, is designed to provide an operator a means to maintain desired lane position and avoid collisions with obstacles during periods of very low visibility. This program is motivated by the fact that specialty vehicles often must operate under inclement weather conditions that produce very low visibility situations. The DAS improves safety for the specialty vehicle operator by providing the necessary cues for lane keeping and collision avoidance normally unavailable during poor visibility conditions.

The primary thrust of the project was snowplow vehicles; however, an ambulance and a state patrol vehicle were also included. Vehicle positioning, collision avoidance, and the driver interface constitute the primary components of the DAS. Vehicle positioning is accomplished through a combination of a Differential Global Positioning System (DGPS) geospatial database system and a roadway magnetic tape/sensor based system. Collision warning and avoidance is accomplished with radar sensors and signal processing techniques which take advantage of information returned by the vehicle positioning system. Finally, information is provided to the driver via the driver interface system, which employs visual, haptic, and auditory interfaces to provide an optimal information path to the driver.

The Field Operational Test (FOT) was to have provided substantiated evidence that the DAS does work as proposed, and that safety and operational benefits are achieved at a favorable benefit:cost ratio.

The DAS was proposed as a means with which to help a driver under conditions of low visibility. It is therefore imperative to document visibility during the course of the field operational test. Visibility was documented in two ways: (1) with infrastructure-based weather stations that were installed along the test route and (2) with an in-vehicle system utilizing a forward looking camera.

A key component of the Field Operational Test (FOT) (but not part of the DAS) was a vehicle data acquisition (vehDAQ) system. (The vehDAQ was originally named “microDAS” in the Technical Systems Requirements document. However, a search turned up other products called “microDAS.” To avoid possible trademark problems and because the design described herein is new, the name vehDAQ has been assigned to the four-camera based data acquisition unit.) The vehDAQ system multiplexes the video signals from four cameras, then compresses and stores the images in real time on a hard drive. Three of the four video cameras were aimed at the driver or the driver interface; the fourth camera was aimed out of the windshield.

The FOT was conducted on Minnesota Trunk Highway 7 (MNTH-7) between Hutchinson, MN to the west and I-494 in Minnetonka, MN to the east, and on a section of County Road 7 (CR-7) near MNTH-7. Magnetic tape was installed on an eight-mile stretch of MNTH-7 between Hutchinson, MN and Silver Lake, MN and on the section of CR-7. The entirety of MNTH-7 between Hutchinson and I-494 was mapped for use with the DGPS system, as was CR-7.

GOALS OF THE EVALUATION

This report documents the evaluation efforts undertaken by the Minnesota Team. There were two evaluation areas: human factors and system performance. Human factors issues include measurable changes in driving performance and operator acceptance. The specific goals were:

- To show the decrement in driving performance caused by very limited visibility.
- To show the improvement in driving performance produced by using the DAS in conditions of poor visibility.
- To show how close the improvements in performance produced by using the DAS in very limited visibility conditions came to restoring the performance level obtained in clear visibility.

In addition to collecting driving performance data, the opinions of the specialty vehicle operators were collected in order to determine the following:

- Whether or not the specialty vehicle operators thought the DAS was useful in conditions of limited visibility.
- How useful various aspects of the DAS were (e.g., lane markings presented on the Head-Up Display, collision warnings on the Head-Up Display (HUD), lane departure warnings presented in three modalities, etc.) in conditions of limited visibility.
- Whether or not the specialty vehicle operators used the magnetic tape backup system and, if they did, how useful it was.
- Whether or not it was stressful or fatiguing to use the DAS in conditions of limited visibility.
- Whether or not the specialty vehicle operators were comfortable with the positioning of the Head-Up Display and the DAS projection system.
- Whether or not the specialty vehicle operators would like on-coming traffic to be shown on the Head-Up Display.
- The specialty vehicle operators' assessment of the potential usefulness of the DAS.

DATA COLLECTED

Visibility Data

Visibility data were collected throughout the FOT at six meteorological sites that were distributed along the Test Route. Vaisala PWD-11 sensors, which measure Meteorological Optical Range (MOR), were installed at these six sites. MOR measurements in the range 10 to 2,000 meters were taken at five minute intervals throughout the FOT.

Engineering Data and Video Data

Engineering unit data (i.e., from GPS position data, magnetic tape lane position data, inertial measurement unit (IMU) data, radar "hits," etc.) were collected by the vehDAQ system installed on each of the test vehicles. In addition to the engineering data, the vehDAQ system recorded video input from four cameras, multiplexing the four video signals, and storing the captured images in real time on the hard drive. The video and engineering data stored on the hard drives

were transferred to DVD-RAMs. Subsequently, the driving performance data were derived from the engineering data.

Questionnaire Data
Subjective data were collected from the operators by administering a User Acceptance Questionnaire/Survey instrument.

PERFORMANCE AND SURROGATE MEASURES

Visibility Measures
The visibility data collected at the six meteorological sites along the test route provided information as to the prevailing visibility throughout the FOT. These data were of particular interest during snowfalls.

Driving Performance Measures
The engineering data collected by the vehDAQ were used to derive the following driving performance measures used for the evaluation of the DAS.

- Vehicle speed.
- Vehicle trajectory instability.
- Duration of *unintentional* lane departures (i.e. length of time for which part of the vehicle is out of lane).
- Response to collision avoidance warnings.

Questionnaire Responses
Subjective data were collected from the operators by administering a User Acceptance Questionnaire/Survey instrument.

ANALYSIS
The first step in evaluating the performance of the DAS during the FOT was to examine the visibility data, so that the driving performance data obtained under the various visibility conditions could be compared.

Statistical Approach
The specific hypotheses for evaluating the DAS in the FOT deal with the effects of variations in visibility and the use of the DAS on four driving performance measures—vehicle speed, vehicle trajectory instability, lane departure duration, and the collision avoidance reaction time.

Throughout the FOT, driving performance data were extracted from the engineering data then categorized in terms of visibility level, operator, test vehicle, and test route segment. Once all the test data were compiled, the *comparative statistical analysis* could commence.

When the FOT was completed, the next step in the comparative statistical analysis was to test the driving performance data for normalcy, kurtosis and skew, and transform the data if necessary. Analysis-of-Variance (ANOVA) paradigms were to be used to compare the driving performance data obtained in each of the three main conditions.

The goal of the comparative statistical analysis was to determine whether there were statistically significant differences in lane departure duration, vehicle trajectory instability, vehicle speed, and collision avoidance reaction time for:

1) Driving in clear visibility conditions.
2) Driving in very limited visibility conditions with the DAS *On*.
3) Driving in very limited visibility conditions with the DAS *Off*.

EXTENUATING CIRCUMSTANCES

The Mildest Winter on Record

Unfortunately, the winter of 2001-2002 was the mildest on record in Minnesota, and there were only two relatively heavy snowfalls—on March 8-9 and March 14-15.

In the March 8-9 snowfall there were:

- No visibility readings below 100 meters.
- No visibility readings in the 100 to 199 meter range.
- Visibilities in the 200-to-299-meter range were recorded at four of the six meteorological sites.

For the March 8-9 snow event, the driving performance records indicate that none of the six test vehicles were operating anywhere on the Test Route during the times that visibilities in the 200 to 299 meter range were recorded at four of the meteorological sites.

In the March 14-15 snowfall there were:

- No visibility readings below 100 meters.
- Visibilities in the 100 to 199 meter range were recorded at one of the six meteorological sites: 15 minutes at Site #4.
- Visibilities in the 200-to-299-meter range were recorded at four of the six meteorological sites.

The driving performance records for the March 14-15 snow event indicate that none of the six test vehicles were operating anywhere on the Test Route during the 15 minutes that the visibility was between 100 and 199 meters. The driving performance records do show two operators drove when the 200-to-299 meter visibility levels were recorded at one site. The video data obtained while these operators drove during these times revealed that the forward view was clear for both operators, neither operator was using the Head-Up Display, and that neither operator had to reduce speed. (It is important to note that the Head-Up Display is designed for very low visibility conditions. Use in good visibility can lead to distraction and "tunnel vision.") This video data is provided on the CD ROM which accompanies this report.

At no time during the FOT, were any of the specialty operators exposed for *sustained* periods to the kind of conditions for which the DAS was designed.

RESULTS/CONCLUSIONS

Driving Performance Data

The goal of the FOT was to determine whether, by using the DAS, the performance of the specialty vehicle operators was enhanced in conditions of very limited visibility. Driving performance data was to have been collected under the following visibility conditions: (1) clear visibility; (2) very limited visibility with the DAS *On*; and (3) very limited visibility with the DAS *Off*.

Vast amounts of driving performance data were collected during the FOT. But, all these driving performance data fell into the first visibility category. No driving performance data were collected at any time during the FOT when there was very limited visibility (i.e., visibility levels below 100 meters or in the 100- to 199-meter range). Therefore, no driving performance data were collected in conditions of very limited visibility with the DAS *On*, or in conditions of very limited visibility with the DAS *Off*.

This means that *comparative statistical analysis* could not be used to test the FOT hypotheses. Because no data was collected with the operators driving in conditions of very limited visibility with the DAS *On*, or in conditions of very limited visibility with the DAS *Off*, no statistically relevant conclusions about the effect of using the full Driver Assistive System on (1) vehicle speed, (2) vehicle trajectory instability, (3) collision avoidance reaction time, or (4) lane departure duration can be drawn.

However, with regard to *lane departure duration*, it is possible to conduct a comparative statistical analysis to test a different *subsidiary* hypothesis. Often the operators drove with the DAS switched *On* but with the Head-Up Display pushed up out of the way; when this happened the operators could *not* receive the visual lane departure warning although they did receive auditory and haptic lane departure warnings. It is thus possible to test the following hypothesis:

- It is expected that the lane departure duration is to be shorter in *good* visibility conditions when the DAS is *On* than in *good* visibility conditions when the DAS is *Off*. (The DAS can be on, but the driver has the option to move the combiner of the HUD out of the way. In good visibility, the HUD is best left in the UP position.)

The hypothesis that the lane departure duration would be shorter in *good* visibility conditions when the DAS is *On* than in *good* visibility conditions when the DAS is *Off* was upheld for one ambulance driver while the opposite result was obtained for two snowplow operators. The reason for obtaining the opposite result with the two snowplow operators is perhaps to be found in the responses to the questionnaire. As is reported in the chapter IV, section 2, Questionnaire *(Areas of Potential DAS Improvement)* below, several snowplow operators said they would like the lane departure warnings to be tied to a lane wider than the standard 12-foot lane, so they would not get lane departure warnings when they are plowing the center line and right edge line. Apparently, they found it difficult to reposition the virtual lane makers while they were driving. It is quite likely that they deliberately ignored the warnings in order to plow the center line or edge line, so their responses to the auditory and haptic warnings were longer when the DAS was *On*. In line with this reasoning and for purposes of comparison, if the weather conditions were good and snowplow operators were not plowing and the DAS was off, then shorter lane

departures would be expected. However, if the snowplow operators were plowing whether the DAS was off or on, then longer lane departures would be expected as operators typically move out of lane to clear shoulders and road centerlines.

Questionnaire responses

Extensive questionnaire data relating to the operator's opinions about the DAS were collected at the end of the FOT. Because of the mild winter none of the operators used the DAS under conditions of *sustained* low visibility. As a result, the questionnaire data are of very limited use. The operators were only able to guess at the opinions they might have had if they had experienced the DAS under the conditions for which it was designed.

The subjective questionnaire data were obtained from 13 of the 21 specialty vehicle operators who participated in the FOT. They included all eight snowplow operators, four of the ambulance drivers, and one state highway trooper. The remaining eight ambulance drivers had very limited experience with the Driver Assist System.

Before receiving a questionnaire, drivers were screened with the question, "During the past winter, in how many shifts did you use the Driver Assist System in conditions of limited visibility (snow or fog)?" Depending on the answer to that question, each driver was given one of two questionnaires, that were identical in format, but the two types were worded slightly differently.

The questionnaire was designed to focus on the operators' experience with the DAS in limited visibility conditions. Originally the questionnaire was going to be administered four times throughout the FOT. Because there were no snowfalls of any significance until very late in the FOT, the questionnaire was given only once in early April, 2002.

The operators did not experience periods of *sustained* poor visibility, and five of the 13 interviewed said that they *never* drove in poor visibility conditions. The remaining eight operators said they had some experience of low visibility conditions during the FOT, although only one reported encountering poor visibility in more than four shifts. Because the operators were not exposed to very low visibility conditions for *sustained* periods of time and, according to their subjective reports, had relatively little experience of "limited visibility" conditions, the *usefulness* of the questionnaire must be questioned.

Because of the lack of "wintry" weather, there were occasions when the operators chose to use the DAS to gain experience and to test the system. The DAS, however, was *not* designed for use in conditions when visibility is good—it was designed for use when visibility is very poor. Consequently, *the operators' responses about the DAS that were obtained in the interviews should be considered with caution*. These opinions might be considerably different if they experience the DAS in conditions of *sustained* low visibility.

Favorable Responses to the DAS

- Each of the 13 operators, without exception, said that he or she thinks the concept and potential of the DAS is "great."

- Many snowplow operators expressed the opinion that the DAS would be far more useful in out-state Minnesota where low visibility conditions occur more often than on MNTH-7 between Hutchinson and Minneapolis.

Areas of Potential DAS Improvement

- The DAS is not reliable—*thus dependability is a big issue*. Several drivers said they would not use the DAS as currently implemented in harsh conditions, because of a fear of getting stranded without another truck equipped with a similar system nearby to rescue them.
- Visibility through the combiner used for the Head-Up Display was a problem for several snowplow operators. They found it hard to detect snow drifts (until they were nearly upon them) and other subtle changes in the road surface/texture.
- Reflections from the combiner used for the Head-Up Display were also a problem for six of eight snowplow operators—e.g., one said, "I can't use this thing. I'm going to run into somebody."
- Vibration of the combiner used for the Head-Up Display was a source of annoyance to most operators.
- Nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings.
- Several snowplow operators said they would like the lane departure warnings to be tied to a lane width larger than the standard 12-foot lane, so they would not get lane departure warnings when they cross the center line and right edge line. They found it difficult to reposition the virtual lane markers (which the DAS currently allows) while they were driving, so they would prefer a greater default width.
- More concentration is needed to use the Head-Up Display when the visibility is good, than is needed if it is not used when the visibility is good.
- All operators said they were concerned with the way the DAS is currently configured in the cab. They complained that the combiner was too close to the head and, in addition, many of them were hit in the shoulder by the projector. The ambulance drivers were particularly uncomfortable with the arrangement of the hardware in their cab—they did not like losing the sun visor and the projector inhibited the communication between the driver and the paramedic when performing routine job functions.
- Eight of the 13 operators expressed concern that oncoming traffic is not displayed on the Head-Up-display. Ambulance drivers in particular were concerned because they often must pass other vehicles.
- Nine of the 13 operators stated that the lane departure warnings go off in the wrong place—sometimes as much as four feet from the correct position. It seems that places where the lane splits occur are where the warnings are the least correct.

<u>Additional Considerations</u>

It was worth making some additional comments about three of the bulleted points above. First, with regard to the comment that nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings, it should be noted that during the low visibility conditions for which the DAS was designed, there would likely be far fewer other vehicles present, and consequently there would also likely be fewer collision avoidance warnings (rectangles) on the combiner.

Second, several snowplow operators said they would like the lane departure warnings to be tied to a lane width larger than the standard 12-foot lane. They indicated that they would like to have greater lane width adjustment flexibility so that lane departure warnings would not be given when operators crossed the center line and right edge line. Operators found it difficult to reposition the virtual lane markers (which the DAS currently allows) while they were driving, so they would prefer a greater default width. Though the snowplow operators said they would like a greater default width, a preferable alternative solution would be to modify the DAS to make it easier to reposition the virtual lane. Considerable care needs to be taken in deciding how to deal with this problem.

Third, the operators indicated that they had to concentrate more when they used the DAS in good visibility than when they did not use the DAS in good visibility. It should be noted that this says nothing about whether or not more concentration would be required if they were to use the DAS in poor visibility than if they did not use the DAS in poor visibility. Furthermore, the DAS was not designed for use under good visibility conditions.

Willingness to Participate in Subsequent Field Testing of the DAS

- Each operator stated that this was not a good winter to test the system. All 13 operators interviewed indicated that they would like to see the program extended, and hope that they will have the opportunity to use the system in the low visibility conditions that occur in a typical Minnesota winter.

The specialty operators' lack of experience in very low visibility conditions, coupled with a lack of driver trust in a system they experienced early on when it was unreliable, makes evaluation highly problematic. Because the operators had no opportunity to use the DAS in sustained low visibility conditions, the *usefulness* of the questionnaire responses is in doubt. A guiding principle of usability studies is that the technology or device to be evaluated should always be tested under the circumstances for which it was designed and conversely, it should never *solely* be tested in conditions when the users do not need it.

STUDY CONTINUATION, FUTURE WORK

The FHWA has decided against sponsoring another year of Field Operational Testing for this system. Based on the results of this study, and in particular, the driver view that the system has significant potential, Mn/DOT has decided to extend the FOT for an additional year. Presently, discussions are underway to determine the scope and extent of the testing to be undertaken during the winter of 2002-2003.

Based on driver interviews and subsequent discussions, a number of changes have been made or will be made to the system. Below, driver comments and the resulting changes to the system are provided.

Operator response:

The DAS is not reliable—*thus dependability is a big issue*. Several drivers said they would not use the DAS as currently implemented in harsh conditions, because of a fear of getting stranded without another truck equipped with a similar system nearby to rescue them.

System modification:

Reliability is a difficult entity to quantify. To some operators, an occasional radar target would appear on the screen when there was no physical object present from which a radar return should appear. (This was a phenomena not seen before the FOT. U of MN radar processing technology provides the opportunity to filter returns from elements in the geospatial landscape, but there is no means to filter returns from something that is not part of the geospatial landscape.) To them, this made the system unreliable. To others, it was a period during a transition from one GPS base station to another when the GPS solution would be lost.

The solution to the radar problem will require support from Eaton Vorad. Whether Eaton Vorad is willing to support this limited application is yet to be determined. GPS transitions have been improved with more recent versions of Trimble firmware for the ms750 receiver. Upgrading vehicle GPS systems to this firmware release should significantly reduce the time it takes the receiver to transition from one base station to another. This has been tested, and the system is now much improved when compared to the units used during the past winter.

Operator response:

Reflections from the combiner used for the Head-Up Display were also a problem for six of eight snowplow operators. For example, one operator said, "I can't use this thing. I'm going to run into somebody."

System Modification:

Complaints of this sort are likely due to the operator not properly adjusting the intensity/brightness of the displays located inside their vehicle. Both the driver interface and HUD projector have variable brightness controls which must be dimmed for low ambient light level operation. The long gap between training and actual system use due to the unique weather pattern of the winter of 01 – 02 probably led to the drivers forgetting where/how to dim their displays. To address this issue, drivers will be retrained, and an instruction "cheat sheet" will be provided for each vehicle as a brief users' manual.

Operator Response:

Visibility through the combiner used for the Head-Up Display was a problem for several snowplow operators. They found it hard to detect snow drifts (until they were nearly upon them) and other subtle changes in the road surface/texture.

System Modification:

This response likely arises because the system was not used in very low visibility conditions. Under those conditions, it is difficult to see snow drifts because of contrast issues, and other subtle changes in the roadway because of poor lighting and obscured visual paths. Excessive brightness on the combiner may overpower light transmitted through the combiner; reducing projector brightness may address this problem.

Operator response:

Vibration of the combiner used for the Head-Up Display was a source of annoyance to most operators.

System modification:

Combiner mounts will be modified to make them stiffer and less susceptible to vibration.

Operator response:

Nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings.

System modification:

System software will be modified to provide only warnings regarding the closest two or three obstacles. This will greatly reduce the clutter in the HUD.

Operator response:

All operators said they were concerned with the way the DAS is currently configured in the cab. They complained that the combiner was too close to the head and, in addition, many of them were hit in the shoulder by the projector. The ambulance drivers were particularly uncomfortable with the arrangement of the hardware in their cab—they did not like losing the sun visor and the projector inhibited the communication between the driver and the paramedic when performing routine job functions.

System modification:

Unfortunately, a solution to this problem is beyond the scope of this project. Because of the optical properties required of the HUD, the projector is required to be a fixed distance from the combiner. Because of this fixed distance requirement, the remaining mounting option is that of installing the projector and ancillary optics in the dashboard of the vehicle. This is beyond the scope of this project.

Operator response:

Eight of the 13 operators expressed concern that oncoming traffic is not displayed on the Head-Up display. Ambulance drivers in particular were concerned because they often must pass other vehicles.

System modification:

This is a limitation of the Eaton Vorad radar. Extensive changes to the design of the radar front end and of the signal processing software would be needed to provide information regarding on-coming traffic. It is unlikely that these changes will be made by Eaton Vorad for this FOT. Drivers will simply be unable to rely on radar information for oncoming traffic.

Operator response:

Nine of the 13 operators stated that the lane departure warnings go off in the wrong place—sometimes as much as four feet from the correct position. It seems that places where lane splits occur are where the warnings are the least correct.

System modification:

These errors have two possible sources. The likely candidate is that during the GPS transition, the GPS system converges to an incorrect position solution. If this is the case, the recent firmware release by Trimble should correct the problem. The less likely candidate is an error or errors associated with the database. However, the database was thoroughly checked after it was completed, and no errors of this magnitude have been located. Nevertheless, the database will be checked before the extension to ensure that it is error free.

In all, the deficiencies mentioned by the drivers are for the most part problems for which tractable solutions exist. System modifications, complemented by training refresher courses and more frequent use of the system should address a significant portion of the drivers' complaints. It is likely, however, that significant use may uncover other issues which will need to be addressed. The key is to achieve sustained use of the system in conditions for which it was designed.

If an additional evaluation were to be conducted, there should be more frequent one-on-one interaction with the operators directly following their shift to obtain more immediate information regarding the operators' thoughts on the DAS.

As a final comment, it should be noted that the "rules of engagement" for this FOT was that once the system was released, no modifications to the system were allowed unless the issue was determined to be safety critical. This limited the ability of the team to respond to issues raised by the operators during the actual test. Some operators felt that their needs/issues were not adequately addressed during the duration of the test; this led to some less than favorable responses to the system by the drivers.

Chapter 1
PROJECT OVERVIEW

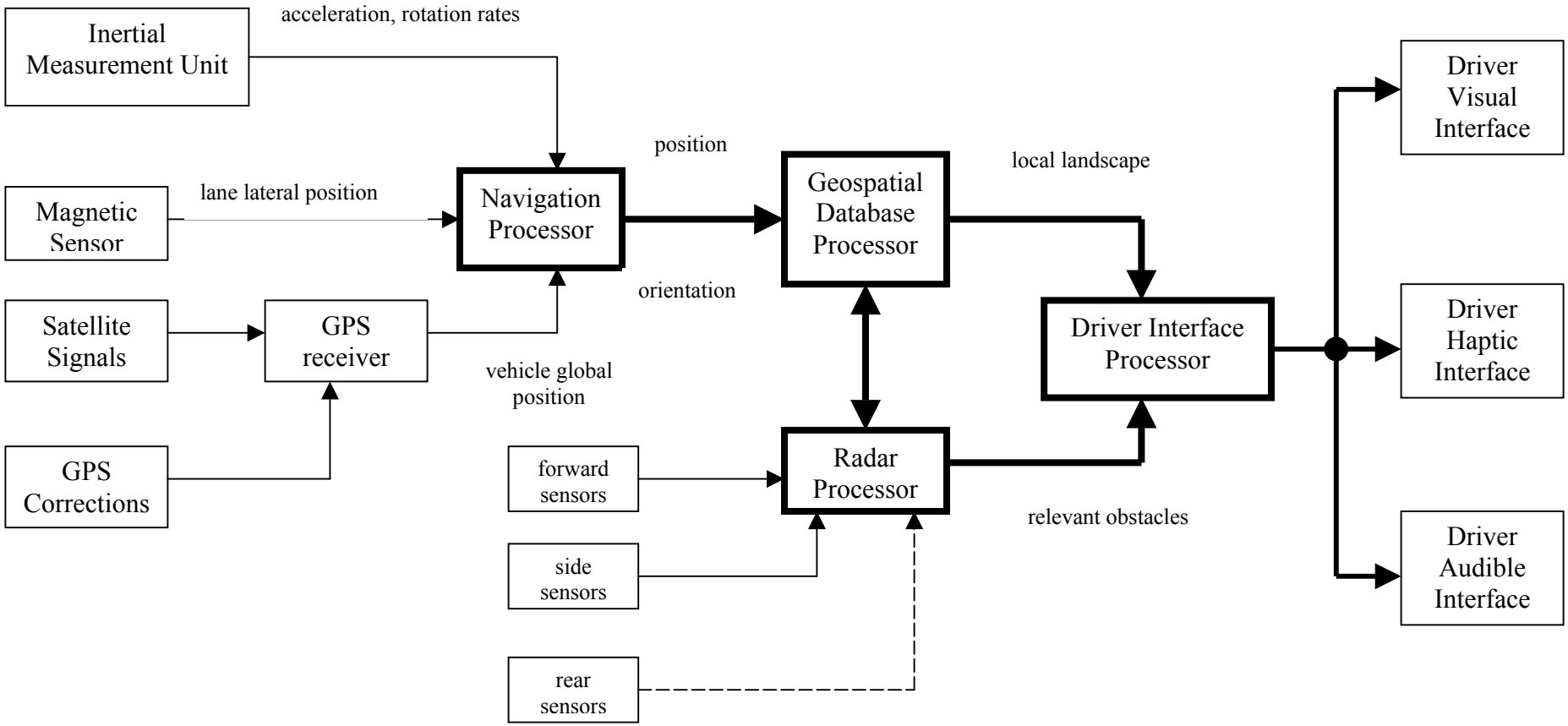
The Driver Assistive System (DAS) which is under evaluation for the US DOT Specialty Vehicle Generation Zero Field Operational Test is designed to provide a driver a means to maintain desired lane position and avoid collisions with obstacles during periods of very low visibility. This program is motivated by the fact that specialty vehicles often must operate under inclement weather conditions. Typically associated with these inclement weather conditions are very low visibility situations. The DAS improves safety for the specialty vehicle operator by providing the necessary cues for lane keeping and collision avoidance normally unavailable during poor visibility conditions. The DAS, when placed in public safety vehicles, also improves safety conditions for the general public by facilitating all-weather emergency services, and in the case of snowplows, opening roads and keeping them passable in heavy weather for other emergency vehicles and the general motoring public.

