Development of a
Maintenance Decision Support System

SD2002-18 Phase II Interim Report

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16. Abstract

This report is a summary of the work done during the second year of a multi-year pooled fund study of the Departments of Transportation in South Dakota, North Dakota, Minnesota, Indiana, Iowa, and Colorado. The South Dakota DOT was the lead agency. The intent of the complete project is to develop and deploy a maintenance decision support system (MDSS) for transportation department personnel who deal with winter maintenance.

This report addresses Phase II of the project, which incorporates the lessons learned in the development and execution of the Limited Deployment Tactical Integration test to design and build software to support an MDSS demonstration test.

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PURPOSE OF STUDY

The purpose of this study was to develop a system capable of integrating accurate weather forecasts, road condition reports, and maintenance resource information so proactive maintenance decisions can be made before and during adverse weather events, resulting in a higher level of service, reduced operational costs, and safer highway conditions.

OBJECTIVES

The objectives of the MDSS study were to:

- Assess the need for, potential benefit of, and receptivity to MDSS concepts in participating state transportation departments

- Define functional and user requirements for an operational MDSS

- Build and evaluate an operational MDSS

- Improve the ability to forecast road conditions

The primary focus of Phase II was the development and evaluation of an operational MDSS.

RESEARCH TASKS

This project report represents the concerted efforts of the Maintenance Decision Support System (MDSS) Pooled Fund Study (PFS), which is a partnership between the states of Colorado, Indiana, Iowa, Minnesota, North Dakota and South Dakota and Meridian Environmental Technology Inc. (Meridian), during Phase II work accomplished between January 2004, and November 2004. The State of South Dakota serves as the lead state in the Pooled Fund Study project.

The original multi-year plan MDSS research plan outlined fourteen primary tasks. The Phase I Research Plan addressed some or all of the requirements in seven of these fourteen tasks:

- Task 1: Define project scope and research plan

- Task 2: Evaluate the FHWA Functional Prototype

- Task 3: Interview maintenance personnel to improve understanding of maintenance needs

- Task 4: Evaluate state communications, networking, and data processing environments

- Task 5: Assess institutional receptivity

- Task 6: Propose an architecture for the MDSS

- Task 10: Identify research requirements to support MDSS

Phase I of the research project was completed in December of 2003. The reader is referred to the SD2002-18 Phase I Final Report for further background information.

Phase II of the PFS MDSS Research Plan was initiated in January of 2004. The Phase II Research Plan continued to address Tasks 3, 4, and 10 from above, plus:

- Task 7: Construct a limited-deployment prototype MDSS

- Task 8: Prepare a plan for the deployment and evaluation of the prototype MDSS

- Task 9: Deploy the prototype and evaluate its performance under 2003-2004 winter conditions

- Task 11: Recommend modifications and identify limitations requiring additional research

- Task 12: Make improvements and deploy improved prototype MDSS during winter 2004-2005

SIGNIFICANT FINDINGS

The following paragraphs summarize the significant findings from these tasks.

TASK 3: EXPAND MDSS KNOWLEDGE BASE

The definition and characterization of road segments will have substantial impact on the evolution of an MDSS solution. Maintenance operations must respond to different road conditions on distinct stretches of road, conditions induced by the road's differential response to weather and environmental factors. But the response scheme not only depends upon the field conditions but also on operational resource capabilities. A major part of the operational decision is driven by available resources (equipment, materials, and personnel) both along specified routes and as part of a network of routes within a single agency's jurisdiction. Existing maintenance response patterns are complex and form a distinct component of the broader decision process. The unique maintenance activity for a specific segment of highway must consider these broader operational requirements.

TASK 4: STATES' PROCESSING AND COMMUNICATIONS CAPABILITIES

The IT departments in the member states each have unique processing and security requirements. Initial discussions during the Technical Panel meetings indicated that most of the member states used a centralized processing program such as Citrix to handle client-based applications. During implementation of the client-based PFS MDSS program, Meridian has found that only South Dakota will utilize Citrix to support the MDSS program. Technical Panel members and/or the IT groups within the member states not running Citrix will take responsibility to see that the test software and updates are maintained on users' computers.

Maintenance data collection is in its infancy in most states. Collection techniques are highly dependent upon communications options; therefore, the communications infrastructure within a state will be instrumental in the maturation of this technology. Currently, states are solving communications requirements on a case-by-case basis. The expansion of the maintenance data collection process will require significant planning and development of communications capabilities able to meet the data transfer requirements of the maintenance data collection component of MDSS.