The primary thrust of the project was snowplow vehicles; however, ambulances and police vehicles were also included. The project implemented, operated, and evaluated all necessary infrastructure, in-vehicle sensing technology, in-vehicle processing including algorithms, and driver-vehicle interfaces. Testing of these systems was to have taken place on state and county highways using state and county vehicles under low- visibility conditions such as snow, blowing snow, fog, and night. (More will be said about the mildest Minnesota winter on record in Section 3.1.) Human factors laboratory testing was done to assure the driver-vehicle interface systems are based on the best possible human-centered design. Project results were to have been used to provide the Federal Highway Administration and an independent evaluator with data and to inform decision makers and the general public of the potential for these systems to improve the safety and productivity of the transportation system.

Vehicle positioning, collision avoidance, and the driver interface constitute the primary components of the DAS. Vehicle positioning is accomplished through a combination of a Differential GPS (DGPS) – geospatial database system and a roadway magnetic tape/sensor based system. Collision warning and avoidance is accomplished with radar sensors and signal processing techniques which take advantage of information returned by the vehicle positioning system. Finally, information is provided to the driver via the driver interface system, which employs visual, haptic, and auditory interfaces to provide an optimal information path to the driver. A block diagram of the DAS illustrating components and signal paths is shown in Figure 1.1 on the next page.

The system works as follows:

DGPS and the magnetic tape system provide information regarding the position of the vehicle; DGPS provides global information, and magnetic tape system provides local information in the form of a lateral displacement of the sensor from the magnetic tape. (Lateral lane position is a subset of global position when the geo-spatial database is used. Used together, system robustness can be improved should one or the other system fail or become unavailable. Proprietary techniques are being developed to improve this system.) Vehicle orientation



Note: Rear radar was to have been included as part of this system, but development problems experienced by Altra resulted in no rear radar as part of the FOT. An Eaton based system has been under development for rear collision warning and avoidance. A functioning prototype could not be developed in time for this FOT.

Figure 1.1: Driver Assistive System Block Diagram

data (i.e., vehicle yaw, roll, and pitch rates, lateral, longitudinal, and vertical acceleration) is provided by an Inertial Measurement Unit (IMU). Given vehicle position and orientation, the geo-spatial database is queried to determine the presence and location of all relevant items in the local landscape.

Simultaneously, the vehicle forward- and side-looking radar scan the environment local to the vehicle to detect the presence and location of obstacles around the vehicle. (In the forward view, presence and location means range, range rate, and azimuth angle to the sensed obstacles; in the side view, range within the radar beam is all that is sensed.) For the forward view, the radar processor accepts this raw sensor data, and compares it to the results of the geo-spatial database query. The radar processor then determines radar returns which are a threat to a driver and which returns are associated with fixed elements of the infrastructure. When both the geo-spatial database processor and the radar processor complete their respective tasks, the results are sent to the driver interface processor. The driver interface processor determines whether the vehicle is in its proper lane, detects the possibility of a collision with another vehicle or element of the local environment, and monitors whether all sensors are functioning properly. If the driver is in no danger, no warnings are issued, and the driver is provided continuous assistance from the lane markings on the visual, display present in the vehicle. If the driver is heading for an undesired lane departure or collision with another object, the appropriate warning is issued via the visual, auditory, and haptic channels so that the driver can take appropriate action.

Each of the primary system components may be associated with sensors, infrastructure, processors, and displays. For instance, the vehicle positioning system infrastructure includes magnetic tape embedded in the roadway along the skip line and edge lines, a network of GPS receivers, antennae, and Radio Frequency (RF) modems used to broadcast the GPS correction signals to the proper GPS receivers located on the test vehicles. The geo-spatial database, although resident on each vehicle, can also be considered infrastructure because it locates and provides attributes for each relevant item located near the roadway. These details are further described in the Detailed Design Report (University of Minnesota, 2001) for this project.

A key component of the Field Operational Test (FOT), but not part of the DAS, was the data acquisition system. The FOT was to have provided substantiated evidence that these systems do work as proposed, and that safety and operational benefits are achieved at a favorable benefit:cost ratio. In the FOT, data acquisition capability was present both in-vehicle and as part of the test corridor infrastructure.

The DAS was proposed as a means with which to help a driver under conditions of zero or near zero visibility. It is therefore imperative to document visibility during the course of the field operational test. Visibility was documented in two ways: (1) with infrastructure-based weather stations, and (2) with an in-vehicle system utilizing a forward looking camera.

Along the test corridor, a number of weather stations were installed and networked to provide weather and visibility data to a central server. (The visibility measure provided by the weather station is “meteorological visual range,” which indicates the density of the atmospheric particles that affect the visible-spectrum transfer function of air space between two separated points where

the measurements take place.) These weather stations reported atmospheric conditions including precipitation types, rates, and moisture content in addition to visibility measures.

Local to each vehicle was a vehicle data acquisition system (vehDAQ). At the heart of the vehDAQ system is the ability to accept video input from four cameras, multiplex the four video signals, compress the video signals, and then store the compressed captured images in real time to a hard disc mounted on each test vehicle. In addition to the video data, the vehDAQ also recorded audio data and engineering unit data (i.e., GPS position, magnetic tape lane position data, IMU data, radar "hits," etc.) in synchronization with the video data. Three of the four video cameras were aimed at the driver or the driver interface; the fourth camera was aimed out of the windshield. The camera aimed out the windshield recorded the forward view of the road scene. The intent is to use the images captured via the windshield camera to determine a "motorist's visibility index" which quantifies the effective visibility available to the driver at any time during the FOT. (The vehDAQ was named "microDAS" in the Technical Systems Requirements document. However, a search turned up other products called "microDAS." To avoid possible trademark problems and because the design described herein is new, the name vehDAQ has been assigned to the four camera based data acquisition unit.)

The FOT took place primarily on Minnesota Trunk Highway 7 (MN TH7) between Hutchinson, MN to the west and I-494 in Minnetonka, MN to the east. Because of the involvement of McLeod County in the FOT with their drivers and snowplow, a section of County Road 7 (CR 7) near MN TH7 was also included in the FOT. Magnetic tape was installed on an eight-mile stretch of MN TH7 between Hutchinson, MN and Silver Lake, MN and on a section of CR 7. The entirety of MN TH 7 between Hutchinson and I-494 was mapped for use with the GPS system, as was CR 7. A map of the MN TH 7 corridor is shown in Figure 1.2 below.

Figure 1.2: Map of the Test Corridor – Minnesota Trunk Highway 7

Evaluation

This report documents the evaluation efforts undertaken by the Minnesota Team. To complement the work undertaken by the independent government evaluator, Battelle, the Minnesota evaluation team focused on two specific areas of the evaluation: human factors and benefit:cost analyses. Human factors issues include driver acceptance, reduction in driver fatigue, the effectiveness of the driver interface, and the measurable changes in driver performance.

Chapter 2
EVALUATION EXECUTION

2.1 GOALS

The DAS was developed in order to assist specialty vehicle operators with driving in very low visibility conditions. Specialty vehicle operators are sometimes faced—particularly in rural areas—with very low visibility conditions when falling, blowing, and/or drifting snow causes whiteouts or near-whiteouts. The DAS presents a virtual representation of the roadway and provides warnings of vehicles ahead on a Head-Up Display that is mounted in front of the driver. The DAS also provides multi-modality lane departure warnings—a *visual* warning is given on the Head-Up Display; an *auditory* warning is presented via speakers mounted in the cab; and a *haptic* warning is presented via the driver's seat.

The FOT was conducted in the winter of 2001-2002 with the expectation that there would be a number of occasions when there would be very limited visibility conditions. Our ***overall goal*** was to discover if the DAS did indeed assist specialty vehicle operators when they drove in very limited visibility conditions—conditions that would be considered hazardous for those driving without the assistance of the DAS. To this end, we planned to collect driving performance data from specialty vehicle operators when they drove in conditions of (1) clear visibility, (2) very limited visibility with the DAS switched *On*, and (3) very limited visibility with the DAS switched *Off*. Obtaining these data would have enabled us to address the overall goal by means of the following ***specific goals***:

- To show the decrement in driving performance caused by very limited visibility.
- To show the improvement in driving performance produced by using the DAS in conditions of very limited visibility.
- To show how close the improvements in performance produced by using the DAS in very limited visibility conditions came to restoring the performance level obtained in clear visibility.

In order to address these specific goals, the following driving performance measures were collected:

- Vehicle speed
- Vehicle trajectory instability [This measure of steering control is described in more detail in section 4 of this chapter.]
- Duration of lane departures (i.e., the length of time for which part of the vehicle is out of lane)
- Response to collision avoidance warnings

The specific hypotheses relating to these driving performance measures are presented in section 2.3 of this chapter.

In addition to collecting driving performance data while the specialty vehicle operators drove, a questionnaire was given to the specialty vehicle drivers to obtain information regarding their opinions. The goal in administering the questionnaire was to determine the following:

- Whether or not the specialty vehicle operators thought the DAS was useful in conditions of limited visibility.
- How useful various aspects of the DAS were (e.g., lane markings presented on the Head-Up Display, collision warnings on the Head-Up Display, lane departure warnings presented in three modalities, etc.) in conditions of limited visibility.
- Whether or not the specialty vehicle operators used the magnetic tape backup system and, if they did, how useful it was.
- Whether or not it was stressful or fatiguing to use the DAS in conditions of limited visibility.
- Whether or not the specialty vehicle operators were comfortable with the positioning of the Head-Up Display and the DAS projection system.
- Whether or not the specialty vehicle operators would like on-coming traffic to be shown on the Head-Up Display.
- The specialty vehicle operators' assessment of the potential usefulness of the DAS.

Assume that it was determined after the FOT analysis that the following two conditions held:

(1) when the specialty vehicle operators were facing conditions of very limited visibility and the DAS was switched *On*, their driving performance was improved when compared to their driving performance in conditions of very limited visibility with the DAS switched *Off*, and
(2) that the opinions of the specialty vehicle operators were favorable toward using the DAS.

In this case, the recommendation would be to continue the development of the DAS. After this development, installing the DAS in other snowplows in the Mn/DOT fleet would improve snowplow operations in areas of the state that routinely experience very low visibility conditions. The DAS could also be installed in the vehicles of ambulance drivers and state troopers, making it far easier for them to respond to emergency calls.

2.2 PREVIOUS RELATED WORK

Prior work leading up to the Field Operational Test can be categorized into two groups: work performed as part of this contract, and work performed outside of the contract. To put things in a historical perspective, outside work will be discussed first.

2.2.1 Outside Work

The human factors work undertaken as part of this contract had a precedent in the work of Tabler (1984), Wilson (1965), and Hawkins (1987).

Tabler (1984) describes some of the difficulties in measuring visibility under snowy conditions. These difficulties include the effects of variation in the number and size of the snow particles, variation in the strength and direction of the prevailing winds, and the possible deposition of frost, ice, snow or water on the optical surfaces of the sensor. In addition to difficulties in measuring visibility, other factors complicate the relationship between traffic speed and visibility variations related to snow. These factors include the condition of the road surface and its effect on traction, and whether or not already-fallen snow is obscuring the lane markings.

In spite of the difficulties with measuring visibility under snowy conditions, Tabler (1984) describes the Wyoming Visual Range Monitoring System which is installed along a 124 km section of Interstate 80 between Laramie and Walcott Junction, Wyoming. Using visual range measurements in conjunction with other weather parameters including wind speed, wind direction, temperature, relative humidity, and precipitation rates enabled the Wyoming DOT to develop an algorithm for determining when a road should be closed to traffic because of poor visibility or when motorists should be warned to reduce speed because of impending low visibility conditions due to blowing snow. Wyoming reported that the visibility monitoring program in conjunction with an aggressive snow fence policy lead to a 70% reduction in crashes during blowing snow conditions.

There are fewer complications involved in describing the relationship between traffic speed and visibility variations related to fog. Wilson (1965) describes an attempt to reduce traffic speed in fog. At that time, Wilson said "No automatic measuring device which correlates fog density, background brightness and other pertinent factors to visibility (the distance that a motorist can see) is available" (p. 44). Because of this "fog was determined by measuring the distance that the study researchers could see fixed objects (signs, poles, trees, bridges, etc.) while observing and measuring traffic" (p. 45). Wilson reports that for the 1963-1964 winter fog season there were only 10 days of limiting fog, and only seven days for the 1964-1965 (through January 1965) winter fog season. However, they were able to collect some observational data at the roadside. On one test road, Skyline Boulevard (then a four-lane divided expressway) in San Francisco near the San Mateo County Line, Wilson and his researchers found that:

- For "moderate volume traffic" (between 1,200 and 2,000 vehicles per hour) there were reductions in speed of 12.4% (from a mean speed of 49.8 mph to 43.6 mph) caused when fog reduced visibility to less than 200 ft or 61 meters.
- For "low traffic volumes" (which Wilson does not define, but which are presumably less than 1,200 vehicles per hour) there were reductions in speed of 11.3 % (from a mean speed of 50.3 mph to 44.6 mph) caused when fog reduced visibility to less than 200 ft. or 61 meters.

Wilson found there was an intervention that could be used to reduce speed still further. By posting speed limits on specially-installed commercially-available matrix signs these speeds

could be reduced by a further 11.9% (to 37.9 mph) in moderate traffic volumes and by a further 9.2% (to 40.0 mph) in low traffic volumes. Traffic speeds were reduced more by posting speed limits of 40 mph than they were by posting a 45 mph limit. Further limitations in the posted speed (to 35 mph) *did not* lead to still further reduced traffic speeds.

Hawkins (1987) provides an extensive examination of the effect on traffic speed of limitations in visibility caused by fog. Hawkins reports the results of four observational studies that were conducted on English motorways. In all four studies visibility was measured both subjectively (by human observation) and objectively (using permanently installed Transport and Road Research Laboratory Fog Detectors developed by Jeffrey; 1972). Sumner, Baguley and Burton (1977) conducted the first of these studies on the M4 Motorway. White and Jeffrey (1980) conducted the second, also on the M4 Motorway. Hawkins conducted the remaining two studies himself—one on the M1 Motorway at Trowell and the second on the M1 at Osterley. Taken together these four studies provide an extensive set of data that show the relationship between varying degrees of limited visibility (caused by fog) and traffic speed. Some of the more important findings reported by Hawkins are summarized below.

First, for traffic traveling in the fast lane of the motorway—where the average speed was 82 mph (132 km/h)—the studies reported by Hawkins (1987) showed the following:

- When the visibility was more than 300 meters, there were no reductions in speed for traffic traveling in the fast lane.
- When the visibility was below 300 meters, reductions in speed began to occur—but only for the vehicles traveling in the fast lane.

Second, for traffic traveling in the slow lanes of the motorway—where the average speed was 58 mph (93 km/h)—the studies reported by Hawkins (1987) showed the following:

- When the visibility was more than 250 meters, there were no reductions in speed for vehicles traveling in the slow lanes.
- When the visibility was below 250 meters, reductions in speed began to occur for the vehicles traveling in the slow lane of the motorway.

Third, the studies reported by Hawkins (1987) showed, in all lanes of the motorway, that:

- The greatest reductions in speed did not occur until the visibility level dropped into the 150-180 meter range.
- Traffic speed was reduced by 25% to 30% as the visibility approached 100 meters.

These reductions in speed occur at higher visibility ranges than the 61-meter visibility level investigated by Wilson (1965).

It is important to note that the Hawkins works suffers from two deficiencies. First, Hawkins (1987) does not define how his subjective measurements of visibility were made. Second, a technical description of the Fog Detectors used in the study is unavailable. Both of these facts make it difficult to precisely extrapolate the Hawkins results into expected behavior for the drivers participating in the FOT.

In contrast, the FOT was conducted on highways in Minnesota with the visibility limited by falling and blowing snow and measured by Vaisala sensors (located at the six meteorological

sites). The Vaisala sensors measure the Meteorological Optical Range (MOR), defined as the length of the path through the atmosphere required to reduce the luminous flux (in a collimated beam emanating from an incandescent lamp at a color temperature of 2700 K) to 0.05 of its original value [with the luminous flux being evaluated by means of the photopic luminosity function of the International Commission of Illumination (CIE)]. (This measure of MOR was used in the Wyoming system as described in Tabler. This partially validates the approach.) The data reported by Hawkins (1987) were collected on British motorways in fog with the visibility measured by Transport and Road Research Laboratory Fog Detectors. The problems with the Hawkins study is that his paper does not state the principles on which these fog measurements are made, so accurate extrapolation to MOR is difficult. However, generalizations based on the results of the Hawkins study can indicate trends related to this FOT.

Given these caveats, the results reported by Wilson (1965) and Hawkins (1987) lead to the following expectations about the likely usefulness of the DAS during low visibility conditions in the FOT:

- With visibilities greater than 300 meters, the DAS would likely not be needed by the operators.
- With FOT visibilities in the 200- to 299-meter range, the DAS would be somewhat useful.
- With FOT visibilities in the 100- to 199-meter range, the DAS would be very useful.
- With FOT visibilities less than 100 meters as described by Hawkins, the DAS would be extremely useful—without it, it would likely be impossible to drive.

In addition to these conditions, the DAS is likely to be very useful when the visibility is clear (i.e., greater than 300 meters), but the road to be traveled is completely snow-covered so that the lane markings are obscured.

In the following chapter (Chapter 3: Extenuating Circumstances), substantiation of these expectations is provided using data collected during the FOT.

2.2.2 Previous Project Results

Human factors work undertaken by the University of Minnesota during this contract consisted of three components. The first component was a simulator study to determine both the effectiveness of lane departure and collision avoidance warnings to drivers, and whether a particular combination of warning modality (haptic, visual, or auditory) was more effective than other combinations. The two simulator studies are described in Harder, Bloomfield, and Chihak (in press).

The second component was a field study to primarily determine whether drivers with no previous exposure to this DAS could effectively use it under conditions of zero visibility. The field test was conducted on a closed track at the University of Minnesota Rosemount Research Station in

Rosemount, Minnesota. For this field test, the objectives were to determine whether experienced snowplow operators could drive on real roads in conditions of zero visibility using the integrated system tested in simulator experiments, and whether they were comfortable with the system. This field test demonstrated that it was possible to drive a snowplow around a 4.2-mile track, with several sharp turns, when the visibility was zero (the forward view was completely occluded with curtains mounted inside the cab) using only the DAS. Even though they could not see the actual road surface, the snowplow operators drove at speeds that were reasonable for the environment. They did this because they "felt" the road surface as they drove (i.e., they used the proprioceptive information that they received while driving on snow covered roads). The Rosemount Field Test is described by Bloomfield and Harder (in press). An earlier account of both the simulator studies and the Rosemount Field Test appears in the Detailed Design Report delivered to the Minnesota Department of Transportation (University of Minnesota; 2001).]

The third component was an experiment involving state patrol officers and ambulance drivers who drive at significantly higher speeds than snowplow operators. This test was motivated by the results of a pilot simulator study. During the pilot simulator study, test subjects showed a propensity to "overdrive" their vehicle when provided with the DAS. Based on this finding, it was hypothesized that adding motion cues to the HUD would provide a driver feedback indicative of their present speed, and would reduce the tendency of a driver to "overdrive" this system. To test this hypothesis, Brainerd International Speedway in Brainerd, Minnesota, was leased for a five-day period, the track was mapped, and both ambulance and state patrol drivers followed a specific protocol aimed at determining whether the presence of motion cues in the HUD had a positive effect on speed regulation. Results from that study indicated that the motion cues did result in lower vehicle speeds, and as a result, motion cues were designed into the HUD that was released for the FOT. The results of the Brainerd study have recently been documented, and will be submitted to the FHWA as an appendix to the Detailed Design Report that was finalized in June of 2001.

2.3 FOT HYPOTHESES

The goal of the FOT was to determine whether, by using the DAS, the performance of the specialty vehicle operators was enhanced in conditions of limited visibility. Driving performance data was to be collected under the following three visibility conditions:

- Clear visibility.
- Very limited visibility with the DAS *On*.
- Very limited visibility with the DAS *Off*.

With data collected under these three conditions, it is possible to make the following comparisons:

- Comparisons between the various types of driving performance data obtained in clear visibility and the driving performance data obtained in very limited visibility with the

DAS *Off* would show the decrement in driving performance caused by very limited visibility.

- Comparisons between the driving performance data obtained in very limited visibility with the DAS *On* and driving performance data obtained in very limited visibility with the DAS *Off* would show the improvement in driving performance produced by using the DAS in conditions of very limited visibility.

- Comparisons between the driving performance data obtained in very limited visibility with the DAS *On* and driving performance data obtained in clear visibility would show how close the improvements in performance produced by using the DAS in very limited visibility conditions came to restoring the performance level obtained in clear visibility.

Driving performance is expected to be best in good visibility conditions, marginal in very limited visibility conditions with the DAS *On*, and poor in very limited visibility conditions with the DAS *Off*. The specific hypotheses for the driving measures obtained in the FOT were as follows. [Please note details of the measures mentioned in the hypotheses are given in section 5.1 (FOT Measures) of this chapter.]

Vehicle speed hypotheses

- The vehicle speed is expected to be faster in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The vehicle speed is expected to be faster in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The vehicle speed is expected to be faster in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Vehicle trajectory instability hypotheses

- The vehicle trajectory instability is expected to be less in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The vehicle trajectory instability is expected to be less in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The vehicle trajectory instability is expected to be less in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Collision avoidance reaction time hypotheses

- The collision avoidance reaction time is expected to be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *Off*
- The collision avoidance reaction time is expected to be shorter in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The collision avoidance reaction time is expected to be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Lane departure duration hypotheses

- The lane departure duration is expected to be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The lane departure duration is expected to be shorter in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The lane departure duration is expected to be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

2.4 DATA COLLECTED

In order to carry out an evaluation of the DAS, three kinds of data were collected during the FOT: (1) visibility data; (2) driving performance data and video data; and (3) questionnaire data.

2.4.1 Visibility Data

Visibility data were collected throughout the FOT at six meteorological sites that were distributed along the Test Route as shown in Figure 2.1.