TASK 7–9: LIMITED DEPLOYMENT TACTICAL INTEGRATION TEST

Interactions between DOT participants and the Meridian trainers proved to be a valuable extension of the Phase I process, since discussions regarding specific maintenance operations generated detailed interactions regarding maintenance practices. The test demonstrated that additional work was needed to:

- resolve segmentation issues;
- provide more automated maintenance data collection techniques;
- create a more user-friendly user interface;
- improve the accuracy of the meteorological forecasts; and,
- adjust the processing and presentation of a few inconsistencies in the MDSS software

TASK 10–11: RESEARCH

An extensive list of research requirements needed to support the MDSS effort was presented in Phase I. A considerable amount of code from research findings was integrated into the PFS MDSS application during Phase II. Evaluation of this code becomes an important part of the Demonstration Test. The changes will not be directly evident to DOT users, but their presence will be noticed by the performance of the MDSS application. Key research elements included in the Version 1.0 release include an array of chemical options; latent heat exchanges associated with chemical applications; the effects of traffic on the contaminant layer; a more detailed analysis of frost; the interaction of frost with pavement surfaces; the characteristics of ice bonding to pavement surfaces; and heat balance relationships associated with the balance of long wave radiation.

TASK 12: SOFTWARE DESIGN AND IMPLEMENTATION

The primary activity during Phase II was the development of an operational PFS MDSS application as part of the LDTI test and in preparation for the Demonstration Test. The development effort focused on all critical components of the PFS MDSS design to include:

- the input and integration of observed and forecasted weather information;
- the generation of road condition analyses and forecasts with the incorporation of the effects of chemicals, abrasives, and plowing actions;
- the input and integration of maintenance actions transmitted by field personnel;
- the generation of the recommended maintenance responses based upon available maintenance resource options, projected pavement conditions induced by the weather, and local operational constraints; and,
- a user interface that permits exceptional flexibility and capability.

The Graphical User Interface provides an extensive set of tools that may be tailored to suit the needs of a user community with a broad spectrum of capabilities. It may be customized to provide two or three key displays for those not comfortable with computers or to permit a full complement of capabilities for the power user

CONCLUSIONS

Phase II is a transition from the assessment phase of the PFS MDSS research effort to a demonstration of an operational decision support system. The Limited Deployment Tactical Integration test demonstrated that the detailed processing capabilities of the Road Condition Forecast and Analysis component of MDSS could provide route specific information reflecting road conditions associated with maintenance actions performed and input by test participants. The Meridian development team addressed the limitations found in the LDTI test and greatly expanded the client side user interface. Version 1.0 of the PFS MDSS represents the result of this development effort. The objective of transitioning from concept to an operational prototype has been accomplished. The next phase is to implement and evaluate the performance of the PFS MDSS solution.

RECOMMENDATIONS

Based on the findings and conclusions of this study, the researchers recommend the following to the PFS member states:

- a full evaluation of the performance of the PFS MDSS application during the winter of 2004–2005's Demonstration Field Test for Year One (DFT-1);

- the continued development of maintenance data collection methods that merge with the processing requirements of the PFS MDSS;

- the development of a presentation format that integrates the scientific components of MDSS into an expression that is more meaningful to maintenance personnel;

- that the MDSS program test new forecasting techniques that offer the potential to improve the accuracy of the forecast; and,

- the continued integration and testing of scientific and technological approaches to improve the capability of the PFS MDSS.

PROBLEM DESCRIPTION

Numerous agencies involved in highway maintenance activities have realized the benefits of Road Weather Information Systems (RWIS), but have also seen the limitations of these systems in the operational support of maintenance activities. The primary limitations have been:

- Data presentations in a scientific format rather than in terms maintainers understand;

- The requirement for maintenance personnel to interpret additional weather-related data as part of their decision process;

- The need to interpolate point-specific observations into route-specific estimates; and

- The lack of a mechanism to transfer RWIS observations and pavement specific forecasts into actual maintenance practices.

Presentations of pavement-specific information from RWIS are in scientific terminology foreign to many maintenance personnel. Plus, a number of the observed values are valid in certain conditions but are incorrect in others. It requires a thorough understanding of the measurement process and existing conditions to assess whether the numbers visible on the user interface are realistic. Maintenance personnel typically don't have the time or the inclination to assess whether the current set of readings are valid. Furthermore, many of today's weather-related winter maintenance issues occur in areas or timeframes that are different from the point-specific RWIS observations. Thus, maintenance personnel must decide what treatments to apply and when to apply them, based upon imperfect knowledge of current pavement conditions, current and forecast weather conditions, and available maintenance techniques and resources. In large part, these decisions are presently guided by the prior experience of maintenance personnel and supervisors.