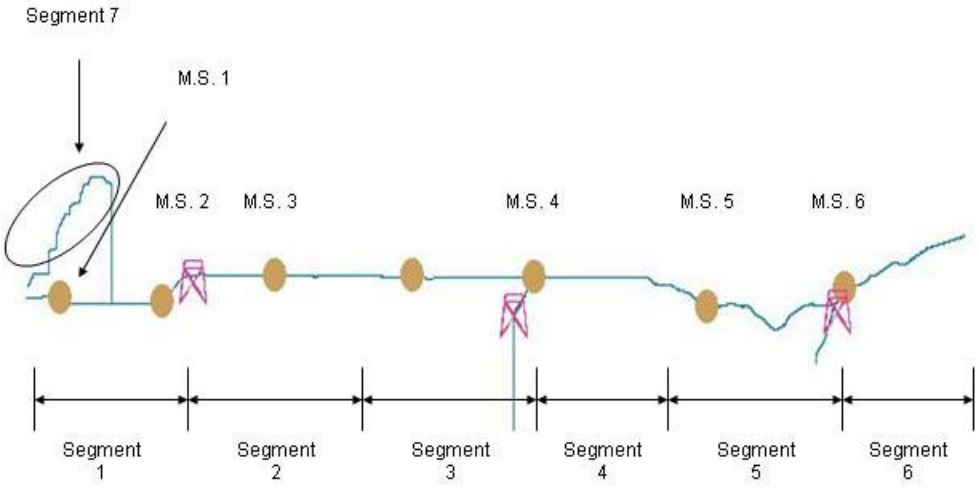


Figure 2.1: Plan View of MNTH-7 Showing the Locations of the Meteorological Sites (MS—mustard dots) - [Also Shown Are the 7 Segments of the Test Route, and the GPS Base Stations (pink towers)]

The Test Route is divided into seven segments (these seven segments are described in detail in section 2.6.3). As Figure 2.1 shows, the first and second meteorological sites were located in Segment #1; Site #3 was located in Segment #2; Site #4 was located on the boundary of Segment #3 and Segment #4; Site #5 was located in Segment #5; and Site #6 was located in Segment #7. Figure 2.1 also shows an additional meteorological site in Segment #3—this is a Mn/DOT Remote Weather Information Station (RWIS).

Vaisala PWD-11 sensors were installed at the six FOT meteorological sites. To reiterate, Vaisala sensors measure Meteorological Optical Range (MOR), which is defined as the length of path through the atmosphere that is required to reduce the luminous flux (in a collimated beam that emanates from an incandescent lamp at a color temperature of 2700 K) to 0.05 of its original value [with the luminous flux being evaluated by means of the photopic luminosity function of the International Commission of Illumination (CIE)].

At five-minute intervals, the following data were collected at each meteorological site:

- MOR measurement in the range of 10-2000 meters
- Precipitation type: precipitation, snow, rain, mixed
- Precipitation accumulation

In addition to these data, at meteorological site #1, the following data were collected, also at five minute intervals:

- Wind speed: maximum speed of 75 m/s
- Wind direction: 8 degrees or better resolution, 5 degrees or better accuracy
- Temperature: -40°F to +140°F, accuracy of +/- .5°F
- Relative Humidity: 0 to 100%, accuracy of +/-5%

2.4.2 Driving Performance Data and Video Data

Driving performance data were derived from the engineering unit data (i.e., from GPS position data, magnetic tape lane position data, IMU data, radar "hits," etc.) that were collected by the vehDAQ system which was installed on each of the test vehicles. The vehDAQ system recorded the engineering data on hard drives that were also installed in each test vehicle. In addition to the engineering data, the vehDAQ system recorded video input from four cameras, multiplexing the four video signals, and storing the captured images in real time on the hard drive.

Engineering unit data collected by the vehDAQ at 10 Hz rates included:

gps data mm-dd-yy
gps time
gps x
gps y
gps z
gps quality index
gps number of satellites
gps hdop
vehicle speed (mph)
vehicle heading
imu rot x rate
imu rot y rate
imu rot z rate
imu accel x
imu accel y

imu accel z
control panel master on-off switch
steering position
brake position
turn signal status
driver specified lateral offset
vehicle lateral offset
3M sensor status - left
3M sensor distance - left
3M sensor status - right
3M sensor distance - right
audio volume
altra sensor status (1 if altra driver is working, 0 if dead)
altra prog_status[0] (1 if left sensor working, 0 if dead)
altra prog_status[1] (1 if right sensor working, 0 if dead)
altra prog_status[2] (left sensor alarm, 0 nothing there, 1 close alarm, 2 far alarm)
altra prog_status[3] (right sensor alarm, 0 nothing there, 1 close, 2 far)
number of radar targets
  [for each radar target]
  target x,
  target y,
  target x_dot,
  target y_dot

Video data complemented the engineering unit data. Four views were collected and stored at a 30 Hz rate. Four views were captured: driver's hands, driver's feet, driver's face, and a forward view out of the windshield. Video data was synchronized with engineering unit data (using GPS time), and was compressed and written to a removable hard drive in real time. Each vehicle was assigned three 36 Gbyte hard drives; one in transit between the vehicle shop and the University, one undergoing an archival process, and a third in the vehicle.

At the University, the video and engineering data stored on the hard drives were transferred to DVD-RAMs which were cataloged and stored. The hard drives were cleared and returned to the field for further use in the FOT, and the data written onto DVD-RAM were used for subsequent analysis.

2.4.3 Questionnaire Data

In addition to the driving performance data, subjective data were collected from the operators by administering a User Acceptance Questionnaire/Survey instrument. The instrument was developed in collaboration with Human Factors personnel from Battelle. An example of the questionnaire is provided in Appendix A below.

2.5 MEASURES

As described in section 3 directly above, three types of data were collected: (1) visibility data, (2) driving performance data and video data, and (3) questionnaire data.

2.5.1 Visibility

The visibility data collected at the six meteorological sites along the test route provided information as to the prevailing visibility throughout the FOT. These data were of particular interest during snowfalls. Measures of atmospheric visibility were MOR; other atmospheric measures include precipitation type and precipitation rate.

2.5.2 Driving Performance

Unlike the visibility data, the driving performance measures used for evaluation of the DAS were derived from the engineering data collected by the vehDAQ.

The driving performance measures used for the evaluation are measures that can be influenced by the DAS. They are measures related to steering, speed, lane departures, and responses to vehicles ahead. Data pertaining to driving performance measures that could not be influenced by the DAS were not collected. No data related to driving through a red light or running a stop sign (if they occurred) were collected because the DAS does not provide any information about the location of traffic lights or stop signs.

The engineering data collected by the vehDAQ were used to derive the following driving performance measures.

- Vehicle speed.
- Vehicle trajectory instability. This measure of steering control, defined as "steering instability" by Bloomfield and Carroll (1996), is the variability around the line of best fit for the vehicle trajectory. See Figure 2.2 below.
- Duration of lane departures (i.e. length of time for which part of the vehicle is out of lane).
- Response to collision avoidance warnings.

2.5.2.1 Vehicle Speed Measures

Vehicle speed data acquired while the vehicle is in lane and not subject to immediate collision avoidance maneuvers are used to determine the average speed of the vehicle.

2.5.2.2 Lane Keeping / Lane Departure Performance

All lane departures are identified and denoted for every occasion on which vehicle leaves the lane by crossing either the lane marker to the left of the vehicle or the lane marker to the right of the vehicle. The lane departures are sorted into *intentional* and *unintentional* lane departures—*intentional* lane departures occur when the operator uses the turn signal (to indicate a turn or a lane change); *unintentional* lane departures are those that occur when the operator does *not activate the turn signal*. For all *unintentional* lane departures, the duration of the lane departure is identified.

For all lane departures (whether *intentional* or *unintentional*), the distance and time traveled during the lane departure is computed. The lane position and vehicle speed data obtained while the vehicle is partially out of lane are not used to establish the in-lane driving performance. (The lane position and vehicle speed data obtained when the vehicle is within 50 meters of a traffic light and may be slowing down are not used to determine the in-lane driving performance.)

In this analysis, lane keeping performance is measured by determining the vehicle trajectory instability as defined in Bloomfield and Carroll (1996). It is important to note that vehicle trajectory instability provides a measure of driving performance that *removes* the bias associated with a driver who tends to "hug" the centerline or conversely, tends to "hug" the fog line. The tendency of a driver to "hug" one side of the lane or other is a typically a matter of personal preference. The variability of their tendency is measured by vehicle trajectory instability.

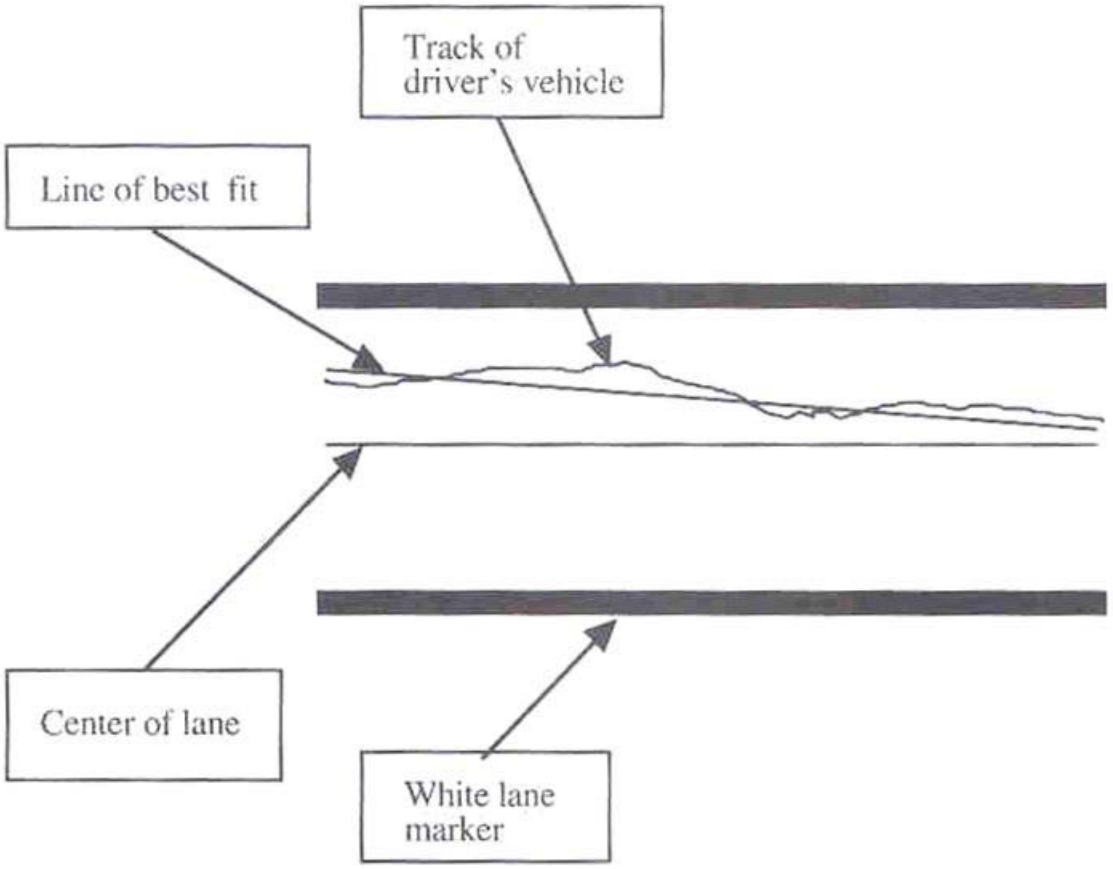


Figure 2.2: Vehicle Trajectory Instability is the Area Between the Track of the Vehicle and the Line of Best Fit (from Bloomfield and Carroll, 1996)

Driving instability measures are computed for each of the seven segments of the roadway which comprise the test route. (Or, if the entire segment is not traveled, the portions of the segment traveled.) The segments mentioned here are the segments used to describe the areas represented by the meteorological stations, and are fully described in section 2.6.3.) Using vehicle trajectory recorded for each continuous trip along the test route, the instability measure for that trip in that segment is computed by

$$I_p = \sqrt{\left[\sum p^2 - \frac{(\sum p)^2}{n} - \frac{\left\{ \sum xp - \frac{(\sum x)(\sum p)}{n} \right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}} \right] \div (n-2)}, \qquad (1)$$

where:

I_p is the vehicle trajectory instability (which Bloomfield and Carroll called the steering instability),

p is the point representing the center of the operator's vehicle at which the line-of-best-fit crosses the perpendicular across the lane after the vehicle has traveled distance x,

x is the distance traveled by the vehicle in the segment of the road, and

n is the number of data points obtained in the time it takes for the vehicle to travel distance x.

The summations are taken over the entirety of trajectory for that particular segment. ("x" represents the longitude, and "p" represents the latitude.) With this measure, the variability of the vehicle trajectory is quantified independently of whether a driver prefers one side of the road over the other.

2.5.2.3 Duration of Lane Departures

For all *unintentional* lane departures, the duration of the lane departure is identified.

2.5.2.4 Collision Avoidance Response Performance

A collision avoidance event is identified when the radar indicates the presence of an object in the lane 6.0 seconds or less ahead of a snowplow, or 3.0 seconds or less ahead of the ambulance or within 50 feet of the vehicle ahead. Driving performance data are examined from the time the object was detected by the radar until the driver's vehicle passes the object or the collision warning goes off.

Whether or not the operator reduces speed or changes course is determined. If the operator reduces speed, the amount of the reduction and the distance from the object at which the speed reduction begins are determined. If the operator changes course, the lateral extent of the change and the distance from the object at which the change in course begins are determined.

2.5.3 Questionnaire Responses

In addition to the visibility data and the objective driving performance measures, subjective data were collected from the operators by administering a User Acceptance Questionnaire/Survey instrument. The instrument was developed in collaboration with Human Factors personnel from Battelle. The particular questions that were asked and the specialty vehicle operators' responses to them are presented in chapter IV of this report.

2.6 ANALYSIS

The first step in evaluating the performance of the DAS during the FOT was to examine the visibility data in order to determine the times when the specialty vehicle operators were driving under various visibility conditions. This was done so the driving performance data obtained under the various visibility conditions could be compared.

The driving performance data were also categorized in terms of the participants, the test vehicles, and the various segments of the test route. These factors are discussed below. That discussion is followed with a description of the statistical approach used to compare driver performance under the various visibility conditions.

2.6.1 Participants

Twenty-nine specialty operators (eight snowplow operators, nineteen ambulance drivers, and two state highway troopers) each took part in one of four training sessions that were conducted in Hutchinson, Minnesota in October 2001. Subsequently, two of the snowplow operators, seven of the ambulance drivers, and one of the state highway troopers did not participate in the FOT. However, two additional snowplow operators were added to the study, although the training they received was shorter than that of the other participants.

At the end of the FOT, data were available for a total of 21 specialty operators (eight snowplow operators, twelve ambulance drivers, and one state highway trooper).

It should be noted that two snowplow operators were assigned to each snowplow, one assigned to the A shift, the other to the B shift; that all twelve ambulance drivers drove in the single ambulance used in the FOT; and that the state highway trooper was the only driver of the test patrol vehicle.

2.6.2 Test Vehicles

The FOT involved the following vehicles:

- Four snowplows.
- One ambulance.
- One state highway patrol vehicle.

The DAS was installed on all six test vehicles. In addition, for the FOT, the vehDAQ was installed in order to collect the data needed to evaluate the DAS.

2.6.3 Test Route Breakdown

During the FOT, the six test vehicles were driven on the state and county highways on which they normally operate. Before the FOT began, the infrastructure (the GPS base stations and the on-vehicle geospatial database) required to provide global satellite positioning information for the DAS was installed on the following highway sections.

- An approximately 45-mile section of MNTH-7, between Hutchinson and the Twin Cities.
- An approximately four-mile section of CR-7, northeast of Hutchinson.

In addition, the infrastructure needed to provide magnetic tape positioning information, which was a redundant system to the DGPS, was installed on the following two highway sections.

- The approximately eight-mile segment of MNTH-7, between Silver Lake and Hutchinson.
- The approximately four-mile section of CR-7, near Hutchinson.

For data analysis purposes, the test routes were sub-divided into seven test segments. Segments #1 to #6 were in the approximately 45-mile section of MNTH-7, while segment #7 was the approximately four-mile section of CR-7. The seven road segments are shown in Figure 2.1. Details of the segments—including their start and end points, the characteristics of the highway, the terrain they pass through, and whether they are rural or urban in nature—are given below.

Segment #1: MNTH-7 from the Intersection with Michigan Avenue in Hutchinson to the Intersection with Lane Avenue (in Silver Lake). Segment #1 is approximately eight miles long. It was equipped for both global satellite positioning and magnetic tape positioning. The segment is of straight horizontal alignment with flat to slightly rolling profile. It is a two-lane highway, with the exception of an extended section where three lanes allow for passing. Traffic traveling from west to east encounters their passing section first; this traffic then travels by the passing section for the opposing traffic. There are no controlled intersections or thru-stops for traffic traveling on Segment #1. There is no street lighting in Segment #1 with the exception of a brief portion (approximately 0.6 miles) in the Hutchinson city boundaries and an even smaller portion (approximately 0.1 miles) in Silver Lake, immediately before Lane Avenue. There are occasional off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Segment #2: MNTH-7 from the Intersection with Lane Avenue (in Silver Lake) to the Intersection with McLeod CSAH-1 (Old Highway 261). Segment #2 is approximately five miles long. Like Segment #1, it is of straight horizontal alignment with flat to slightly rolling profile, and is all two-lane highway. However, it has no passing lanes. There are no controlled intersections or thru-stops for traffic traveling on Segment #2. There is no street lighting in Segment #2 with the exception of a brief portion (approximately 1.0 mile) in Silver Lake, immediately after Lane Avenue. Again, there are occasional off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Segment #3: MNTH-7 from the Intersection with McLeod CSAH-1 (Old Highway 261) to the Intersection with MNTH-25. Segment #3 is approximately nine miles long. This segment is also of straight horizontal alignment and flat to slightly rolling profile. It is also a two-lane highway with no passing lanes. There are no controlled intersections or thru-stops for traffic traveling on Segment #3. There is no street lighting in Segment #3 with the exception of lighting at the intersection with MNTH-25. Again, there are occasional off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Segment #4: MNTH-7 from the Intersection with MNTH-25 to the Intersection with Main Street [County Road 92/30 (CR-92/30)] in St. Bonifacius. Segment #4 is approximately six miles long. Until it reaches the boundary of St. Bonifacius, this segment (1) is of straight horizontal alignment and flat to slightly rolling profile; (2) is a two-lane highway with no passing lanes; and (3) has no controlled intersections or thru-stops. Within the boundaries of St. Bonifacius, it remains a two-lane highway. However, there is a traffic light at Main Street (CR-92/30). There is no street lighting in Segment #4, with the exception of the lighting at the intersection with MNTH-25 at the beginning of the segment, and the lighted intersections within the St. Bonifacius boundaries, at the end of the segment. Again, there are occasional off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Segment #5: MNTH-7 from the Intersection with Main Street (CR-92/30) in St. Bonifacius to the Intersection with MNTH-41. Segment #5 is approximately eight miles long. The segment begins with a traffic light. Then, within the boundaries of St. Bonifacius, it is a two-lane highway. The remainder of this segment, to the East of the boundaries of St. Bonifacius, (1) has more abrupt hills, as well as curves, and trees along the highway, (2) is a two-lane highway, and (3) has no controlled intersections or thru-stops. In Segment #5, there is street lighting at the beginning of the segment, at the intersections within the boundaries of St. Bonifacius, and then at subsequent intersections or T-junctions in the segment. Again, there are occasional off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Segment #6: MNTH-7—from the Intersection with MNTH-41 to the Intersection with I-494. Segment #6 is approximately nine miles long. This segment also (1) has more abrupt hills, curves, and trees along the highway, (2) is a two-lane highway, and (3) has several controlled intersections, but no thru-stops. In addition, the final portion of this segment is urban and is a four-lane divided highway with a median barrier. There are eight non-coordinated traffic signals in this segment. In Segment #6, there is street lighting at all but one of the intersections or T-junctions (the exception is the Oak Street intersection). There is some off-street lighting (lights from residences or buildings) that is unlikely to assist drivers in very low visibility conditions.

Segment #7: CR-7, north of Hutchinson, to the point where CR-7 ends. Segment #7 is approximately four miles long. It is a two-lane highway with some winding curves and hills near Hutchinson. Following the section with curves and hills, it is relatively straight. There is no street lighting in Segment #7 with the exception of a brief portion (approximately 1.0 mile) within the Hutchinson city boundaries. There are infrequent off-street lights (lights from residences or buildings) that are unlikely to assist drivers in very low visibility conditions.

Please note that the 21 operators for whom data exists drove their normal routes during the FOT and the routes were not evenly distributed across the seven test segments. This means that there are various amounts of data for each of the seven test segments.

2.6.4 Statistical Approach

The specific hypotheses for evaluating the DAS in the FOT deal with the four driving performance measures (vehicle speed, vehicle trajectory instability, lane departure duration, and the collision avoidance reaction time), the visibility conditions, and the use of the DAS. The driving performance data are also categorized in terms of the participants, the test vehicles, and the various segments of the test route.

After determining the visibility conditions under which the specialty vehicle operators drove, the driving performance data collected in each of the seven route segments were scrutinized for inconsistencies. For example, there were occasional data transients in the vehicle speed records, where a single datum indicated a speed that was very much lower or very much higher than the preceding and following data. This can be explained by a GPS transition from Fix to Float or *vice versa.* When data inconsistencies were located, they were removed from the data set. However, if the inconsistencies were the result of unusual driving performance, the video record was examined to determine the specific conditions (and causes, where possible) under which it occurred.

During the FOT, the hard drives were delivered and the data from them were transferred to DVD-RAMs. Data sorting by visibility level, by operator, by test vehicle, and by test route segment was carried out.

Once the FOT was complete, the driving performance data were to be assigned to one of the three Main Conditions:

1) driving with clear visibility;
2) driving in very limited visibility conditions with the DAS *On*;
3) driving in very limited visibility with the DAS *Off*.

The next step in the comparative statistical analysis was to involve testing the driving performance data for normalcy, kurtosis & skew, and to transform the data, if necessary (Ferguson, 1959; Emerson, 1991). Analysis-of-Variance (ANOVA) paradigms were to be used to compare the driving performance data obtained in each of the three Main Conditions.

The goal was to determine whether there were statistically significant differences in driving performance for lane departure durations, vehicle trajectory instabilities, vehicle speeds, and collision avoidance reaction times for the following conditions:

1) clear visibility conditions;
2) very limited visibility conditions with the DAS *On*; and
3) very limited visibility conditions with the DAS *Off* .

The results of this analysis are provided in chapter 4.0.

Chapter 3
EVALUATION

3.1 EXTENUATING CIRCUMSTANCES – THE MILDEST WINTER ON RECORD

Because the purpose of the FOT was to determine whether using the DAS enhanced the performance of specialty vehicle operators when they faced conditions of limited visibility, it was unfortunate that the winter of 2001-2002 was the mildest on record in Minnesota.

The average temperature for the months in which the FOT was conducted is presented in Table 3.1. Table 3.1 also shows how much warmer or colder the temperature was during the FOT than the average temperature for each month (based on temperatures since 1992). The data, which were obtained from the National Climate Data Center (NCDC), Asheville, North Carolina, were recorded at the Minneapolis-St. Paul Airport. [Data from Hutchinson Muni-Butler Field Airport were not available from NCDC.]

Month	**Temperature**	**Compared to average** (1992 to current month)
November 2001	41.3 deg	10.5 deg **above** average
December 2001	26.8 deg	7.8 deg **above** average
January 2002	22.1 deg	8.9 deg **above** average
February 2002	25.9 deg	6.2 deg **above** average
March 2002	22.9 deg	6.6 deg below average

Table 3.1: The Average Monthly Temperature for Each Month from November 2001 to March 2002 and its Difference from the Average Temperature Since 1992 (Data for Minneapolis-St. Paul—Source the NCDC, Asheville, North Carolina)

As can be seen from Table 3.1, the average monthly temperatures were considerably higher than average in November 2001, December 2001, January 2002 and February 2002.

Precipitation data for the months in which the FOT was conducted are presented in Table 3.2. Table 3.2 also compares these data to the average precipitation for each month (based on data from 1992). As with the temperature data, the precipitation data, were obtained from the NCDC, Asheville, North Carolina, and were recorded at the Minneapolis-St. Paul Airport. [Data from Hutchinson Muni-Butler Field Airport were not available from NCDC.]

As Table 3.2 shows there was considerably more precipitation than normal in November 2001. However, since (as can be seen from Table 3.1) the average temperature in November 2001 was 41.3 deg (well above freeing point) there was virtually no snow. No snow days were missed because of the delay in starting the FOT.

Table 3.2 also shows that the amount of precipitation in January 2002 was only 0.35 inches—72% less than the average precipitation (of 1.24 inches) since 1992, and far less snow than normal.

Month	Precipitation	Compared to average (1992 to current month)
November, 2001	2.76 inches	0.78 inches above average
December, 2001	0.89 inches	0.07 inches above average
January, 2002	0.35 inches	0.89 inches **below** average
February, 2002	0.46 inches	0.14 inches **below** average
March, 2002	1.41 inches	0.21 inches **below** average

Table 3.2: The Average Monthly Precipitation for Each Month from November 2001 to March 2002 and its Difference from the Average Temperature Since 1992 (Data for Minneapolis-St. Paul—Source the NCDC, Asheville, North Carolina)

During the time that the FOT was conducted, there were several occasions when it did snow. However, there were only two relatively heavy snowfalls. They occurred less than a week apart near the end of the FOT, on March 8-9 and March 14-15. High winds were also associated with these two snowfalls. Because these snowfalls consisted of wet, heavy snow, the high winds contributed little to low visibility because when the snow landed on the ground, it remained there.

Visibility was measured in two ways during the FOT. First, directly, at six meteorological sites and second, indirectly, by using video image analysis. The second method involves inferring visibility by comparing each image obtained during the FOT with a standard image acquired before the FOT began. Originally the plan was to use the second inferential method of measuring visibility to screen the vast amount of data obtained during the FOT. However, because of the very limited number of occasions on which there was poor visibility, this was unnecessary. There were also problems with the implementation of the inferential method, in particular with positioning the camera used to acquire that imagery—the camera view was often partially or completely occluded with snow and/or condensation. The operator's view was not occluded because windshield wipers removed the snow and condensation from their viewpoint. (Please see Appendix D for further information about the inferential method.)

As the following discussion will show, there were very few occasions when there were poor visibility conditions during the FOT. During the poor visibility conditions, there were no occasions when an operator needed to use the DAS. The discussion of visibility that follows in the rest of this chapter is based on the direct visibility measurements.

The six meteorological sites recorded local atmospheric visibility measurements at five minute intervals throughout the FOT. The sites were situated between five and twelve miles apart along MNTH-7.

The visibility data obtained from each of these sites was examined for each of these snowfalls.

3.2 VISIBILITY IN THE MARCH 8-9 SNOWFALL

The first major snowfall of the 2001-2002 winter occurred on March 8-9. The number of minutes that each of the six meteorological sites along the Test Route had relatively low visibility (i.e., visibility levels below 400 meters) during that snowfall is shown in Table 3.3. In the table, visibilities below 400 meters are sub-divided into the 300 to 399 meter range, the 200 to 299 meter range, and the 100 to 199 meter range.

Visibility Measurement Sites	Visibility Range — 300-399 meters	Visibility Range — 200-299 meters	Visibility Range — 100-199 meters
#1	60 minutes	5 minutes	none
#2	30 minutes	20 minutes	none
#3	90 minutes	40 minutes	none
#4	none	none	none
#5	10 minutes	none	none
#6	25 minutes	30 minutes	none

Table 3.3: Total Time That Atmospheric Optical Range was in the 300-399, the 200-299, and the 100-199 Meter Range at the Six Meteorological Sites for the March 8-9 Snowfall

The data shown in Table 3.3 are also presented in Figure 3.1, with the visibility levels again sub-divided into the 300 to 399, the 200 to 299, and the 100 to 199 meter ranges.

Both Table 3.3 and Figure 3.1 show that the visibility at the six meteorological sites in the March 8-9 snowfall was never less than 100 meters. The table and figure indicate that there were also no visibility readings in the 100 to 199 meter range. There were no readings in the 200-to-299-meter range at two of the sites. The most time in this range was only 40 minutes, at Site #3.

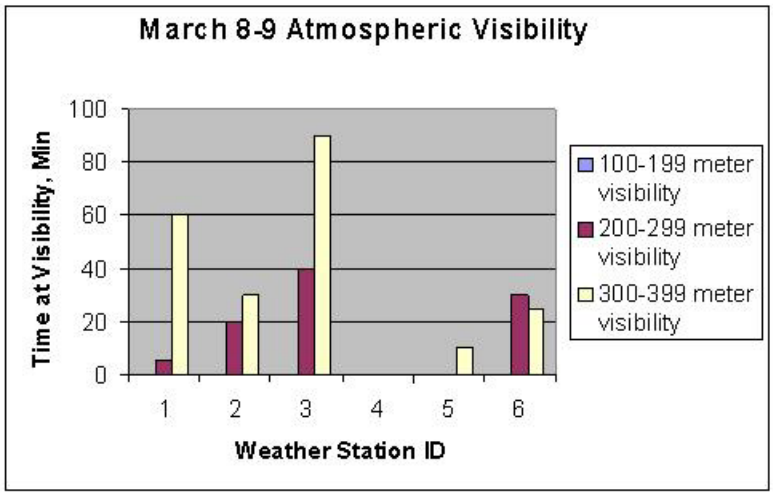


Figure 3.1: Total Time That Visibility Was in the 300-399, the 200-299, and the 100-199 Meter Range at the Six Meteorological Sites for the March 8-9 Snowfall

To further illustrate the lack of low meteorological visibility, for each meteorological station, visibility conditions are plotted for this snow event. Forty-eight hours of visibility data are provided for each of the stations; data were recorded at five minute intervals. For the period for 8-9 March, atmospheric visibility during this forty-eight hour period for each of the six visibility stations are shown in Figures 3.2-3.7.

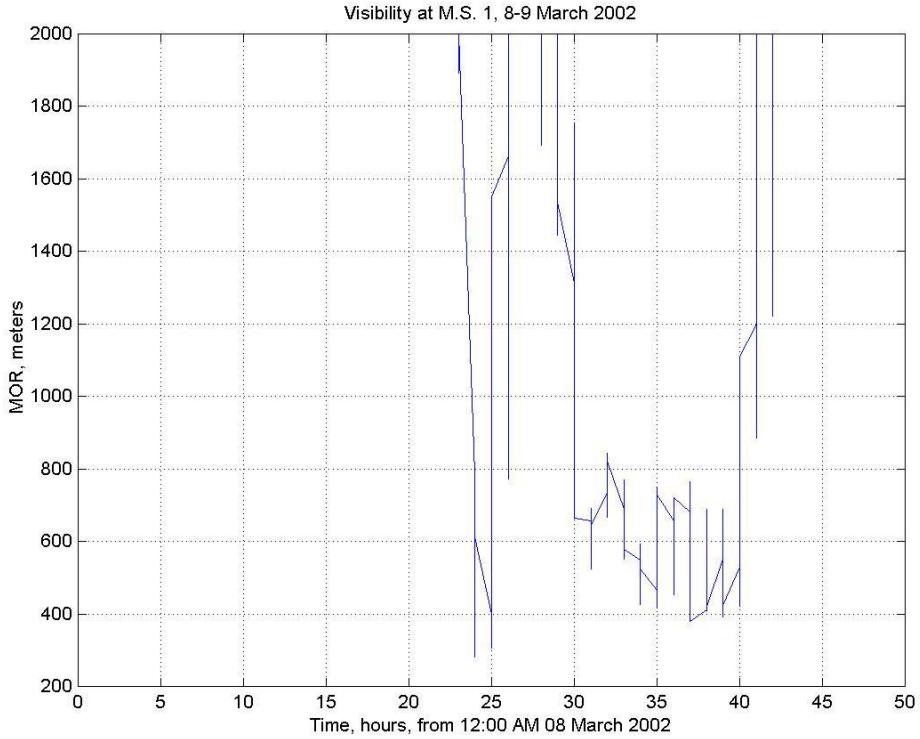


Figure 3.2: Meteorological Visual Range Measurements for the 08 March Snow Event for Meteorological Site #1 in Hutchinson

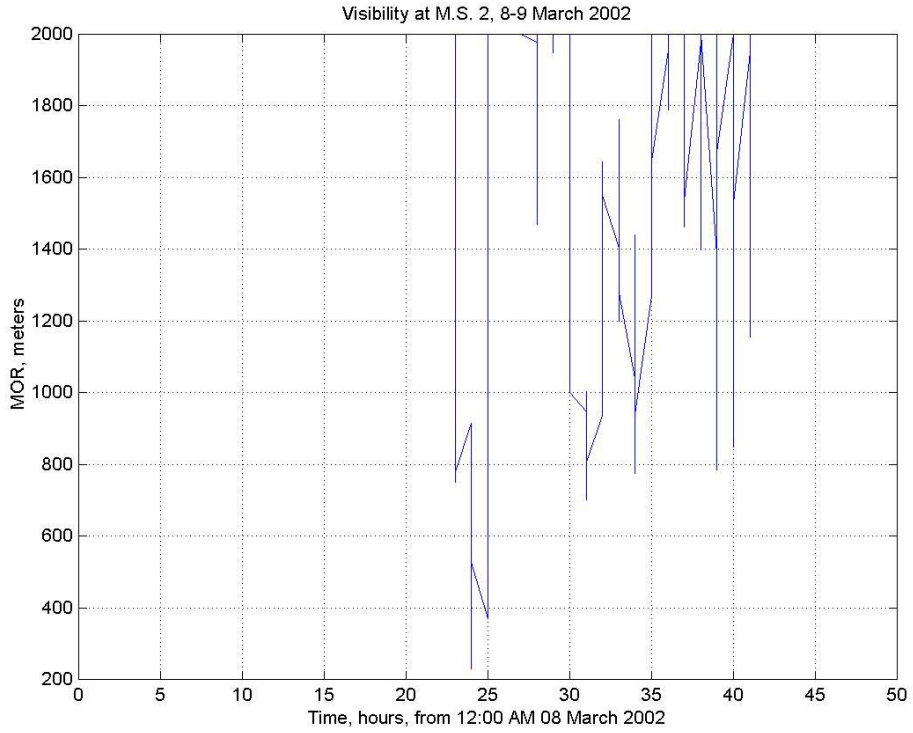


Figure 3.3: Meteorological Visual Range Measurements for the 08 March Snow Event for Meteorological Site #2 Near Silver Lake

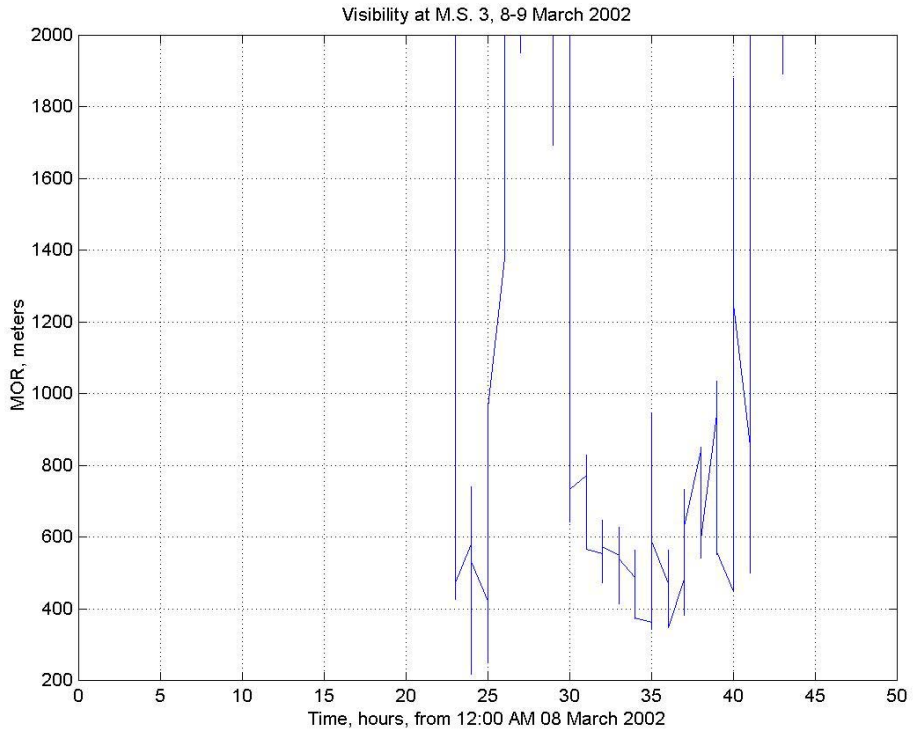


Figure 3.4: Meteorological Visual Range Measurements for the 08 March Snow Event for Meteorological site #3between Silver Lake and Mayer

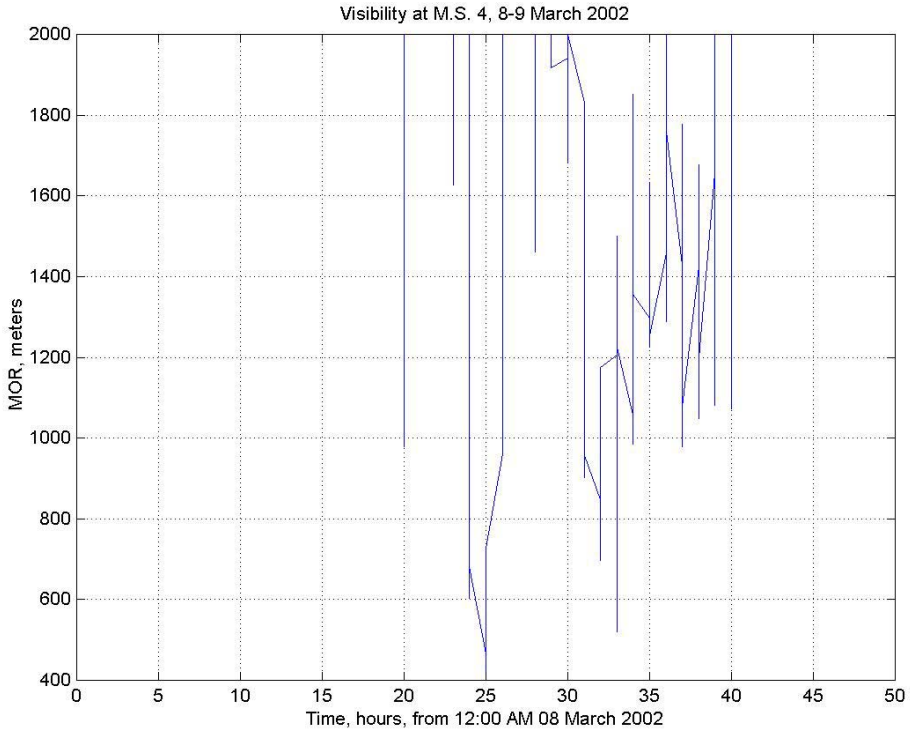


Figure 3.5: Meteorological Visual Range Measurements for the 08 March Snow Event for Meteorological Site #4 Near Mayer

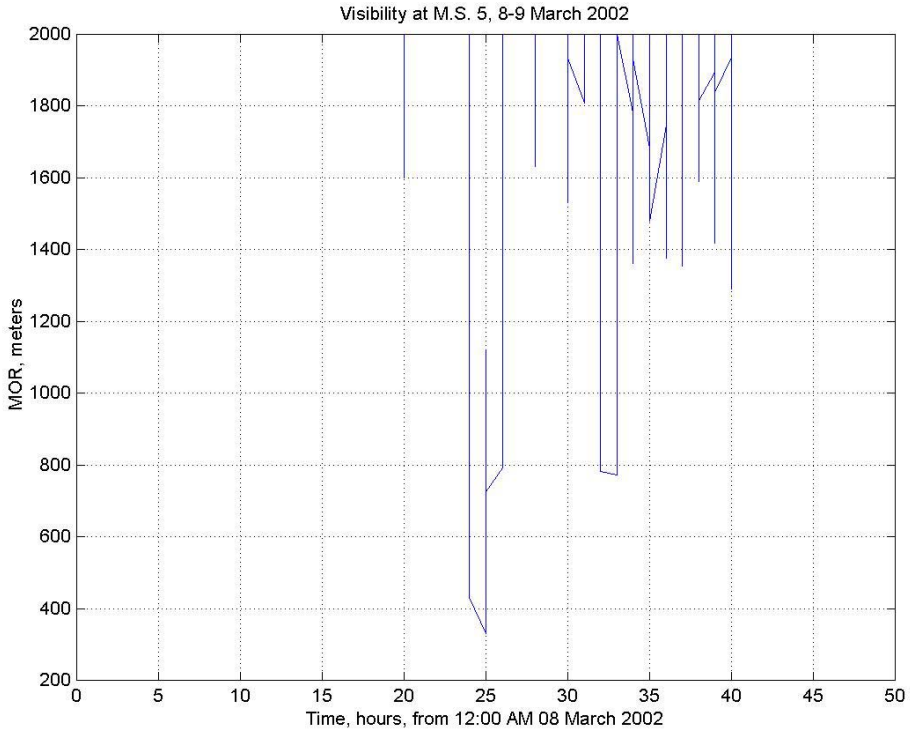


Figure 3.6: Meteorological Visual Range Measurements for the 08 March Snow Event for Meterological Site #5 East of St. Bonifacius

Figure 3.7: Meteorological Visual Range Measurements for the 08 March Snow Event for Meteorological Site #6 Near Excelsior

3.3 VISIBILITY IN THE MARCH 14-15 SNOWFALL

The second major snowfall of the 2001-2002 winter occurred, six days after the first, on March 14-15. The number of minutes that each of the six meteorological sites along the Test Route had relatively low visibility (i.e. visibility levels below 400 meters) during the second major snowfall is shown in Table 3.4. In the table, visibilities below 400 meters are sub-divided into the 300 to 399 meter range, the 200 to 299 meter range, and the 100 to 199 meter range.

Visibility Measurement Sites	Visibility Range — 300-399 meters	Visibility Range — 200-299 meters	Visibility Range — 100-199 meters
#1	55 minutes	none	none
#2	none	none	none
#3	25 minutes	35 minutes	none
#4	150 minutes	5 minutes	15 minutes
#5	205 minutes	110 minutes	none
#6	90 minutes	40 minutes	none

Table 3.4: Visibility Range Time. Total Time That Visibility Was in the 300-399, the 200-299, and the 100-199 Meter Range at the Six Meteorological Sites for the March 14-15 Snowfall

The data shown in Table 3.4 are also presented in Figure 3.8, with the visibility levels again sub-divided into the 300 to 399, the 200 to 299, and the 100 to 199 meter ranges.

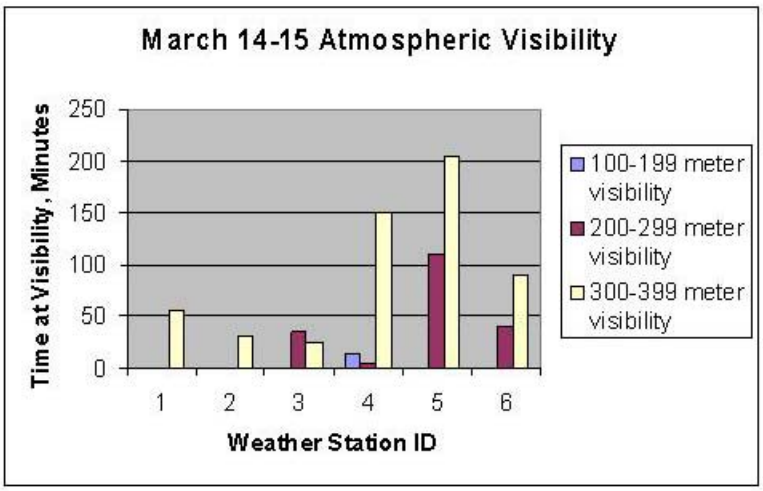


Figure 3.8: Total Time That Visibility Was in the 300-399, the 200-299, and the 100-199 Meter Range at the Six Meteorological Sites for the March 14-15 Snowfall

Both Table 3.4 and Figure 3.8 show that the visibility at the six meteorological sites in the March 14-15 snowfall, while a little worse than the March 8-9 snowfall, was also never very poor. Again, there were no visibility readings below 100 meters. However as the table and figure show, for the March 14-15 snowfall, there was one site, Site #4, at which visibility readings were recorded in the 100-to-199-meter range—but this was only for 15 minutes. Table 3.4 and Figure 3.8 show that, while there were no readings in the 200-to-299-meter range at two of the meteorological sites, the visibility level was in this range for 110 minutes at Site #5.

Visibility during the forty-eight hour snow event was recorded at each of the meteorological sites located along MN TH 7 at five minute intervals. The meteorological optical range for each of these sites is presented in Figures 3.9-3.14.

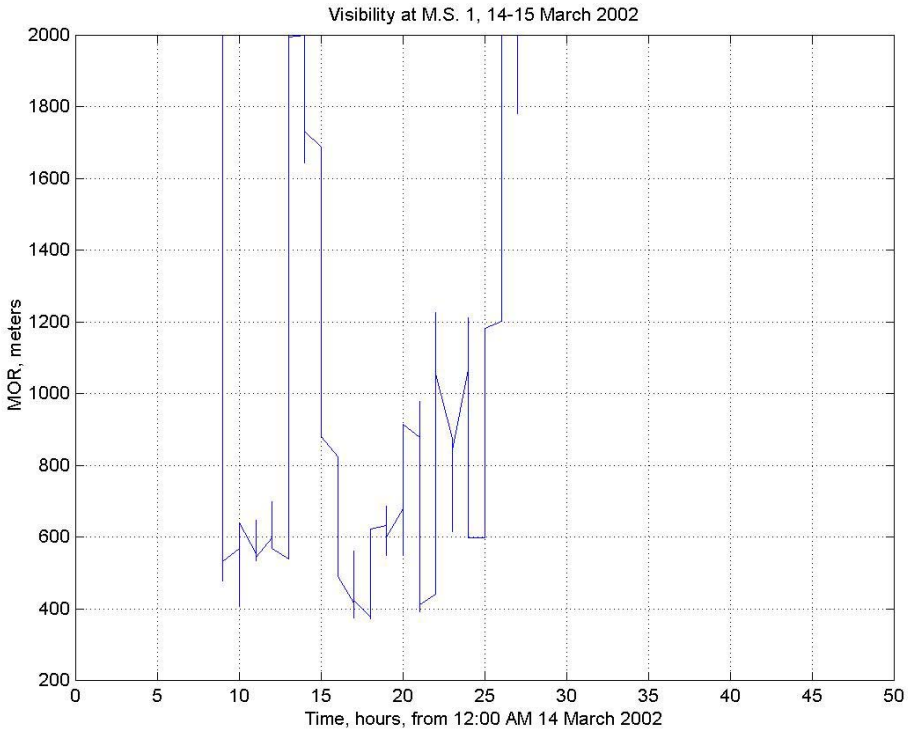


Figure 3.9: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #1 Near Hutchinson

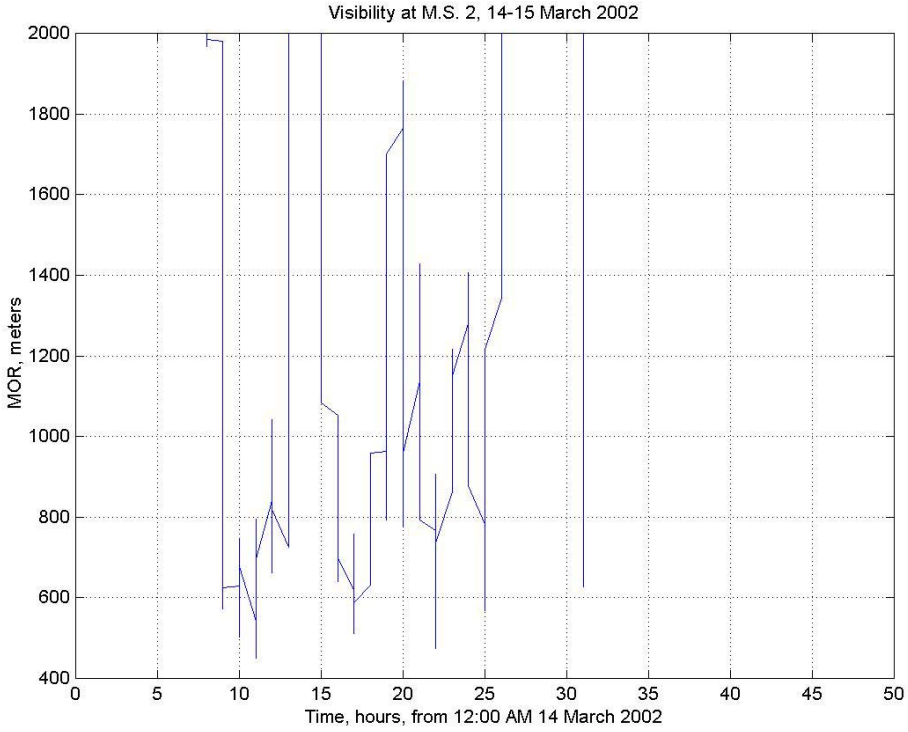


Figure 3.10: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #2 Near Silver Lake

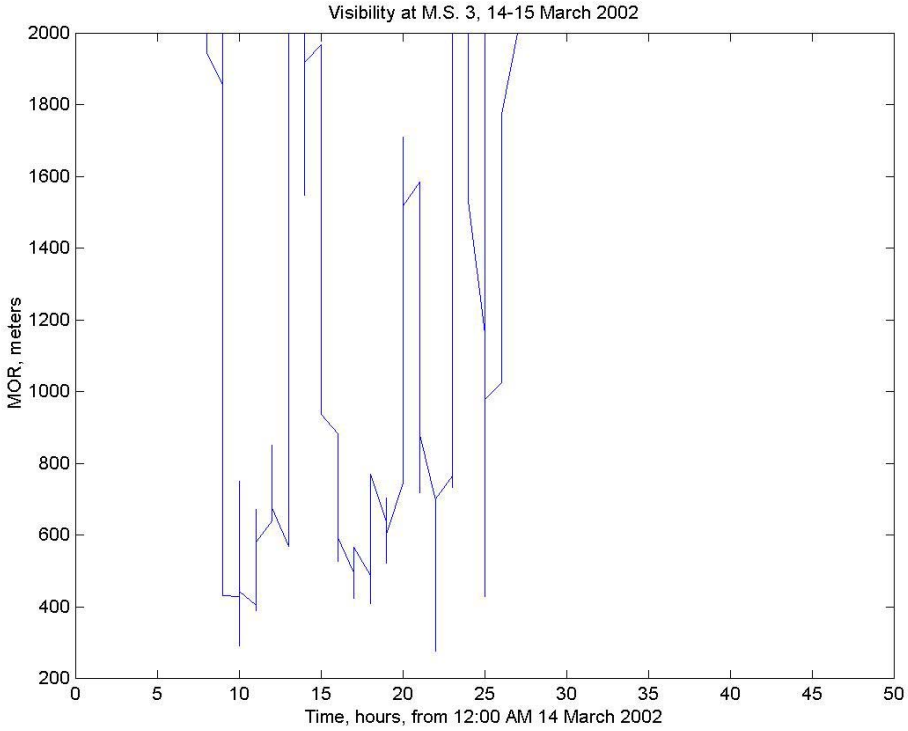


Figure 3.11: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #3between Mayer and Silver Lake

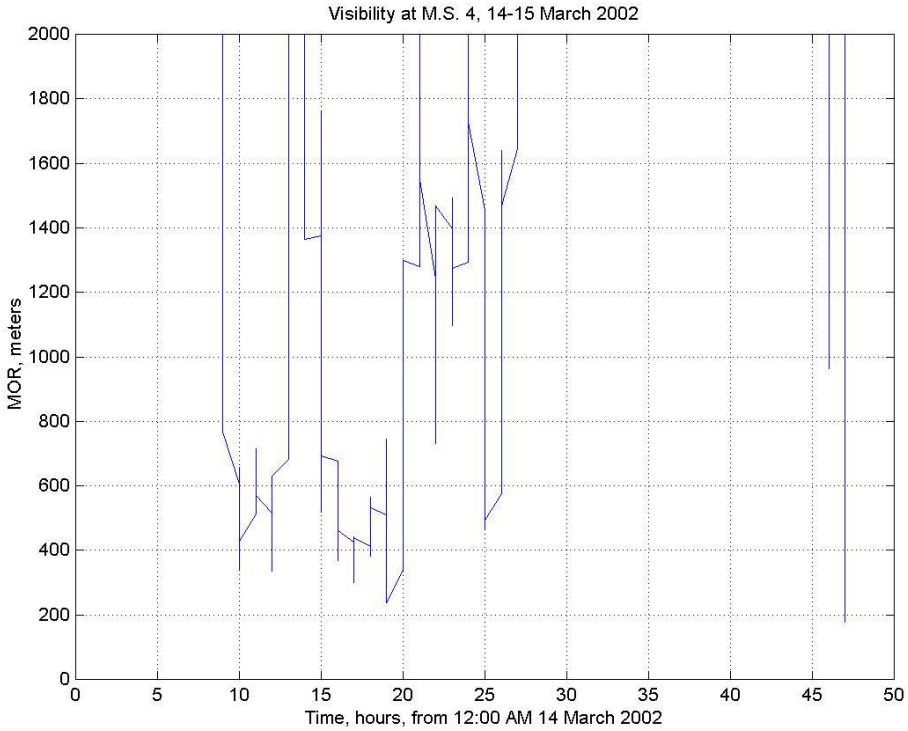


Figure 3-12: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #4 Near Mayer

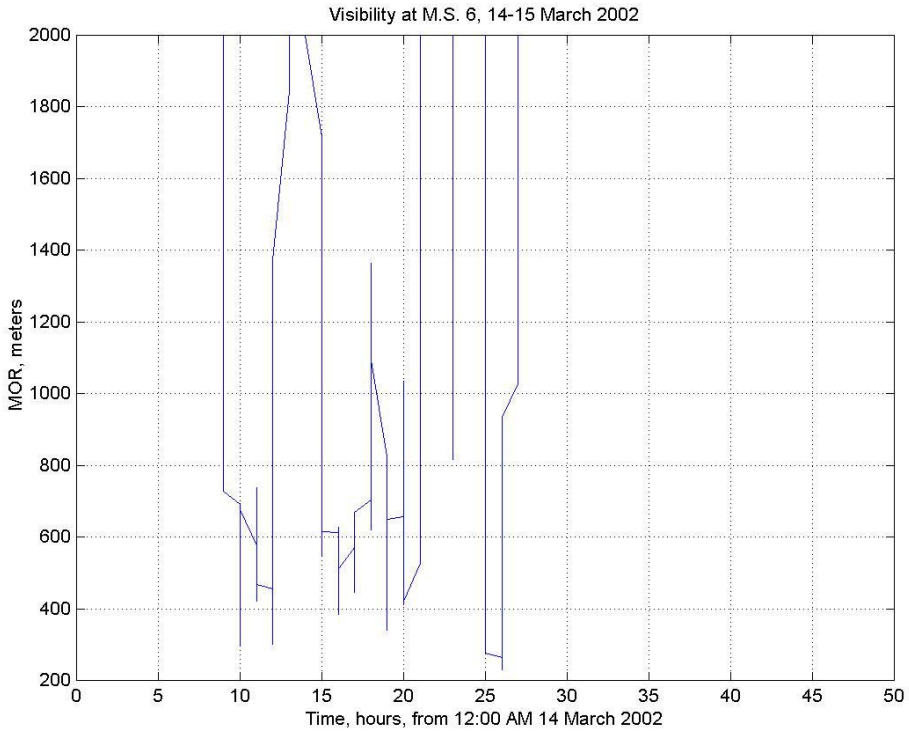


Figure 3.13: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #5 East of St. Bonifacius

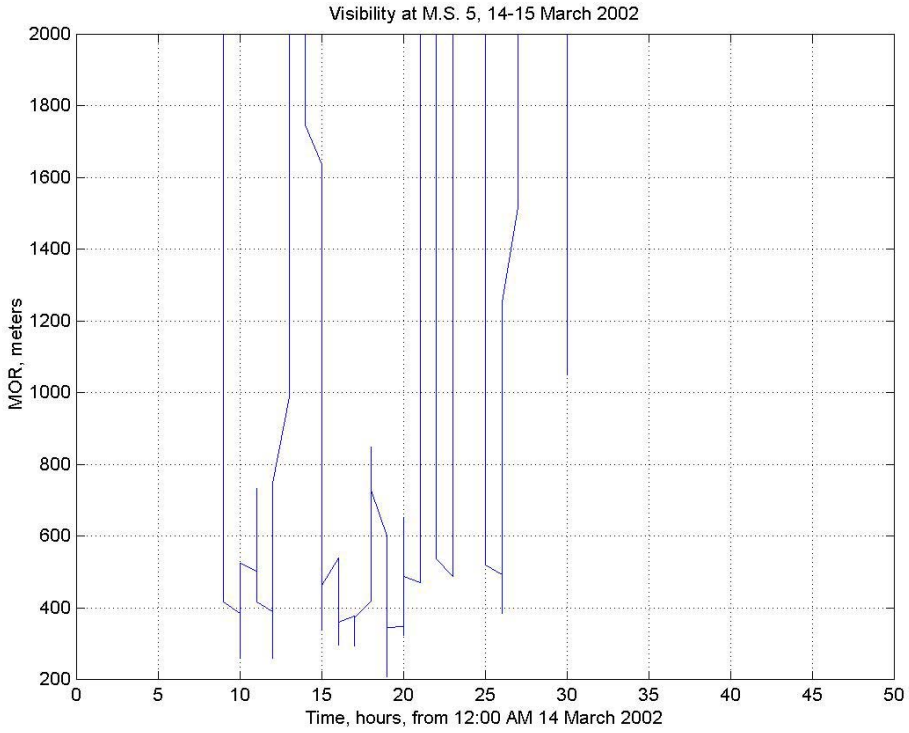


Figure 3.14: Meteorological Visual Range Measurements for the 14 March Snow Event for Meteorological Site #6 Near Excelsior

3.4 DRIVING IN LOW VISIBILITY CONDITIONS DURING THE MARCH 8-9 SNOWFALL

Table 3.3 and Figure 3.1 show the length of time when the visibility was limited during the March 8-9 snowfall. The next step was to determine which, if any, operators drove during the times that the visibility was limited.

For the March 8-9 snowfall, visibility was never below 199 meters at any of the six meteorological sites. As Table 3.3 and Figure 3.1 indicated, visibility levels between 200 and 299 meters were recorded briefly at four of the meteorological sites—five minutes at Site #1, twenty minutes at Site #2, forty minutes at Site #3, and five minutes at Site #6.

When the driving performance records of the six test vehicles were checked, it was found that none of the vehicles were operating anywhere on the Test Route during the times that visibilities in the 200 to 299 meter range were recorded at any of the sites.

3.5 DRIVING IN LOW VISIBILITY CONDITIONS DURING THE MARCH 14-15 SNOWFALL

For the March 14-15 snowfall, visibility was never below 100 meters at any of the sites. As Table 3.4 and Figure 3.8 indicate, the visibility was briefly between 100 and 199 meters at only one site—15 minutes at Site #4. The driving performance records of the six test vehicles were checked. None of the vehicles were operating anywhere on the Test Route at that time.

Table 3.4 and Figure 3.8 indicate that, for the March 14-15 snowfall, visibility levels between 200 and 299 meters were recorded briefly at four of the meteorological sites—35 minutes at Site #3, 5 minutes at Site #4, 110 minutes at Site #5, and 40 minutes at Site #6.

When the driving performance records of the six test vehicles were checked, it was found that none of them were operating anywhere on the Test Route during the times that visibilities in the 200 to 299 meter range were recorded at Site #3, Site #4, or Site #6.

The driving performance records did show that there were two drivers—both snowplow operators—who drove at times that coincided briefly with times at which the 200-to-299 meter visibility levels were recorded at site #5 during the March14-15 snowfall. The first of these snowplow operators drove during a 20-minute period that coincided with a time when the visibility level at Site #5 was in the 200-to-299 meter range. The second snowplow operator drove during a 10-minute period that coincided with a time when the Site #5 visibility level was in the 200-to-299 meter range. However, during these times, neither operator was driving in the vicinity of Site #5. The video data obtained while these operators drove during times that coincided with 200 to 299 meter visibility at Site #3 were reviewed. The video data revealed that, at the times in question, the forward view was clear for both operators, neither operator was using the Head-Up Display, and that neither operator needed to reduce speed.

3.6 USING HEAD-UP DISPLAY WITH DAS *ON* DURING THE MARCH 8-9 AND MARCH 14-15 SNOWFALLS

As is made clear in the two preceding subsections, there were no occasions during both the March 8-9 and March 14-15 snowfalls when the visibility was less than 300 meters that any operator was driving while using the Head-Up Display.

Table 3.5 shows the status of the DAS and the status of the HUD during all shifts that were driven during the two snowfalls.

Subject	Date	DAS Status	HUD Status	Total time HUD used during shift
201	8 March	*Off*	Not used	—
201	9 March	*On*	Used once	3 hours 39 minutes
201	14 March	*On*	Used once	1 hour 16 minutes
201	15 March	*On*	Not used	—
202	8 March	*Off*	Not used	—
202	14 March	*On*	Used 4 times	3 hours 26 minutes
202	15 March	*Off*	Not used	—
204	8 March	*On*	Used once	12 minutes
205	14 March	*Off*	Not used	—
208	15 March	*Off*	Not used	—

Table 3.5: Use of the Head-Up Display During the March 8-9 and March 14-15 Snowfalls

As Table 3.5 shows subject 201 drove four shifts during the March 8-9 and March 14-15 snowfalls. This subject did not use the Head-Up Display in two of these shifts (on March 8 and March 15), but used it on one occasion in each of the other shifts (for 3 hours and 39 minutes on March 9; and for 1 hour 16 minutes on March 14).

Table 3.5 shows subject 202 drove three shifts during the March 8-9 and March 14-15 snowfalls. This subject did not use the Head-Up Display in two of these shifts (on March 8 and March 15), but used it on four separate occasions on March 14 (for 56 minutes, 47 minutes, 37 minutes, and 1 hour and 6 minutes for a total of 3 hours and 26 minutes).

Table 3.5 shows that subject 204 drove one shift during the March 8-9 snowfall (and none on March 14-15). This subject used the Head-Up Display on one occasion (for 16 minutes) during this shift.

The table also shows that subjects 205 and 208 each drove one shift during the March 14-15 snowfall, but that neither of them drove using the Head-Up display.

For the two snowfalls, three operators drove using the Head-Up Display for a total of 8 hours 33 minutes. However, as mentioned at the beginning of this subsection, there were no occasions

during either the March 8-9 or March 14-15 snowfalls when any operator drove using the Head-Up Display and the visibility was less than 300 meters. Use of the driving performance data obtained during these 8 hours and 33 minutes is ill-advised for the following reasons—

- Since the data were obtained from only three of the twenty-one specialty vehicle operators who took part in the FOT, the data are clearly not representative, particularly because one of the operators used the Head-Up Display for only 12 minutes.
- Since the data were not obtained under the conditions for which the DAS (and the Head-Up Display were designed), they cannot be used to evaluate the utility of the DAS.

Any conclusions as to the usefulness of the DAS that are based on these data would be misleading.

3.7 DRIVING WHEN THE LANE MARKINGS WERE COVERED WITH SNOW

During the few periods of time when moderately low visibility levels were recorded at a meteorological site, the test vehicles either were not operating near the particular meteorological site or were not operating at all. In spite of this, it was possible that the DAS might have been necessary if there were any occasions when the operators drove with snow completely covering the road surface and obscuring the road markings.

To determine if there were occasions when the operators drove with snow obscuring the road markings, the video data recorded in the test vehicles during the two major snowfalls were thoroughly reviewed. This review showed that at no time was the road surface completely covered with snow. [It should be mentioned that there were occasions when the forward-looking camera's view was completely obscured by snow on the windshield. The camera was mounted out of range of the windshield wipers.]

3.8 OVERALL VISIBILITY DURING THE FOT

Prior to the FOT, expectations based on the results reported by Hawkins (1987) about the likely usefulness of the DAS in limited visibility conditions were as follows:

- With FOT visibilities in the 200- to 299-meter range, the DAS would be somewhat useful.
- With FOT visibilities in the 100- to 199-meter range, the DAS would be very useful.
- With FOT visibilities less than 100 meters, the DAS would be extremely useful—without it, it would likely be impossible to drive.

As mentioned above, the winter of 2001-2002 was the mildest on record in Minnesota, and there were only two relatively heavy snowfalls: on March 8-9 and March 14-15. There were no visibility readings below 100 meters during the March 8-9 snowfall or the March 14-15 snowfall, or at any other time during the FOT. At meteorological optical ranges below 100 meters, it is likely to be nearly impossible to drive without the DAS.

The March 14-15 snowfall produced a visibility level between 100 and 199 meters for 15 minutes at only one site (Site #4). A check of the driving performance records of the six test

vehicles showed none were operating anywhere on the Test Route during those fifteen minutes. This was the only time when visibility readings between 100 and 199 meters were recorded during the FOT; there were no readings in this range during the March 8-9 snowfall or at any other time during the FOT.

The last of the limited visibility ranges in which the expectation is that the DAS would be somewhat useful was the 200- to 299-meter visibility range. For the March 8-9 snowfall, visibility readings were found in this range at four of the six meteorological sites. Similarly for the March 14-15 snowfall, visibility readings were found in the 200- to 299-meter visibility range at four meteorological sites. The driving performance records showed that two operators in the March 14-15 snowfall were driving when this visibility range was recorded. However, the driving records showed that none of these three operators was driving near the sites where the 200- to 299-meter visibilities were recorded. Figure 3.15 illustrates a representative view these operators had through the windshields when the 200- to 299-meter visibilities were recorded at one of the meteorological sites.

Figure 3.15: Typical Video Frame of a Snowplow Operator Driving When a Visibility Level of Between 200 and 299 Meters Was Recorded During the March 14-15 Snowfall

Going clockwise from the top right quadrant of the image, Figure 3.15 shows the following.

- The operator (with face obscured for confidentiality reasons).
- The operator's feet.
- The operator's hands and the steering wheel.
- The forward view through the windshield.

Inspection of the upper left quadrant of the video frame in Figure 3.15 shows the extent to which visibility was reduced. However, inspection of the upper right quadrant shows that this reduction

in visibility did not make it necessary for the operator to use the Head-Up Display—it is folded up towards the ceiling of the cab.

Data is provided to document the view out of the windshield for visibility in the 200-299 meter range. On the CD ROM which accompanies this report, twenty minutes of data is provided in the "Video Clip" folder on the CD. Four video clips, containing five minutes of video each, are available as .avi files. These five minute videos capture the local visibility for a snowplow operating in close proximity (passing within 620 meters of meteorological site #5) during the time that a meteorological optical range (MOR) of 200-299 meters was reported. Excerpts of those video files, as shown in figures 3.16 – 3.19, provide a reference against which MOR can be judged against human visual acuity.

Figure 3.16: Video Frame of a Snowplow Operator Driving Within 600 Meters of Meteorological Site #5 During the Time Visibility Levels Between 200 and 299 Meters Were Recorded During the March 14-15 Snowfall - Note HUD is Folded Up and Not In Use

Figure 3.17: Video Frame of a Snowplow Operator Driving 7 Seconds After a MOR Between 200 and 299 Meters Was First Recorded at Meteorological Site #5 During the March 14-15 Snowfall

Figure 3.18: Final Video Frame Taken of a Snowplow Operator Driving While a MOR Between 200 and 299 Meters Was Recorded at Meteorological Site #5 During the March 14-15 Snowfall

For comparative purposes, Figure 3.19 shows a video frame of the same operator while he was driving with a higher, if still somewhat restricted, visibility level between 400 and 499 meters.

Figure 3.19: Video Frame of a Snowplow Operator Driving When a Visibility Level of Between 400 and 499 Meters Was Recorded

Again, inspection of the upper left quadrant of Figure 3.19 shows the extent of the reduction in visibility. And, inspection of the upper right quadrant shows that the operator did not find it necessary to use the Head-Up Display when the visibility was between 400 and 499 meters.

A final video frame comparison is provided in Figure 3.20. This video frame was taken when a snowplow operator was driving with the good to excellent visibility conditions that were the norm during the FOT.

Figure 3.20: Video Frame of a Snowplow Operator Driving When the Visibility Was Equal to or Greater Than 2,000 Meters

Again, inspection of the upper left quadrant in Figure 3.20 shows the view through the windshield when the visibility was equal to or greater than 2,000 meters. And the upper right quadrant of the figure shows that the operator was not using the Head-Up Display—it is folded up towards the ceiling of the cab.

After considering the visibility levels encountered during what turned out to be the mildest Minnesota winter on record and looking at the driving performance records and the video data records, the following conclusion is inescapable:

At no time during the FOT, were any of the specialty operators exposed for *sustained* periods to the kind of conditions for which the DAS was designed.

3.9 LIMITED DATA SETS

The technology was implemented/operational in December and the FOT lasted for three months. Driving performance data were collected throughout this period. However, this vast amount of data was collected in one condition—when the specialty vehicle operators drove in conditions of good visibility. No driving performance data were obtained in either of the other two conditions. This state of affairs is illustrated in Figure 3.21.

Figure 3.21 illustrates that there was an overabundance of driving performance data collected while the operators drove in good visibility conditions, but that the operators did not drive in very limited visibility conditions at all—neither with the DAS *On*, nor with the DAS *Off*.

Unfortunately this means that the *comparative statistical testing* that is described in section 2.6 of this report could not be conducted.

Figure 3.21: An Illustration of the Amount of Data That was Obtained During the Field Operational Test for the Three Data Comparison Conditions

3.10 PROBLEMS WITH THE OPERATOR TRAINING

There were several problems with the operator training that began with four classroom sessions in October 2001. Difficulties with the GPS system were documented in the Validation Report of July 2002. To Recap, the GPS units originally purchased came from Leica. It was determined that the Leica units were incapable of transitioning between base stations. Leica acknowledged the problem, decided not to fix the problem, and refunded our purchase price. Trimble ms750 receivers were purchased to replace the Leica units. This problem with GPS units lead to some of the training issues listed below.

Training problems can be described as follows:

- There were longer delays than initially planned between the classroom and in-vehicle training because of GPS problems.

- Because of GPS receiver problems, the FOT start date was delayed by more than six weeks, after the training had been given. The delay increased the likelihood that some information imparted during training may have been lost.

- Because of job changes, two snowplow operators were added to the study after the classroom training sessions had been conducted. The training that these two operators received was shorter than that received by the other participants.

- The time from system release (late December 2001) and the first significant snow event (08 March 2002) could have led to driver performance problems because drivers simply forgot what was taught during training. The lack of consistent snowfall had far-reaching effects not only with regard to training, but to the FOT in general.

4.0 RESULTS/CONCLUSIONS

4.1 DRIVING PERFORMANCE DATA

The goal of the FOT was to determine whether, by using the DAS, the performance of the specialty vehicle operators was enhanced in conditions of very limited visibility. We expected to collect driving performance data under the following visibility conditions: (1) clear visibility; (2) very limited visibility with the DAS *On*; and (3) very limited visibility with the DAS *Off*.

Vast amounts of driving performance data were collected during the FOT. But as Figure 3.21 shows, all these driving performance data fell into the first visibility category. Because no operator was driving near the sites where brief periods of limited visibility were recorded, no driving performance data were collected in conditions of very limited visibility with the DAS *On*, or in conditions of very limited visibility with the DAS *Off*.

This means that the proposed *comparative statistical analysis* could not be conducted, and that none of the following FOT hypotheses could be tested:

Vehicle speed hypotheses

- The expectation that vehicle speed would be faster in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The expectation that vehicle speed would be faster in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The expectation that vehicle speed would be faster in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Vehicle trajectory instability hypotheses

- The expectation that vehicle trajectory instability would be less in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The expectation that vehicle trajectory instability would be less in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The expectation that vehicle trajectory instability would be less in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Collision avoidance reaction time hypotheses

- The expectation that collision avoidance reaction time would be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The expectation that collision avoidance reaction time would be shorter in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The expectation that collision avoidance reaction time would be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

Lane departure duration hypotheses

- The expectation that the lane departure duration would be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *Off*.
- The expectation that the lane departure duration would be shorter in very limited visibility conditions with the DAS *On* than in very limited visibility conditions with the DAS *Off*.
- The expectation that the lane departure duration would be shorter in clear visibility conditions than in very limited visibility conditions with the DAS *On*.

With regard to *lane departure duration*, although no operator drove in conditions of very limited visibility, it is possible to conduct a comparative statistical analysis to test a subsidiary hypothesis. Even though the Head-Up Display was most often pushed up out of the way (and thus was not used), if the DAS was switched *On*, the operators still received lane departure warnings via the auditory and haptic modalities. It is thus possible to test the following hypothesis.

- The lane departure duration is expected to be shorter in *good* visibility conditions when the DAS is *On* than in *good* visibility conditions when the DAS is *Off*.

Before testing this hypothesis, it was determined whether each of the lane departures was *intentional* or *unintentional*. As mentioned in section 2.5.2 (Measures, *Driving Performance*), *intentional* lane departures were defined as those that occur when the operator uses the turn signal (to indicate a turn or a lane change); and *unintentional* lane departures were defined as those that occur when the operator does *not activate the turn signal*.

Lane departure data were examined for each of the 21 operators from whom driving performance data were obtained in the FOT. Table 4.1 shows the number of occasions on which each subject *unintentionally* went out of lane when the DAS was switched *On*, and when the DAS was switched *Off*.

For data which lend themselves to parametric statistics, skewness can be addressed with the use of a logarithmic transformation (Ferguson, 1958). However, the problem of extreme inequalities cannot be addressed by any transformation. Therefore a *nonparametric* measure was needed to test the hypothesis that lane departure durations will be shorter in *good* visibility conditions when the DAS is *On* than they will be in *good* visibility conditions when the DAS is *Off*. The *Kolmogorov-Smirnov two-sample test*, the nonparametric statistic that is used with distributions that are highly skewed like the distributions of *durations* associated with the lane departures is the appropriate test for these data. This test is concerned with the degree of similarity between two cumulative distributions that are equated by plotting cumulative proportion as a function of duration. The Kolmogorov-Smirnov twosample test has a power-efficiency rating of approximately 95% (Siegel and Castellan, 1988), but is more conservative than the equivalent parametric *t* test (when the two tests are compared using data which meet parametric requirements).

Subject	Number of Lane Departures (DAS *Off*)	Number of Lane Departures (DAS *On*)
201	2,390	1,735
202	2,991	1,013
203	12	199
204	409	985
205	47	105
206	2,983	35
207	472	245
208	799	102
301	639	156
401	100	50
402	301	44
403	108	19
404	275	33
405	90	4
406	340	5
407	233	—
408	48	—
409	22	—
410	48	—
411	56	—
412	121	—

Table 4.1: Number of Unintentional Lane Departures that Occurred with the DAS Off and the DAS On for 8 Snowplow Operators (Subjects # 201-208), one State Highway Trooper (Subject # 301), and 12 Ambulance Drivers (Subjects # 401-412)

The Kolmogorov-Smirnov test was used to test the data obtained from seven of the eight snowplow operators, the single State Highway trooper and four of the ambulance drivers. As Table 4.1 shows, there were very few lane departures when the DAS was *On* for nine operators [one snowplow operator (Subject #206) and for eight ambulance drivers (Subjects #405 through #412) who had very few or no lane departures in one of the two conditions]. There were insufficient data to test the subsidiary hypothesis for these nine operators. The results of using the Kolmogorov-Smirnov test to compare the lane departure durations obtained when the DAS was *On* with the durations obtained when the DAS was *Off* for the remaining 12 operators for whom there were sufficient data are shown in Table 4.2.

Subject	Test Result
201	Not significant
202	Lane departure durations *longer* with DAS *On* (significant at the $p<0.05$ level)
204	Not significant
205	Lane departure durations *longer* with DAS *On* (significant at the $p<0.01$ level)
206	Not significant
207	Not significant
208	Not significant
301	Not significant
401	Not significant
402	Lane departure durations *shorter* with DAS *On* (significant at the $p<0.01$ level)
403	Not significant
404	Not significant

Table 4.2: Results of Using the Komogorov-Smirnov Two Sample Test to Compare the Lane Departure Durations That Occurred When Each Subject Drove in Good Visibility Conditions With the DAS On With the Lane Departure Durations That Occurred When He/She Drove in Good Visibility Conditions With the DAS Off

In Table 4.2, the first seven subjects (#201, #202, and #204 through #208) were snowplow operators, subject #301 was a State Highway trooper, and the last four subjects (#401 to #404) were ambulance drivers.

Table 4.2 shows that, for six of the eight snowplow operators, there were no significant differences in the lane departure durations. However, for the remaining two operators the lane departure durations were significantly longer (at the $p<0.05$ level for subject #202, and at the $p<0.01$ level for subject #204) when the DAS was switched *On* than when it was switched *Off*. Table 4.2 shows there was no significant difference in lane departure durations for the state trooper. Table 4.2 also shows that there were no significant differences in lane departure durations for three of the four ambulance drivers. For the remaining ambulance driver (subject #401) the lane departures were significantly shorter (at the $p<0.01$ level) when the DAS was switched *On* than when it was switched *Off*.

Despite being limited to a nonparametric statistical test that could only be used in a way that was less likely to yield significance (because of the extreme unequal cell frequencies) than the preferred parametric statistical test, statistical significance was achieved for three operators. The hypothesis that the lane departure duration would be shorter in *good* visibility conditions when the DAS is *On* than in *good* visibility conditions when the DAS is *Off* was upheld for one ambulance driver while the opposite result was obtained for two ambulance drivers. The reason for obtaining the opposite result with the two snowplow operators is perhaps to be found the responses to the questionnaire. As is reported in section 4.2, Questionnaire *(Areas of Potential*

DAS Improvement) below, several snowplow operators said they would like the lane departure warnings to be tied to a lane wider than the standard 12-foot lane, so they would not get lane departure warnings when they are plowing the center line and right edge line. Apparently, they found it difficult to reposition the virtual lane makers while they were driving. It is quite likely that they deliberately ignored the warnings in order to plow the center line or edge line, so their responses to the auditory and haptic warnings were longer when the DAS was *On*. In line with this reasoning and for purposes of comparison, if the weather conditions were good and snowplow operators were not plowing and the DAS was off, then shorter lane departures would be expected. However, if the snowplow operators were plowing whether the DAS was *Off* or *On*, then longer lane departures would be expected.

4.2 QUESTIONNAIRE DATA

Extensive questionnaire data relating to the operators' opinions about the DAS were also collected at the end of the FOT. Unfortunately, because of the mild winter none of the operators used the DAS under conditions of *sustained* low visibility. As a result, the questionnaire data are of limited use because the operators were only able to postulate the opinions they might have had if they had experienced the DAS under the conditions for which it was designed.

The subjective questionnaire data were obtained by surveying and interviewing (in one-on-one interviews) 13 of the 21 specialty vehicle operators who participated in the FOT. These 13 operators included all eight snowplow operators, four of the ambulance drivers, and one state highway trooper. The remaining eight ambulance drivers had very limited experience with the Driver Assist System, and therefore were not interviewed.

The 13 operators responded to one of two questionnaires. The questionnaires were identical in format, but the two types were worded slightly differently; one questionnaire was geared toward operators who used the DAS in what they defined as limited visibility, while the other was geared toward operators who did not use the DAS in what they defined as limited visibility. Before receiving a questionnaire, drivers were screened with the question, "During the past winter, in how many shifts did you use the Driver Assist System in conditions of limited visibility (snow or fog)?" Depending on the answer, each driver was given one or the other questionnaire.

It should be noted that the questionnaire was designed to focus on the operator's experience with the DAS in limited visibility conditions. The original intent was to administer this survey on four separate occasions at reasonable intervals throughout the FOT. Because there were no snowfalls of any significance until very late in the FOT, these plans were substantially curtailed. The questionnaire was given only once in early April, 2002.

In Chapter 2.0 of this report, the March 8-9 and March 14-15 snowfalls were discussed and it was reported that no operators experienced periods of *sustained* very low visibility. Of the 13 operators interviewed in April, five said that they had *never* driven in limited visibility conditions during the FOT. The remaining eight operators said they had some experience of low visibility conditions during the FOT, although only one reported encountering poor visibility in more than four shifts. This is highlighted in Figure 4.1 which shows the number of shifts in

which the operators said they encountered what they defined as "limited visibility." Please note that these estimates include only brief exposures to limited visibility, meaning that low visibility was encountered at least once during a particular shift. Because the operators were not exposed to very low visibility conditions for sustained periods of time and, according to their subjective reports had relatively little experience of what they said were "limited visibility" conditions, the validity of the results of the questionnaire must be treated with caution.

Because of the lack of "wintry" weather, there were occasions when the operators chose to use the DAS to gain experience and to test the system. The DAS, however, was not designed for use in conditions when visibility is good. Consequently, *the operators' responses about the DAS that were obtained in the interviews should be considered with caution.* Their questionnaire responses might be considerably different if they experienced the DAS in conditions of *sustained* low visibility.

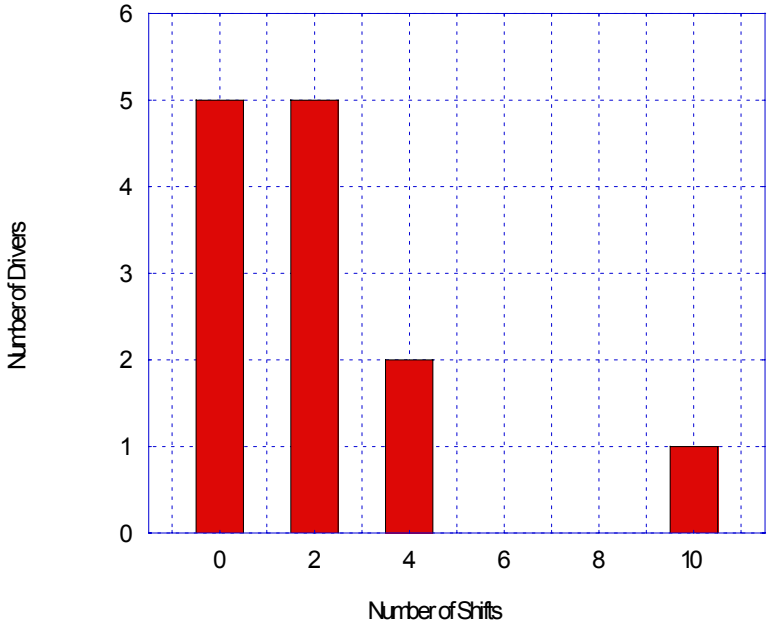


Figure 4.1: Number of Shifts when DAS was Used by Operators Who Briefly Experienced "Limited Visibility"

The next three subsections present comments made by the operators in their responses to the questionnaire and interview. First comments favorable to the DAS are presented. Then comments on possible improvements to the DAS are presented. Next, comments relating to the operators' willingness to participate in another FOT are given. After these three subsections, there is a fourth subsection which presents the questionnaire and responses to the questions in it.

4.2.1 Favorable Responses to the DAS

- Each of the 13 operators, without exception, said that he or she thinks the concept and potential of the DAS is "great."
- Many snowplow operators expressed the opinion that the DAS would be far more useful in out-state Minnesota where low visibility conditions occur more often than on MNTH-7 between Hutchinson and Minneapolis.

4.2.2 Areas of Potential DAS Improvement

Inspection of the questionnaire responses, however, shows that the operators were not particularly satisfied with the system as they experienced it. They commented on the following areas where improvements to the current system might be made.

- The DAS is not reliable—*thus dependability is a big issue*. Several drivers said they would not use the DAS as currently implemented in harsh conditions, because of a fear of getting stranded without another truck equipped with a similar system nearby to rescue them.

- Visibility through the combiner used for the Head-Up Display was a problem for several snowplow operators. They found it hard to detect snow drifts (until they were nearly upon them) and other subtle changes in the road surface/texture.

- Reflections from the combiner used for the Head-Up Display were also a problem for six of eight snowplow operators. For example, one operator said, "I can't use this thing. I'm going to run into somebody."

- Vibration of the combiner used for the Head-Up Display was a source of annoyance to most operators.

- Nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings.

- Several snowplow operators said they would like the lane departure warnings to be tied to a lane width larger than the standard 12-foot lane, so they would not get lane departure warnings when they cross the center line and right edge line. They found it difficult to reposition the virtual lane markers (which the DAS currently allows) while they were driving, so they would prefer a greater default width.

- More concentration is needed to use the Head-Up Display when the visibility is good, than is needed if it is not used when the visibility is good.

- All operators said they were concerned with the way the DAS is currently configured in the cab. They complained that the combiner was too close to the head and, in addition, many of them were hit in the shoulder by the projector. The ambulance drivers were particularly uncomfortable with the arrangement of the hardware in their cab—they did

not like losing the sun visor and the projector inhibited the communication between the driver and the paramedic when performing routine job functions.

- Eight of the 13 operators expressed concern that oncoming traffic is not displayed on the Head-Up-display. Ambulance drivers in particular were concerned because they often must pass other vehicles.

- Nine of the 13 operators stated that the lane departure warnings go off in the wrong place—sometimes as much as four feet from the correct position. It seems that places where lane splits occur are where the warnings are the least correct.

Additional Considerations

It was worth making some additional comments about three of the bulleted points above. First, with regard to the comment that nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings, it should be noted that during the low visibility conditions for which the DAS was designed, there would likely be far fewer other vehicles present, and consequently there would also likely be fewer collision avoidance warnings (rectangles) on the combiner.

Second, several snowplow operators said they would like the lane departure warnings to be tied to a lane width larger than the standard 12-foot lane. They indicated that they would like to have greater lane width adjustment flexibility so that lane departure warnings would not be given when operators crossed the center line and right edge line—they found it difficult to reposition the virtual lane markers (which the DAS currently allows) while they were driving, so they would prefer a greater default width. Though the snowplow operators said they would like a greater default width, a preferable alternative solution would be to modify the DAS to make it easier to reposition the virtual lane. Considerable care needs to be taken in deciding how to deal with this problem.

Third, the operators indicated that they had to concentrate more when they used the DAS in good visibility than when they did not use the DAS in good visibility. It should be noted that this says nothing about whether or not more concentration would be required if they were to use the DAS in poor visibility than if they did not use the DAS in poor visibility. Furthermore, the DAS was not designed for use under good visibility conditions.

4.2.3 Willingness to Participate in Subsequent Field Testing of the DAS

Each operator stated that this was not a good winter to test the system. All 13 operators interviewed indicated that they would like to see the program extended, and hope that they will have the opportunity to use the system in the low visibility conditions that occur in a typical Minnesota winter.

4.2.4 Questionnaire Responses

As mentioned above, the 13 operators responded to one of two questionnaires, depending on how they answered the question, "During the past winter, in how many shifts did you use the DAS in conditions of limited visibility (snow or fog)?" Based on the answer to this question, each driver

was given one or the other questionnaire. The ambulance drivers and snowplow operators had similar collective responses, so their data are combined within the two groups. Please note that the responses of the snowplow operators and ambulance drivers who said that they *had not* used the DAS in limited visibility conditions are presented with a *gray* background. The state highway trooper's responses were very different from those of the other participants so those data are considered separately below. The responses to questionnaire are presented in Tables 4.3 through 4.26.

Question	Overall Mean
1. In general, how useful is the Driver Assist System in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	59 s.d. = 26 minimum = 22; maximum = 90
2. When you drive your vehicle, how useful are the lane markings on the Head-Up display, in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	65 s.d. = 20 minimum = 37; maximum = 95
3. When you drive your vehicle, how useful is it to see objects ahead on the Head-Up display in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	57 s.d. = 32 minimum = 21; maximum = 96
4. When you change lanes, how useful is the side-looking radar in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	36 s.d. = 25 minimum = 0; maximum = 73
5. When you drive your vehicle, how useful are lane departure warnings in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	54 s.d. = 23 minimum = 17; maximum = 94

Table 4.3: Usefulness of the DAS for Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
1. In general, how useful do you think the Driver Assist System would be in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	52 s.d. = 25 minimum = 22; maximum = 84
2. When you drive your vehicle, how useful do you think the lane markings on the Head-Up display would be in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	59 s.d. = 28 minimum = 27; maximum = 87
3. When you drive your vehicle, how useful do you think it would be to see objects ahead on the Head-Up display in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	64 s.d. = 24 minimum = 28; maximum = 87
4. When you change lanes, how useful do you think the side-looking radar would be in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	51 s.d. = 29 minimum = 22; maximum = 91
5. When you drive your vehicle, how useful do you think lane departure warnings would be in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	57 s.d. = 26 minimum = 24; maximum = 91

Table 4.4: Usefulness of DAS for Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
6. How much do you like the lane departure warning that is a red line on the Head-Up Display in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	56 s.d. = 31 minimum = 9; maximum = 94
7. How much do you like the lane departure warning that sounds like a rumble strip in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	27 s.d. = 29 minimum = 0; maximum = 74
8. How much do you like the lane departure warning with the vibration at the edge of the seat in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	62 s.d. = 36 minimum = 13; maximum = 100
9. The lane departure warning is a combination of the red line (on the Head-Up display), the sound of the rumble strip, and the vibrating seat. Would you prefer some other type of warning?	Yes (%) 29 No (%) 71

Table 4.5: Lane Departure Warning System for Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
6. How much do you think you would like the lane departure warning that is a red line on the Head-Up Display in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	70 s.d. = 13 minimum = 51; maximum = 84
7. How much do you think you would like the lane departure warning that sounds like a rumble strip in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	40 s.d. = 29 minimum = 6; maximum = 72
8. How much do you think you would like the lane departure warning with the vibration at the edge of the seat in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	54 s.d. = 35 minimum = 0; maximum = 82
9. The lane departure warning is a combination of the red line (on the Head-Up display), the sound of the rumble strip, and the vibrating seat. Would you prefer some other type of warning?	Yes (%) 20 No (%) 80

Table 4.6: Lane Departure Warning System for Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question: 10. (a) Did you use the magnetic tape back-up system?	Driver Response (%)
Yes	43
No	57

Table 4.7: Magnetic Tape System - Responses by Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Those who responded yes to Question 10 (a) above were instructed to answer 10 (b) below. Those who responded no to Question 10 (a) above were instructed to answer 10 (c) below.

Question	Overall Mean
10 (b) When using the magnetic tape back-up system, how easy was it to understand where you were on the road? 0 = Very Easy 100 = Very Difficult	44 s.d. = 31 minimum = 9; maximum = 63
10 (c) If you were to use the magnetic tape back-up system, how easy do you think it would be to understand where you are on the road in conditions with limited visibility (snow or fog)? 0 = Very Easy 100 = Very Difficult	20 s.d. = 11 minimum = 10; maximum = 33

Table 4.8: Magnetic Tape System Continued - Responses by Drivers Who Said They Had Used the DAS in Conditions of Limited Visibility

Question: 10. (a) Did you use the magnetic tape back-up system?	Driver Response (%)
Yes	20
No	80

Table 4.9: Magnetic Tape System - Responses by Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Those who responded yes to Question 10 (a) above were instructed to answer 10 (b). Those who responded no to Question 10 (a) above were instructed to answer 10 (c).

Question	Overall Mean
10 (b) When using the magnetic tape back-up system, how easy was it to understand where you were on the road? 0 = Very Easy 100 = Very Difficult	16 s.d. = 0
10 (c) If you were to use the magnetic tape back-up system, how easy do you think it would be to understand where you are on the road in conditions with limited visibility (snow or fog)? 0 = Very Easy 100 = Very Difficult	49 s.d. 11 minimum = 37; maximum = 61

Table 4.10: Magnetic Tape System Continued - Responses by for Drivers Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
11. How stressful is it to use the Driver Assist System when visibility (snow or fog) is very low? 0 = Very Stressful 100 = Not at all Stressful	27 s.d. = 17 minimum = 0; maximum = 50

Table 4.11: Stress Associated with DAS for Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
12. Do you need breaks more often than usual when you use the Driver Assist System when visibility (snow or fog) is very low?	100	0
13. Were you more fatigued than usual after using the Driver Assist System when visibility (snow or fog) is very low?	43	57

Table 4.12: Stress and Fatigue for Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
11. How stressful do you think it would be to use the Driver Assist System when visibility (snow or fog) is very low? 0 = Very Stressful 100 = Not at all Stressful	31 s.d. = 17 minimum = 6; maximum = 50

Table 4.13: Stress Associated with DAS for Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
12. Do you think you would need breaks more often than usual when you use the Driver Assist System when visibility (snow or fog) is very low?	20	80
13. Do you think you would be more fatigued than usual after using the Driver Assist System when visibility (snow or fog) is very low?	20	80

Table 4.14: Stress and Fatigue for Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
14. How comfortable are you with where the combiner (the Head-Up display) is placed? 0 = Very Uncomfortable 100 = Very Comfortable	18 s.d. = 18 minimum = 0; maximum = 46
15. How comfortable are you with where the projector panel is placed? 0 = Very Uncomfortable 100 = Very Comfortable	34 s.d. = 31 minimum = 1; maximum = 82

Table 4.15: Ergonomics of the Head-Up Display Hardware for Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
14. How comfortable are you with where the combiner (the Head-Up display) is placed? 0 = Very Uncomfortable 100 = Very Comfortable	30 s.d. = 16 minimum = 2; maximum = 43
15. How comfortable are you with where the projector panel is placed? 0 = Very Uncomfortable 100 = Very Comfortable	35 s.d. = 24 minimum = 4; maximum = 66

Table 4.16: Ergonomics of the Head-Up Display Hardware for Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
16. Would you like to have the final version of the Driver Assist System permanently installed in your vehicle?	57	43
17. If you answered YES to #16 above, would you use the final Driver Assist System if it were permanently installed in your vehicle?	—	100
18. If you answered NO to #16 above, would you use the final Driver Assist System anyway?	50	50
19. Would you recommend the Driver Assist System to other people?	57	43
20. If it becomes technologically possible, would you like to see, displayed on the Head-Up display, the oncoming traffic in the opposing lane?	29	71

Table 4.17: DAS Final Version - Responses from Drivers (n = 7) Who Said They Had Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
16. Would you like to have the final version of the Driver Assist System permanently installed in your vehicle?	60	40
17. If you answered YES to #16 above, would you use the final Driver Assist System if it were permanently installed in your vehicle?	—	100
18. If you answered NO to #16 above, would you use the final Driver Assist System anyway?	67	33
19. Would you recommend the Driver Assist System to other people?	40	60
20. If it becomes technologically possible, would you like to see, displayed on the Head-Up display, the oncoming traffic in the opposing lane?	40	60

Table 4.18: DAS Final Version - Responses from Drivers (n = 5) Who Said They Had Not Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
1. In general, how useful is the Driver Assist System in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	100
2. When you drive your vehicle, how useful are the lane markings on the Head-Up display, in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	100
3. When you drive your vehicle, how useful is it to see objects ahead on the Head-Up display in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	78
4. When you change lanes, how useful is the side-looking radar in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	16
5. When you drive your vehicle, how useful are lane departure warnings in conditions with limited visibility (snow or fog)? 0 = Not at all useful 100 = Very useful	100

Table 4.19: Usefulness of the DAS for State Highway Trooper (n = 1) Who Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
6. How much do you like the lane departure warning that is a red line on the Head-Up Display in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	100
7. How much do you like the lane departure warning that sounds like a rumble strip in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	100
8. How much do you like the lane departure warning with the vibration at the edge of the seat in conditions with limited visibility (snow or fog)? 0 = Very Much Dislike 100 = Very Much Like	100
9. The lane departure warning is a combination of the red line (on the Head-Up display), the sound of the rumble strip, and the vibrating seat. Would you prefer some other type of warning?	Yes (%) — No (%) 100

Table 4.20: Lane Departure Warning System for State Highway Trooper Who Used the DAS in Conditions of Limited Visibility

Question: 10. (a) Did you use the magnetic tape back-up system?	Driver Response (%)
Yes	100
No	—

Table 4.21: Magnetic Tape System - Response by State Highway Trooper Who Used the DAS in Limited Visibility

Since the state highway trooper responded yes to Question 10 (a) he was instructed to answer 10 (b) below and not to 10 (c).

Question	Overall Mean
10 (b) When using the magnetic tape back-up system, how easy was it to understand where you were on the road? 0 = Very Easy 100 = Very Difficult	82
10 (c) If you were to use the magnetic tape back-up system, how easy do you think it would be to understand where you are on the road in conditions with limited visibility (snow or fog)? 0 = Very Easy 100 = Very Difficult	N/A

Table 4.22: Magnetic Tape System Continued - Response by State Highway Trooper Who Used the DAS in Limited Visibility

Question	Overall Mean
11. How stressful is it to use the Driver Assist System when visibility (snow or fog) is very low? 0 = Very Stressful 100 = Not at all Stressful	63

Table 4.23: Stress Associated with DAS for State Highway Trooper Who Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
12. Do you need breaks more often than usual when you use the Driver Assist System when visibility (snow or fog) is very low?	100	—
13. Were you more fatigued than usual after using the Driver Assist System when visibility (snow or fog) is very low?	100	—

Table 4.24: Stress and Fatigue for State Highway Trooper Who Used the DAS in Conditions of Limited Visibility

Question	Overall Mean
14. How comfortable are you with where the combiner (the Head-Up display) is placed? 0 = Very Uncomfortable 100 = Very Comfortable	82
15. How comfortable are you with where the projector panel is placed? 0 = Very Uncomfortable 100 = Very Comfortable	49

Table 4.25: Ergonomics of the Head-Up Display Hardware for State Highway Trooper Who Used the DAS in Conditions of Limited Visibility

Question	Percentage of Drivers	
	No	Yes
16. Would you like to have the final version of the Driver Assist System permanently installed in your vehicle?	—	100
17. If you answered YES to #16 above, would you use the final Driver Assist System if it were permanently installed in your vehicle?	—	100
18. If you answered NO to #16 above, would you use the final Driver Assist System anyway?	N/A	
19. Would you recommend the Driver Assist System to other people?	—	100
20. If it becomes technologically possible, would you like to see, displayed on the Head-Up display, the oncoming traffic in the opposing lane?	—	100

Table 4.26: DAS Final Version - Response from State Highway Trooper Who Used the DAS in Limited Visibility

It should be noted that the state highway trooper had far more experience with the DAS than any other operator. He was the only person who drove the patrol vehicle. In contrast, two snowplow operators shared each snowplow, and all twelve ambulance drivers shared one vehicle. Also the state highway trooper drove on the roads far more frequently than the other specialty vehicle operators. The state highway trooper's much higher usage of the DAS may have resulted in his more enthusiastic responses to the questionnaire.

In conclusion, it is worth repeating that specialty operators' lack of experience in very low visibility conditions, coupled with a lack of driver trust in a system they experienced early on when it was unreliable, makes evaluation highly problematic. Because the operators had no opportunity to use the DAS in sustained low visibility conditions, the usefulness of the questionnaire responses is in doubt. For example, perceptions of the utility of the forward collision avoidance warning might change if drivers were to use the DAS in the low visibility

conditions for which it was designed. The operators mentioned that they did not like to see so many rectangles (indicating a vehicle ahead) on the Head-Up display. Their opinions, however, are based on experience with the DAS in clear visibility when many cars were on the road. When the visibility is very low there should be relatively few vehicles on the road, and they will be traveling at much slower speeds. Consequently, under these conditions there will be far fewer rectangles on the Head-Up display, and this may change operator opinions regarding the usefulness of the warning (e.g., particularly if an operator encounters a stalled vehicle). A guiding principle of usability studies is that the technology or device to be evaluated should always be tested under the circumstances for which it was designed and conversely, it should never *solely* be tested in conditions when the users do not need it.

4.3 STUDY CONTINUATION

The FHWA has decided against sponsoring another year of Field Operational Testing for this system. Based on the results of this study, and in particular, the operator view that the system has significant potential, Mn/DOT has decided to extend the FOT for an additional year. Presently, discussions are underway to determine the scope and extent of the testing to be undertaken during the winter of 2002-2003.

Based on operator interviews and subsequent discussions, a number of changes have been made or will be made to the system. Below, operator comments and the resulting changes to the system are provided.

Operator response:

The DAS is not reliable—*thus dependability is a big issue*. Several drivers said they would not use the DAS as currently implemented in harsh conditions, because of a fear of getting stranded without another truck equipped with a similar system nearby to rescue them.

System modification:

Reliability is a difficult entity to quantify. To some operators, an occasional radar target would appear on the screen when there was no physical object present from which a radar return should appear. (This was a phenomena not seen before the FOT. U of MN radar processing technology provides the opportunity to filter returns from elements in the geospatial landscape, but there is no means to filter returns from something that is not part of the geospatial landscape.) To them, this made the system unreliable. To others, it was a period during a transition from one GPS base station to another when the GPS solution would be lost.

The solution to the radar problem will require support from Eaton Vorad. Whether Eaton Vorad is willing to support this limited application is yet to be determined. GPS transitions have been improved with more recent versions of Trimble firmware for the ms750 receiver. Upgrading vehicle GPS systems to this firmware release should significantly reduce the time it takes the receiver to transition from one base station to another. This has been tested, and the system is much improved.

Operator Response:

Visibility through the combiner used for the Head-Up Display was a problem for several snowplow operators. They found it hard to detect snow drifts (until they were nearly upon them) and other subtle changes in the road surface/texture.

System Modification:

This response likely arises because the system was not used in very low visibility conditions. Under those conditions, it is difficult to see snow drifts because of contrast issues, and other subtle changes in the roadway because of poor lighting and obscured visual paths. Excessive brightness on the combiner may overpower light transmitted through the combiner; reducing projector brightness is may address this problem.

Operator response:

Reflections from the combiner used for the Head-Up Display were also a problem for six of eight snowplow operators. For example, one operator said "I can't use this thing. I'm going to run into somebody."

System Modification:

Complaints of this sort are likely due to the operator not properly adjusting the intensity/brightness of the displays located inside their vehicle. Both the driver interface and HUD projector have variable brightness controls which must be dimmed for low ambient light level operation. The gap between training and actual system use probably led to the drivers forgetting where/how to dim their displays. To address this issue, drivers will be retrained, and an instruction "cheat sheet" will be provided for each vehicle as a brief users' manual.

Operator response:

Vibration of the combiner used for the Head-Up Display was a source of annoyance to most operators.

System modification:

Combiner mounts will be modified to make them stiffer and less susceptible to vibration.

Operator response:

Nine of the 13 operators interviewed volunteered that they were annoyed with the many rectangles of the collision avoidance warnings.

System modification:

System software will be modified to provide only warnings regarding the closest 2 or three obstacles. This will greatly reduce the clutter in the HUD.

Operator response:

All operators said they were concerned with the way the DAS is currently configured in the cab. They complained that the combiner was too close to the head and, in addition, many of them were hit in the shoulder by the projector. The ambulance drivers were particularly uncomfortable with the arrangement of the hardware in their cab—they did not like losing the sun visor and the projector inhibited the communication between the driver and the paramedic when performing routine job functions.

System modification:

Unfortunately, a solution to this problem is beyond the scope of this project. Because of the optical properties required of the HUD, the projector is required to be a fixed distance from the combiner. Because of this fixed distance requirement, the remaining mounting option is that of installing the projector and ancillary optics in the dashboard of the vehicle. This is beyond the scope of this project.

Operator response:

Eight of the 13 operators expressed concern that oncoming traffic is not displayed on the Head-Up-display. Ambulance drivers in particular were concerned because they often must pass other vehicles.

System modification:

This is a limitation of the Eaton Vorad radar. Extensive changes to the design of the radar front end and of the signal processing software would be needed to provide information regarding on-coming traffic. It is unlikely that these changes will be made by Eaton Vorad for this FOT. Drivers will simply be unable to rely on radar information for oncoming traffic.

Operator response:

Nine of the 13 operators stated that the lane departure warnings go off in the wrong place—sometimes as much as four feet from the correct position. It seems that places where lane splits occur are where the warnings are the least correct.

System modification:

These errors have two possible sources. The likely candidate is that during the GPS transition, the GPS system converges to an incorrect position solution. If this is the case, the recent firmware release by Trimble should correct the problem. The less likely candidate is an error or errors associated with the database. However, the database was thoroughly checked after it was completed, and no errors of this magnitude have been located. Nevertheless, the database will be checked before the extension to ensure that it is error free.

In all, the deficiencies mentioned by the drivers are for the most part problems for which tractable solutions exist. System modifications, complemented by training refresher courses and more frequent use of the system should address a significant portion of the drivers' complaints. It is likely, however, that significant use may uncover other issues which will need to be addressed. The key is to achieve sustained use of the system in conditions for which it was designed.

If an additional evaluation were to be conducted, there should be more frequent one on one interaction with the operators directly following their shift to obtain more "immediate" information regarding the operators' thoughts on the DAS.

As a final comment, it should be noted that the "rules of engagement" for this FOT was that once the system was released, no modifications to the system were allowed unless the issue was determined to be safety critical. This limited the ability of the team to respond to issues raised by the operators during the actual test. Some operators felt that their needs issues not adequately addressed during the duration of the test; this led to some less than favorable responses to the system by the drivers.

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APPENDIX A1

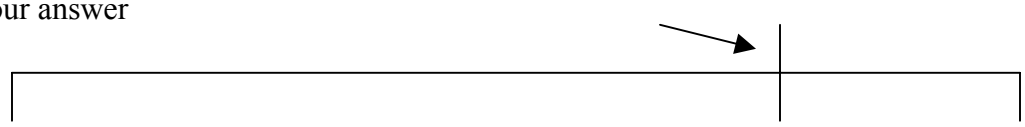
Operator Questionnaires
For drivers with no low visibility experience

Questionnaire

The following questions deal with your experience of driving with the Driver Assist System in your vehicle. A scale follows each question. This scale allows for a range of possible answers. For each question, we would like you to make a mark on the scale in the place that best indicates how you feel about that question.

For example: If you were asked, "How important are seat belts in driver safety?" you might answer as shown below—

Your answer



Not at all Important Very Important

Below you will find a set of five questions about the usefulness of the driver assist system.

1. In general, how useful do you think the Driver Assist System would be in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

2. When you drive your vehicle, how useful do you think the lane markings on the Head-Up display would be in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

3. When you drive your vehicle, how useful do you think it would be to see objects ahead on the Head-Up display in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

4. When you change lanes, how useful do you think the side-looking radar would be in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

5. When you drive your vehicle, how useful do you think lane departure warnings would be in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

The next four questions are about the different parts of the lane departure warning system of the Driver Assist System.

6. How much do you think you would like the lane departure warning that is a red line on the Head-Up Display in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

7. How much do you think you would like the lane departure warning that sounds like a rumble strip in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

8. How much do you think you would like the lane departure warning with the vibration at the edge of the seat in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

9. The lane departure warning is a combination of the red line (on the Head-Up display), the sound of the rumble strip, and the vibrating seat. Would you prefer some other type of warning?

Yes _____ No _____

If you answered YES to #9 above, how should the warning be given?

10. (a) Did you use the magnetic tape back-up system?

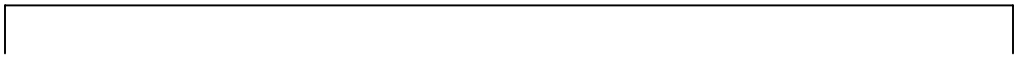
Yes _____ If yes, go to Question b.

No _____ If no, go to Question c.

(b) When using the magnetic tape back-up system, how easy was it to understand where you were on the road?

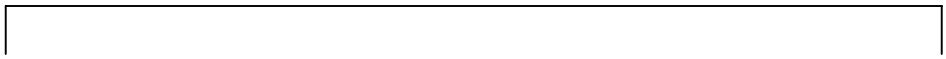
Very Easy Very Difficult

(c) If you were to use the magnetic tape back-up system, how easy do you think it would be for you to understand where you are on the road in conditions with limited visibility (snow or fog)?



Very Easy Very Difficult

11. How stressful do you think it would be to use the Driver Assist System when visibility (snow or fog) is very low?



Very Stressful Not at all Stressful

12. Do you think you would need breaks more often than usual when you use the Driver Assist System when visibility (snow or fog) is very low?

Yes _____ No _____

13. Do you think you would be more fatigued than usual after using the Driver Assist System when visibility (snow or fog) is very low?

Yes _____ No _____

The next two questions ask about the hardware used for the Head-Up display.

14. How comfortable are you with where the combiner (the Head-Up display) is placed?

Very Uncomfortable Very Comfortable

Comments? _____

_____

15. How comfortable are you with where the projector panel is placed?

Very uncomfortable Very Comfortable

Comments? _____

_____

In the Field Operational Test an early version of the Driver Assist System is installed in your vehicle. The following questions relate to the final version of this system.

16. Would you like to have the final version of the Driver Assist System permanently installed in your vehicle?

Yes _____ No _____

17. If you answered YES to #16 above, would you use the final Driver Assist System if it were permanently installed in your vehicle?

Yes _____ No _____

18. If you answered NO to #16 above, would you use the final Driver Assist System anyway?

Yes _____ No _____

19. Would you recommend the Driver Assist System to other people?

Yes _____ No _____

20. If it becomes technologically possible, would you like to see, displayed on the Head-Up display, the oncoming traffic in the opposing lane?

Yes _____ No _____

21. Do you have any suggestions for how the Driver Assist System could be improved?

_____

_____

_____

_____

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_____

22. Finally, do you have any comments about your experience of driving with the driver assist system in the vehicle?

Appendix A2

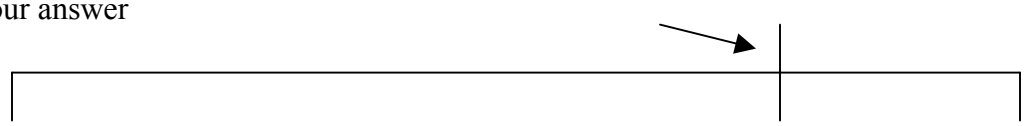
Operator Questionnaires
For drivers with no low visibility experience

Questionnaire

The following questions deal with your experience of driving with the Driver Assist System in your vehicle. A scale follows each question. This scale allows for a range of possible answers. For each question, we would like you to make a mark on the scale in the place that best indicates how you feel about that question.

For example: If you were asked, "How important are seat belts in driver safety?" you might answer as shown below—

Your answer



Not at all Important Very Important

Below you will find a set of five questions about the usefulness of the driver assist system.

22. In general, how useful is the Driver Assist System in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

23. When you drive your vehicle, how useful are the lane markings on the Head-Up display, in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

24. When you drive your vehicle, how useful is it to see objects ahead on the Head-Up display in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

25. When you change lanes, how useful is the side-looking radar in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

26. When you drive your vehicle, how useful are lane departure warnings in conditions with limited visibility (snow or fog)?

Not at all useful Very useful

The next four questions are about the different parts of the lane departure warning system of the Driver Assist System.

27. How much do you like the lane departure warning that is a red line on the Head-Up Display in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

28. How much do you like the lane departure warning that sounds like a rumble strip in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

29. How much do you like the lane departure warning with the vibration at the edge of the seat in conditions with limited visibility (snow or fog)?

Very Much Dislike Very Much Like

30. The lane departure warning is a combination of the red line (on the Head-Up display), the sound of the rumble strip, and the vibrating seat. Would you prefer some other type of warning?

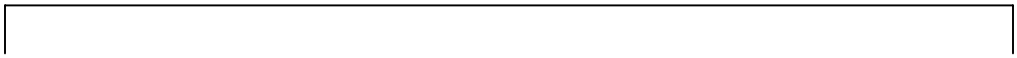
Yes _____ No _____

If you answered YES to #9 above, how should the warning be given?

31. (a) Did you use the magnetic tape back-up system?

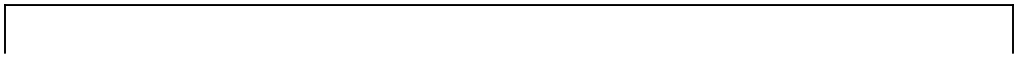
Yes _____ If yes, go to Question b.
No _____ If no, go to Question c.

(b) When using the magnetic tape back-up system, how easy was it to understand where you were on the road?



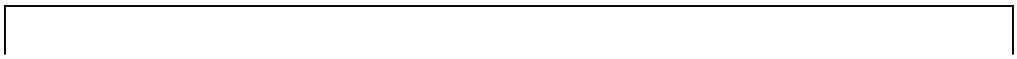
Very Easy Very Difficult

(c) If you were to use the magnetic tape back-up system, how easy do you think it would be to understand where you are on the road in conditions with limited visibility (snow or fog)?



Very Easy Very Difficult

32. How stressful is it to use the Driver Assist System when visibility (snow or fog) is very low?



Very Stressful Not at all Stressful

33. Do you need breaks more often than usual when you use the Driver Assist System when visibility (snow or fog) is very low?

Yes _____ No _____

34. Were you more fatigued than usual after using the Driver Assist System when visibility (snow or fog) is very low?

Yes _____ No _____

The next two questions ask about the hardware used for the Head-Up display.

35. How comfortable are you with where the combiner (the Head-Up display) is placed?

Very Uncomfortable Very Comfortable

Comments? _____

_____

36. How comfortable are you with where the projector panel is placed?

Very uncomfortable Very Comfortable

Comments? _____

In the Field Operational Test an early version of the Driver Assist System is installed in your vehicle. The following questions relate to the final version of this system.

37. Would you like to have the final version of the Driver Assist System permanently installed in your vehicle?

Yes _____ No _____

38. If you answered YES to #16 above, would you use the final Driver Assist System if it were permanently installed in your vehicle?

Yes _____ No _____

39. If you answered NO to #16 above, would you use the final Driver Assist System anyway?

Yes _____ No _____

40. Would you recommend the Driver Assist System to other people?

Yes _____ No _____

41. If it becomes technologically possible, would you like to see, displayed on the Head-Up display, the oncoming traffic in the opposing lane?

Yes _____ No _____

42. Do you have any suggestions for how the Driver Assist System could be improved?

_____

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_____

22. Finally, do you have any comments about your experience of driving with the driver assist system in the vehicle?

APPENDIX B

Using a Head-Up Display in Poor Visibility Conditions I: Investigating Lane Departure Warnings in Two Simulator Experiments.

Kathleen A. Harder, John Bloomfield and Benjamin J. Chihak

In: Gale, A.G. (Editor) *Vision in Vehicles IX* (In press).
Amsterdam, Holland: Elsevier Science Publishers B.V.

USING A HEAD-UP DISPLAY IN POOR VISIBILITY CONDITIONS I: INVESTIGATING LANE DEPARTURE WARNINGS IN TWO SIMULATOR EXPERIMENTS

Kathleen A. Harder
University of Minnesota

John Bloomfield
University of Minnesota & University of Derby

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University of Minnesota

1. INTRODUCTION

1.1 The problem and a possible solution

In winter, in the Northern tier states of the U.S.A. and in Canada, drivers are sometimes faced—particularly in rural areas—with very low visibility conditions when falling, blowing, and/or drifting snow cause whiteouts or near-whiteouts. This is of particular concern for specialty platform drivers—i.e., snowplow operators, ambulance drivers, and highway patrol officers. Recently, several technologies—including the Differential Global Positioning System, digital geo-spatial databases, and forward-looking radar—have been integrated into a single Driver Assist System. This system presents a virtual representation of the roadway ahead and provides warnings of vehicles ahead on a Head-Up Display that is mounted in front of the driver. In addition to aiding in snowy conditions, the system could assist on other occasions where visibility is attenuated—e.g., when there is dense fog or driving rain, or the driver is driving at night on unlit roads, or when there is some combination of these conditions.

1.2 Human factors approach

As this system is developed, we are exploring human factors issues associated with its use—using the back-to-back research strategy, suggested by Gopher and Sanders (1984). We are conducting driving simulation experiments and field studies. To date, we have completed two simulation experiments and a field test. The two simulation experiments are discussed in this paper, while the field study is described by Bloomfield & Harder (in the companion paper in these proceedings).

2. FIXED-BASE SIMULATOR

2.1 The simulator

Both simulator experiments were conducted in a fixed-base wraparound simulator at the University of Minnesota. The simulator vehicle was a full-body 1990 Acura Integra RS. It was enclosed in a spherical wood and steel dome 12.5 ft (3.81 m) high at its apex with a 15.5 ft (4.72 m) internal diameter. Sensors in the car detected accelerator, brake, and steering inputs from the driver. Force feedback was applied to the steering wheel through the steering column with a torque motor. The vehicle had a real-time interface.

Each driver drove the simulator vehicle in a computer-generated environment. This environment was projected, by three Proxima 9250+ projectors, onto a curved seamless 24-ft (7.32-m) by 8-ft (2.44-m) screen within the dome. This screen provided a 156-deg forward view to the driver. An SGI Onyx computer (Reality Engine 2) calculated the vehicle dynamics and generated the visual scenario. Programming for the visual scenario was carried out on MultiGen-Paradigm Vega and SGI Performer APIs. The Onyx also generated engine sounds and road noise, presenting them through a Cerwin-Vega satellite and subwoofer system, mounted in the trunk of the vehicle, and two Aura bass shakers, mounted under the front seats. Information from the Onyx was transmitted to and from the main simulator computer—a PC running Linux—via TCP/IP. The main computer processed all vehicular sensors and controllers. The interface between the main simulator computer and the vehicular hardware was a National Instruments AT-MIO-16E-10 data card.

Three miniature cameras were installed in the simulator vehicle. One camera was positioned on the rear-view mirror, and directed towards the driver's face; a second was positioned on the B-pillar on the passenger side of the vehicle, so that it could record the driver's arm movements; while the third—a low-light camera—was mounted under the steering column and pointing down in order to record the position of the driver's feet on the accelerator and brake. The images from these three cameras—along with the central portion of the driver's forward view of the computer generated environment—were stored together in the four quadrants of each recorded video frame.

2.2 Specific modifications

For the current experiments, a glass combiner was mounted in the simulator vehicle, between the driver and the windshield. This combiner was effectively a two-way mirror. Simultaneously, the driver was able to see the image reflected from the inner surface of the combiner and to view the computer generated environment through the combiner.

In both the experiments reported here, as the driver drove the highway projected on the simulator screen, the Driver Assist System provided two things on the Head-Up Display. First, it provided a virtual representation of the lane markings. Second, a white rectangular outline was used to indicate the presence of an object ahead that was within 350 ft (106.7 m). The outline was the width of truck. And, as the distance between driver and object ahead decreased, the size of the outline increased proportionately.

3. FIRST SIMULATION EXPERIMENT: THE EFFECT OF VARYING VISUAL LANE DEPARTURE AND COLLISION AVOIDANCE WARNINGS

3.1 Experimental conditions

In this experiment, we investigated visual lane-departure warnings and collision-avoidance warnings. There were five lane-departure warnings conditions, one of which was a no-warning control condition. The four warnings involved a change in the virtual centerline (on the left) if the driver drifted out of lane to the left, and a change in the virtual lane edge-line (on the right) if he or she drifted out of lane to the right. The warnings were—a red line warning; a double line warning; a white area warning; and a red area warning.

There were three collision avoidance conditions, one of which was a no-warning control condition. The first warning condition involved two steps—first, an advisory (with the white outline changing from white to yellow) was given as soon as the time to coincidence dropped to 5 s; then, a warning (with the outline changing to red) was given when the time to coincidence dropped to 3 s. The second warning condition had a single step—with the white outline changing from white to red as soon as the time to coincidence dropped to 3 s.

The 15 participants who took part in the first experiment were drawn from general public. Each took part in one experimental session.

The route that each participant drove five times was a two-lane rural road that was 6.21 mi (10 km) long, with a cross street occurring every 1.24 mi (2 km). In order to produce many more lane departures than normal occur, we varied the lane widths varied from trial-to-trial (without informing subjects)—the lane widths were 9 ft (2.74 m), 10 ft (3.05 m), or 11 ft (3.35 m).

While the participants drove they passed a number of vehicles that were on their side of road, that were all stationary, and that were either half in lane or just out of lane. There were also a number of vehicles in the opposing lane that were either in lane or half in lane.

The visibility was set at 98.4 ft (30 m)—this lower even than the visibility range that Hawkins (1988) defines as “thick fog” (this range is 164.0 ft (50 m) to 492.1 ft (150 m)].

3.2 Results

There is only room to briefly summarize the results of this experiment here.

Our main measure of the effect of lane departure warnings was the duration of each lane departure. When we found that these data were highly positively skewed, we used a logarithmic transform to normalize then. An analysis of variance showed that the effect of varying the lane departure warnings was statistically significant (at the $p=0.018$ level). We found that all four warning conditions (the red line warning, with a mean lane departure duration of 0.92 s; the double line warning, with a mean duration of 0.87 s; the white area warning, with a mean

duration of 0.85 s; and the red area warning, with a mean duration of 0.93 s) were all significantly better than the no warning condition (with a mean lane departure duration of 1.76 s).

To investigate the effect of varying the collision avoidance warning conditions, we examined the driving performance of the participants during the last 350-ft (106.7-m)—i.e., within the range of the forward-looking radar—before they reached the stationary vehicles that were half in or just out of their lane. There were 150 of these encounters. Few responses involved a reduction in speed. For 119 of 150 encounters, steering responses occurred. There were fewer steering responses (68%) for the no-warning condition than there were for either the advisory & warning condition (84%) or the warning-only condition (82%). There was no significant difference in the time (or distance) before vehicle was encountered at which responses occurred.

3.3 Warnings selected

The results indicated that the giving a lane departure warning or a collision avoidance warning was clearly better than not providing a warning—but also that, in both cases, there were no differences between warnings. Because of this other selection criteria were needed.

Given that there was no statistical significant difference in the responses of the participants to the four lane departure warnings, we selected which one of them to use in the next study by means of other criteria. There are potential disadvantages with both the white and red area warnings—they could obscure a vehicle or animal that was in the area. And the double-line warning could potentially be confused with a standard usage—a double line is used to indicate that a driver should not cross the centerline into the opposing lane [see the Manual on Uniform Control Devices (MUTCD, 2000)]. The fourth warning condition, involving a change in color of the line being crossed from white to red, was selected because it is consistent with way that red is used in the MUTCD (2000).

Similarly, there was no significant difference in the responses of the participants to the two collision warning conditions. In this case, because many of the participants indicated—in post-experiment interviews—that they did not notice the yellow advisory, the single step warning, in which the white outline changes from white to red as soon as the time to coincidence dropped to 3 s.

4. SECOND SIMULATION EXPERIMENT: THE EFFECTS OF VISUAL, AUDITORY, AND TACTILE LANE DEPARTURE WARNINGS

4.1 Experimental conditions

In this experiment, we investigated the effect of varying the modality used to present lane-departure warnings. For the visual modality we used the red line warning from the first experiment. In addition, we used an auditory warning—an oscillating tone somewhat like a rumble strip—which was delivered by speakers mounted in the simulator vehicle. And the

tactile warning was a vibration—also somewhat like that felt when traveling over a rumble-strip. This was delivered via the sides of the driver's seat.

Whereas the participants in the first experiment were drawn from the general public, for this experiment they were specialty platform operators. Of the 55 participants, 24 were snowplow operators, 14 were ambulance drivers, and 17 state highway troopers. They were divided into two groups with 12 snowplow operators, seven ambulance drivers, and 8 or 9 state highway troopers in each

All the participants took part in one session. They began by trying to drive the experimental route with, without the use of the lane markings or any warnings. Then they drove the route five times always with the lane markings and with one of five warning conditions. All the participants drove with two common warning conditions—i.e., one with no warnings, and another with the lane departure warnings given simultaneously in all three modalities (visual, auditory, and tactile). In addition, one group of participants drove with the lane departure warnings presented in all three single modalities—i.e., with the lane markings and (1) visual warnings; (2) auditory warnings; and (3) tactile warnings. In contrast, the second group drove with the warnings given simultaneously in all three dual modality combinations—i.e., with the lane markings and (1) visual and auditory warnings; (2) auditory and tactile warnings; and (3) tactile and visual warnings.

In this experiment, the collision avoidance conditions were not varied. In all cases, when the participants were within 350 ft (106.7 m) of a vehicle ahead, a white rectangular outline was presented on the Head-Up Display. And this outline changed from white to red as soon as the time to coincidence dropped to 3 s.

The route used in the second experiment was a two-lane rural road, 3.12 mi (5 km) in length and with a cross street occurring every 1.24 mi (2 km), and two small hills that were both 20.34-ft (6.2-m) high and that were 0.68 mi (1.1 km) & 2.73 mi (4.4 km) from the start. In addition, in order to produce more lane departures than normal, without informing subjects, we used a lane width of 10 ft (3.05 m) instead of the US standard 12 ft (3.66 m).

As in the first experiment, while the participants drove the route they passed a number of vehicles that were on their side of road, that were all stationary, and that were either half in lane or just out of lane. There were also a number of vehicles in the opposing lane that were either in lane or half in lane.

For this experiment the route was completely snow covered. As a result, although the visibility was set at 295.3 ft (90 m)—which is near the center of the visibility range that Hawkins (1988) defines as "thick fog" (this range is 164.0 ft (50 m) to 492.1 ft (150 m)]—the combination with snow cover made it appear much worse.

4.2 Results

As with the first experiment, there is only room to briefly summarize the results of the second experiment.

When the participants drove the experimental route without lane markings or any lane departure warnings, we discovered that no participant could stay on the course—even driving as slowly as 5 mph (8.05 km/h).

We also found that the speed at which the participants drove the route increased from trial to trial—across the different warning conditions (which had been randomized in a counter-balanced fashion).

The duration of the lane departure was used to determine the effect of variations in the way lane departure warnings were delivered. Again, these data were highly positively skewed, and we used a logarithmic transform to normalize then. As can be seen in Figures 1 and 2, when a lane departure warning was given, the lane departures were of shorter duration.

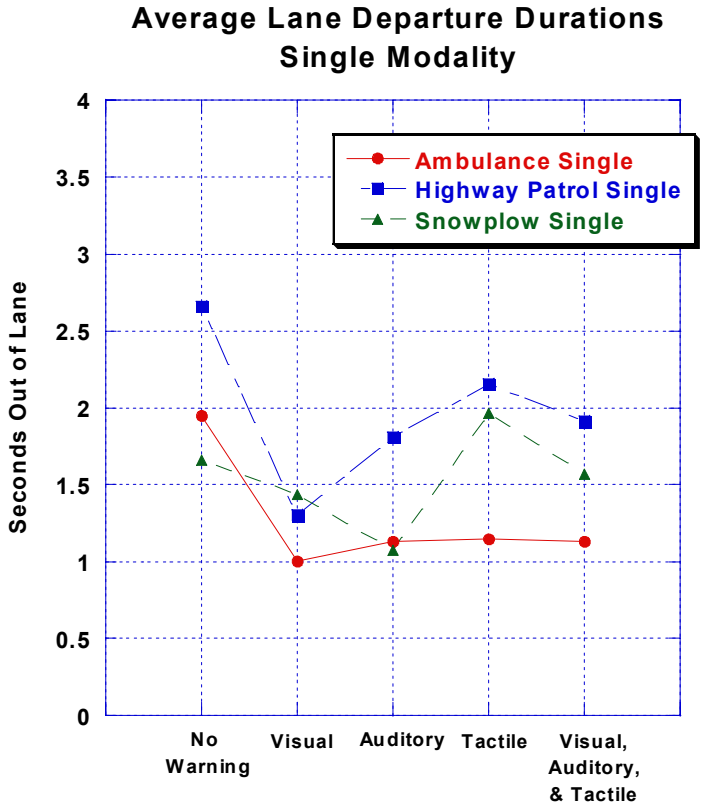

Figure 1: Mean (antilog of mean log) lane departure duration for the snowplow operators, ambulance drivers, and state highway troopers who received single-modality warnings, as well as the triple-modality warning and the no-warning condition. [Numerical Key—Warning #1=No-warning condition; Warning #2=Visual warning; Warning #3=Auditory warning; Warning #4=Tactile warning; Warning #8=Visual plus auditory plus tactile warning.]

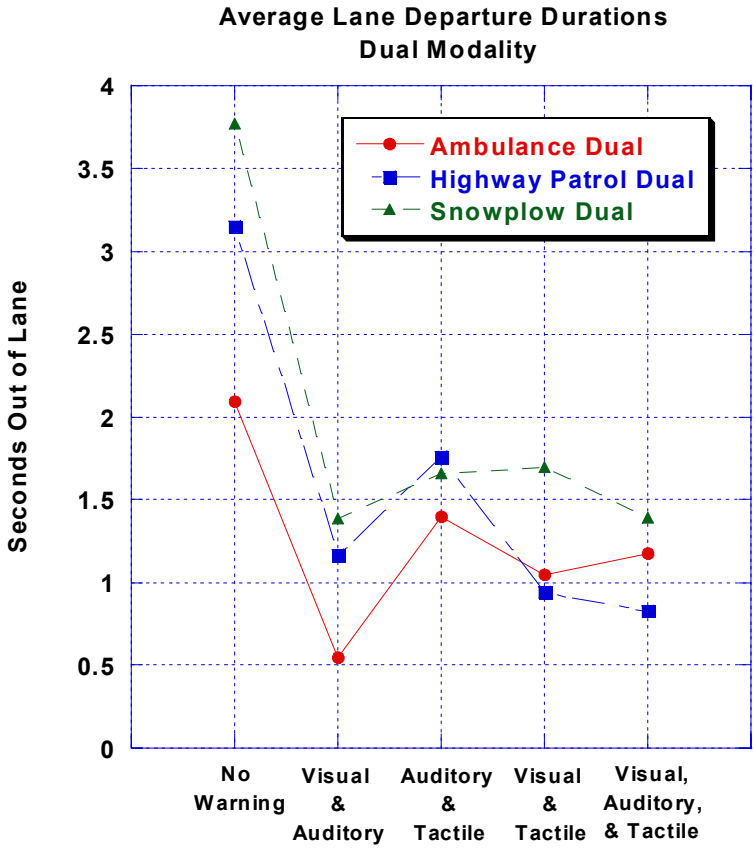

Figure 2: Mean (antilog of mean log) lane departure duration for the snowplow operators, ambulance drivers, and state highway troopers who received single-modality warnings, as well as the triple-modality warning and the no-warning condition. [Numerical Key—Warning #1=No-warning condition; Warning #5=Visual plus auditory warning; Warning #6=Auditory plus tactile warning; Warning #7=Tactile plus visual warning; Warning #8=Visual plus auditory plus tactile warning.]

Although we did not vary the collision warning conditions in this experiment—instead, the color of the rectangular outline indicating the presence of a vehicle ahead always changed as soon as the time to coincidence dropped to 3 s—we still examined the driving performance during the last 350-ft (106.7-m) before the participants reached that vehicle. The percentage of steering responses that occurred for each group of specialty operators is shown in Table 1. For comparison purposes, the table includes data from the participants in the first experiment—i.e., from members of the general public. The table shows that all three groups of specialty vehicle operators had a very high percentage of steering avoidance responses.

Type of operator	Percent of steering responses
Snowplow operators	92.9 %
State highway troopers	92.3 %
Ambulance drivers	99.0%
All specialty vehicle operators	94.3%
Subjects in experiment #1 (general public)	83 %

Table 1: The percentage of steering responses for the three groups of specialty operators (individually and combined) in experiment #2, and for the subjects in experiment #1.

4.3 Warnings selected

As with the first experiment, the results indicated that giving a lane departure warning was better than not providing a warning—but also that it made little difference what modality or combination of modalities was used. However, in their responses to a post-experimental questionnaire, the operators indicated that they preferred the triple modality warning.

As a result of the two simulator experiments reported here, the triple modality lane departure warning and the single step collision avoidance warning, in which the white outline changes from white to red as soon as the time to coincidence dropped to 3 s, were used in the subsequent field test [described in the next paper in these proceedings (Bloomfield and Harder, these proceedings)].

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APPENDIX C

Using a Head-Up Display in Poor Visibility Conditions II: Knowledge Acquisition from Unstructured Interviews in a Field Study.

John Bloomfield and Kathleen Harder

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Amsterdam, Holland: Elsevier Science Publishers B.V.

USING A HEAD-UP DISPLAY IN POOR VISIBILITY CONDITIONS II: KNOWLEDGE ACQUISITION FROM UNSTRUCTURED INTERVIEWS IN A FIELD STUDY

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1. INTRODUCTION

Harder, Bloomfield and Chihak (2001) describe how a number of technologies—including the Differential Global Positioning System (DGPS), digital geo-spatial databases, and forward-looking radar—have been integrated into a single Driver Assist System. The system is capable of presenting virtual roadway information on a Head-Up Display mounted in front of the driver. It is designed to aid specialty platform drivers—i.e., snowplow operators, ambulance drivers, and highway patrol officers—faced with low visibility conditions caused by snow, dense fog or driving rain.

To explore human factors issues associated with the Driver Assist System, we adopted the back-to-back research strategy, suggested by Gopher and Sanders (1984). First, two laboratory experiments that were conducted using a wraparound driving simulator—these are described by Harder et al. (2001). Subsequently, we conducted the field test reported in this paper.

For the field test, our objectives were to determine whether experienced snowplow operators could drive on real roads in conditions of zero visibility using integrated system tested in simulator experiments, and whether they were comfortable with system.

The snowplow that we used in the field test is shown in Figure 1. It was equipped with a Head-Up Display, a Differential Global Positioning System, and digital geo-spatial databases. The aerial used for satellite transmissions can be seen on top of the vehicle in the figure.

2. FIELD TEST

2.1 Environmental conditions for the field test

The field test was conducted on roads within the University of Minnesota's test facility at Rosemount in December 2000 and January 2001. It was conducted after the first snows of the season. Throughout the test, the temperature varied between 30 deg F (minus 1 deg C) and minus 18 deg F (minus 28 deg C), with wind chills as low as minus 50 deg F (minus 46 deg C). Consequently, a mixture of ice and snow covered the 4.5-mile (7.2-km) long course throughout the study. However, there were no test drives when it was actually snowing. If necessary, the

track was plowed at start of each day. It should also be noted that the plow was not mounted during the test runs.

Figure 1. Snowplow equipped with Driver Assist System at Rosemount Test Site. The aerial used for satellite transmissions can be seen on top of the vehicle's cab

2.3 Layout of test course

A schematic of the test course is shown in Figure 2. The test course was essentially in three sections. For the first section of the test track—between Checkpoint #1 and Checkpoint #3—the roadway was two-lanes wide. For the second section of the test track—between Checkpoint #3 and Checkpoint #5—it was three-lanes wide. And for the third section—between Checkpoint #5 and Checkpoint #6—it was only one-lane wide. In all three sections of the test track the surface of the roadway was gravel.

Test personnel were located at the six checkpoints shown in Figure 2 in order to prevent other vehicles from entering the track while a test drive was in progress. At five of the checkpoints (#1, #2, #3, #5 and #6) there were intersections, while at Checkpoint #4 there was a frequently used driveway.

The test drive began at Checkpoint #1. At Checkpoint #2, the road curved to the left. At Checkpoint #3, there was an approximately 120-degree oblique left turn. At Checkpoint #5 there was a 90-degree turn. Between Checkpoint #5 and Checkpoint #6, there were two 90-degree turns—the first to the left, the second to the right. Checkpoint #6 marked the end of the test.

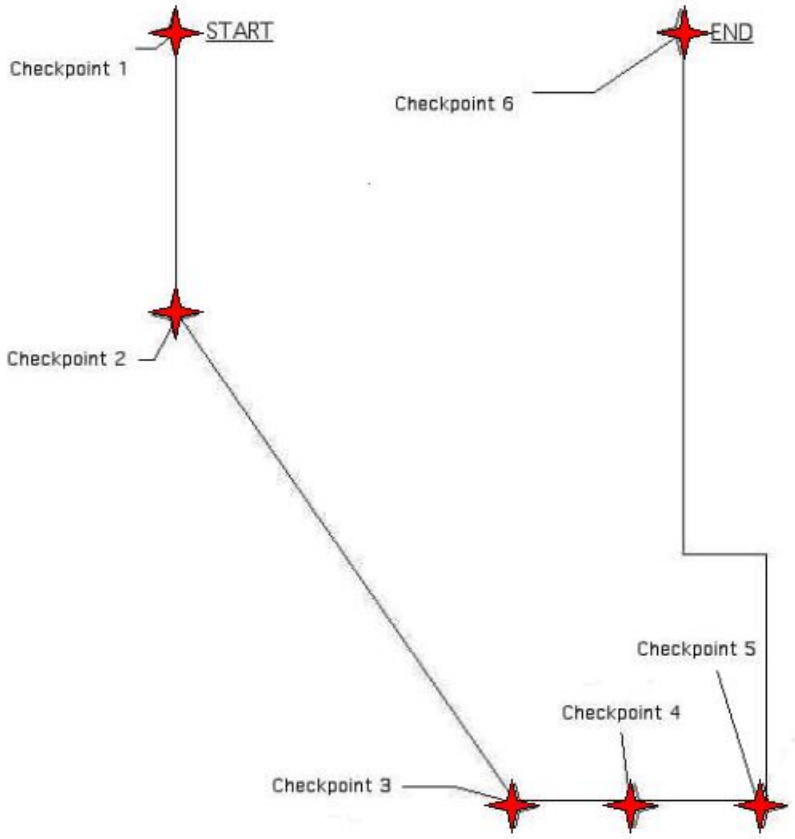

Figure 2: Schematic of the test track showing traffic control checkpoints.

3. PARTICIPANTS

The participants were 13 snowplow operators—ten male, three female. All had been snowplow operators for at least two years. They came from different regions—some plow urban areas, others plow exposed rural areas where whiteouts occur more often.

4. METHOD

Each session was treated as a knowledge acquisition session. The method we used that essentially inverted the knowledge acquisition task manipulation technique used by Bloomfield, Shalin & Corwin (1991). Bloomfield et al. extracted knowledge from highly experienced commercial airline pilots who, during a simulated flight, had their view of their flying instruments occluded, but were given an unobstructed view of the outside world through their cockpit windshield. Here, in the field test, we allowed the snowplow operators full access to their instruments—including the Head-Up display—but completely obscured their view of the

outside world, and our questions focused on the snowplow operators' opinions of new technology. We installed curtains inside the cab to obscure their view. Figure 3 is a photograph taken over the shoulder of an operator. It shows the Head-Up Display and the white curtain that obscured the outside world.

Figure 3. Interior view of snowplow—taken over the shoulder of an operator. The figure shows the Head-Up Display directly in front of the curtains used to occlude the view through the windshield. The projection display used to provide the image seen on the Head-Up Display is in the upper right foreground of the picture

Figure 4 shows a side-on view of the snowplow cab from below. The Head-Up Display is directly above the steering wheel. The projection display that provides the imagery for the Head-Up Display is shown above and to the left of the driver's seat.

Each operator drove around the test course five times. In the first drive, the operator could see out of windshield. In addition, he or she used the Head-Up Display, while the Driver Assist System also presented simultaneously visual, auditory, tactile lane departure warnings.

For the remaining four drives around the test course, the operator drove with zero visibility—the windshield and side windows were covered with opaque white curtains. [For safety reasons, the experimenter in the passenger seat could see out and could alert the operator in case of emergency.]

For the second and third test drives, in addition to the outside world being obscured, the operator used the Head-Up Display, and the Driver Assist System also presented simultaneously visual, auditory, tactile lane departure warnings.

Figure 4. Interior view of snowplow—taken from doorway. The figure shows the Head-Up Display above the steering wheel, and the projection display up and to the left of the driver's seat.

For the fourth and fifth test drives, in addition to the outside world being obscured, using the Head-Up Display, and having simultaneously- presented visual, auditory, tactile lane departure warnings, collision avoidance warnings were used.

5. RESULTS

The first, and perhaps, most important result of the field test was that all of the operators were able to drive in zero visibility conditions using only the Head-Up Display and the simultaneously-presented lane warnings (the binomial test showed that this finding was statistically significant at $p<0.00001$ level).

Sometimes when new technologies are developed there are unintended consequences. On the 120-deg turn between Checkpoints #1 and #3, and the three subsequent 90-deg turns, the lane-markings were not shown on the Head-Up Display—this is because the view provided by the

Head-Up Display coincides with the normal view through windshield, and because *all drivers* when they negotiate sharp turns have to look through the side windows. In spite of having *no* outside view of the world and *no* lane information on the Head-Up Display, the operators were actually able to negotiate these turns. It was possible to drive a snowplow around turns as sharp as 90 deg by driving very slowly (i.e., at 3 mph, or less) and using the combined auditory/tactile warning as a turn advisory ($p<0.00001$—binomial test).

The operators also thought that the Driver Assist System was useful ($p<0.006$—binomial test). The operators who had experience in the more rural (and exposed) areas in Western Minnesota thought the Driver Assist System would be useful if is deployed in their snowplows. The operators who had experience in urban (Twin Cities) area rarely experience whiteout conditions.

With regard to the simultaneously-presented lane departure warnings—(1) in general, the operators said that they found them to be useful; (2) the red-line visual warning was useful; (3) the auditory & tactile warnings perceived by most operators as a single perceptual unit (probably because of their similar oscillatory quality).

With regard to the collision avoidance warnings—(1) for safety reasons only virtual objects were used; (2) the operators liked color change as warning; but (3) they thought that the warning time was too short—given the inertial characteristics of snowplows.

6. FUTURE WORK

The next step in the development of the Driver Assist System is a Field Operational Test that is planned for the winter of 2001-2002. It will involve six fully equipped vehicles—four snowplows, one ambulance, and one highway patrol vehicle. Each will have the Head-Up Display with lane markings, with the three simultaneously presented visual, auditory, and tactile lane departure warnings. Collision avoidance warning will be given when the snowplow is 6 s away from a vehicle ahead—and when the ambulance or highway patrol vehicle is 3 s away. Also, for the Field Operational Test to be successful a heavier snowfall will be needed than there has been in recent years.

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APPENDIX D

Visibility Study

By

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1. Needs for Visibility Assessment in Highway 7 Project

The purpose of the Field Operational Test was to evaluate how much the proposed driver assistive system improves the driver's navigation under real-world low-visibility working conditions. In order to document and quantify how effective the proposed system was, visibilities along with relevant weather conditions were recorded using weather sensors and video cameras during the test period. This document describes the overall system and methods of assessing the visibility conditions.

2. Background on Visibility and MRVI

According to the American Meteorological Society's definition [1], visibility is defined as the farthest distance from an observer where a reasonable size of an object can be identified by bare eye. At night, a known, preferably unfocused, moderately intense light source is placed as the visibility target of recognition. These visibility definitions, although not complicated, present inherent difficulties in actual measurements due to a number of ambiguities. Those include the size and shape of the targets, the light intensities for night targets, the air light intensities of the observing area, the observer's angle to the target, the height of the observation point, and most importantly the requirement that visibility targets be both detected and recognized. These ambiguities were somewhat reduced, since the Middleton's suggestion of the term "visual range" which was defined for daytime as the subjective estimates of atmospheric attenuation of contrast, and for nighttime as the attenuation of flux density [2]. In the Middleton's definition of visual range, the recognition portion of visibility was dropped, from which observer's visual acuity and judgments are no longer an issue. Further narrow definitions of visual ranges were introduced to limit the scope of applications, such as runway visual range, slant visual range, meteorological visual range, etc [3]. Today, the terms "visibility" and "visual range" are almost interchangeably used with the tendency that visual range is more preferably used by scientists and engineers and visibility is more frequently used by non-scientists. In recent Federal Meteorological Handbook No. 1 published by the National Weather Service, the term visibility is still in use and defined as a measurement of the opacity of the atmosphere, and the handbook suggests observation of four different types of visibilities, i.e., prevailing visibility, sector visibility, surface visibility, and tower visibility [5].

Although many types of visibility concepts have been developed as described above, when the term "visibility" is referenced to describe weather conditions, it commonly means the definition, meteorological visual range (MVR), which is typically measured using light-scatter effects of the atmospheric particles in modern days [9,10]. MVR is usually consistent whether it is day or night as long as the density and distribution of the atmospheric particles are the same. Modulated light sources in the transceivers limit measurement influences by air light conditions. Most commercial visibility meters employ a forward light-scatter principle (backward scattering effect is known less accurate), which facilitates a compact sensor design and easy installation for roadside applications [10]. For this Highway 7 project, commercial MVR (forward light-scatter)

sensors specifically designed for highways were installed along the roadside of the test area. Additional weather sensors (i.e., wind direction, wind speed, humidity, and temperature) were installed to augment further details on weather related conditions.

Although the MVR sensor provides data on visibility in a meteorological sense, it alone does not fully describe the visual difficulties motorists experience on the road. For example, visual information is significantly reduced at night and causes driving difficulties; on the other hand, the MVR may indicate a high visibility reading. Similarly, driving against direct sunlight severely limits visual information and thus creating severe driving difficulties. On the other hand, MVR on any sunny days will indicate a very high visibility reading. Another shortcoming of MVR sensors is that it only measures a single spot, so that it cannot effectively represent the space variant nature of visibility. Under any snowstorm, non-uniform distribution of visibility can be easily observed, which clearly indicates that visibility is severely space variant. It was also observed by researchers and practitioners that, during a typical winter storm, atmospheric visibility near the road surface (up to 2 meters) is significantly lower than at a higher elevation due to the snow clouds and drifting snow generated by vehicles and wind [6-8]. However, installing MVR sensors at frequent locations in order to remedy the space variant nature of visibility is prohibitively expensive and not practical. In many cases, dense implementation of MVR sensors is simply not possible even if the cost problem can be solved, because of unavailability of horizontal and vertical spaces on the road. Therefore, there is a need for additional sensors that can capture visual information similar to the effect of motorists experience on the road. For this purpose, color video cameras were installed inside each vehicle in a forward-looking direction to record the information that motorists see in the vehicle heading direction. Video images were continuously recorded throughout the test period and digitally compressed and archived for later reviews and analysis.

Video images recorded provide a detailed view on what the drivers visually experienced during the test period, and thus it is critically important part of the field-test data. However, due to the huge amount of video data, it is very difficult to manually review the entire video images and analyze the driving conditions. As an innovative approach, a new indicator called the **Motorist's Relative Visual Range Index (MRVI)** was introduced in this project, and the computational methods have been developed. MRVI concept is briefly described here. The computation of MRVI is performed based on loss of visibility information relative to an image taken under an ideal weather condition (clear day with no large obstruction of view). MRVI is then normalized to a ranging between zero and one, representing the degree of how close the visual condition is to the ideal condition. MRVI becomes zero when no visual information is available, e.g., total white or black out conditions; MRVI becomes one when the present condition is identical or above to the ideal reference condition. As visual condition improves (or moves) towards the ideal condition, the index increases.

With the introduction of MRVI, how the visual conditions were changed during the trip can be plotted. The plot then can be used for identifying segments of roads that had low visibility. Such sections should be inspected by human operators for further analyses. However, it should be cautioned that MRVI would not be able to perfectly estimate or represent human perception. MRVI is simply an index computed using known image features that contribute towards visibility effects. Human perception is very sophisticated, and no single numerical value

would be able to replace or quantify it. Therefore, it is advised that MRVI should be understood as a mathematical definition that will be presented in Section 4 instead of replacement of human perception or inspection. One should expect MRVI with about 20% of error rate and possible failures in some cases.

3. Overall Visibility System

The overall visibility system consists of instrumentations that are required to measure the following two components based on the background discussed in Section 2:

- meteorological atmospheric conditions: meteorological visual range (MVR), precipitation type/intensity, air temperature, humidity, and wind direction/speed.
- motorist's view of the road condition: forward-looking video images and MRVI.

Figure 1 shows the overall system block diagram. The in-vehicle video camera continuously records digitized video images (compressed as jpeg format) along with the location the vehicle traveled. The recorded video data is then downloaded from the in-vehicle computer and archived into the main Highway 7 Field Operational Test Data archive. Since MRVI is only used for analysis, it is computed off-line by retrieving the video data from the main archive. MVR and weather sensor data are collected through a data acquisition server that polls the weather stations in a predetermined interval, which are archived into the main archive.

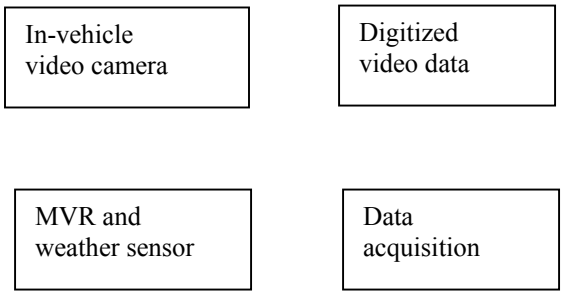

Figure 1: Overall visibility system block diagram