To overcome these deficiencies and improve the overall effectiveness of winter maintenance operations, new solutions must be developed that take better advantage of all data available and that apply sophisticated scientific methods to improve the analysis and forecasting of weather and pavement conditions as well as the application of those improvements in the decision making framework. The challenge is to identify new methods of problem solving associated with winter maintenance and to develop, test and implement these methods for improved operational capabilities. Hence, the challenge of developing a Maintenance Decision Support System is to provide a more effective and efficient maintenance effort.

One of the biggest challenges of deploying a Maintenance Decision Support System is to overcome the inertia of existing maintenance programs. Prior experience of maintenance personnel creates practices that are the most successful approaches discovered by maintainers using the knowledge and data available. However, research indicates that there may often be more effective approaches to winter maintenance available at substantially reduced resource costs. Many of these approaches seem counter-intuitive to today's maintainers because of a general lack of understanding of the complex interactions that occur atop the road. Appropriate combinations of human experience, scientific understanding, and high-performance computing must be used to produce various scenarios that, when made available to maintenance supervisors in an effective decision support framework, will improve decision-making.

STUDY OBJECTIVES

The objectives of the MDSS study are to:

- Assess the need for, potential benefit of, and receptivity to MDSS concepts in participating state transportation departments.

- Define functional and user requirements for an operational MDSS that can assess current road and weather conditions, forecast weather that will affect transportation routes, predict how road conditions will change in response to candidate maintenance treatments, suggest optimal maintenance strategies to maintenance personnel, and evaluate the effectiveness of maintenance treatments that are applied.

- Build and evaluate an operational MDSS that will meet the defined functional requirements in the participating state transportation departments.

- Improve the ability to forecast road conditions in response to changing weather and applied maintenance treatments.

The primary focus of Phase II was the third objective, the development and evaluation of an operational MDSS, but efforts were directed toward the achievement of all four objectives in this phase.

TASK DESCRIPTION

This section describes the efforts associated with the Tasks emphasized in Phase II of the SD2002-18 project.

TASK 3: EXPAND MDSS KNOWLEDGE BASE

Expand the knowledge base on maintenance needs to support MDSS.

This is an ongoing task continued from Phase I of the research project. During Phase I, a series of face-to-face interviews with winter maintenance personnel within the PFS member states was performed. In addition, a survey was developed and distributed to a large sampling of DOT winter maintenance personnel in the participating states. The information gathered in this process was instrumental in guiding the initial design of the PFS MDSS. However, a need for much greater understanding of the needs of maintenance personnel existed in order to further develop and refine the MDSS software. The overall goals of this task were to extend the knowledge base started in Phase I and to develop a sustained dialog between the MDSS PFS developers and field participants.

The Limited Deployment Tactical Integration (LDTI) training sessions executed at the start of the winter test were the first formal efforts to extend the information gathering process commenced in the Phase I Interview sessions. One of the key components of the LDTI test was the collection of field information by route. To implement the collection and display component of the LDTI, it was necessary to confirm detailed information about the test routes, the assignment of equipment and personnel, the route itinerary, and unique characteristics of each route. The new information was gathered from the 10 training sessions and added to the needs requirements document.

After assessing that this approach was not totally effective, the general consensus was that the acquisition of route information for the Demonstration Field Test for 2004–05 would be best carried out in the form of a detailed questionnaire distributed to a select group of test participants and followed up with phone calls. It was decided that the initial survey would seek to address at least some of the following focus areas:

- level of service
- materials
- equipment
- road reporting
- scheduling
- weather information resources
- winter scenarios
- decision time spectrum

A rudimentary question set for each of these categories had been constructed as part of the Phase I interview process, and provided the basis upon which a new detailed maintenance information

Your Contact Information	Name	Work Phone	Cell Phone	E-Mail Address	Garage / Shop

State: (Select State)	Route:	# of Segments in Route:	
Segment #1 Identification	Highway Information	Hwy. #:	Description:
	Begin Location	Mile Marker:	Latitude: Longitude:
	End Location	Mile Marker:	Latitude: Longitude:
	Lane Information	# of Lanes: 2 Lane Treated: (Select Lane) Lane Width:	
	Average Daily Traffic	Total: Truck:	
	Segment Traversal Time	hours minutes	
Segment #1 Pavement Structure	Pavement Layer	Material	Thickness (inches)
	1 (Top)	(Select Material Type)	
	2	(Select Material Type)	
	3	(Select Material Type)	
	4	(Select Material Type)	
	Subgrade	(Select Subgrade Type)	
Segment #8 Identification	Highway Information	Hwy. #:	Description:
	Begin Location	Mile Marker:	Latitude: Longitude:
	End Location	Mile Marker:	Latitude: Longitude:
	Lane Information	# of Lanes: 2 Lane Treated: (Select Lane) Lane Width:	
	Average Daily Traffic	Total: Truck:	
	Segment Traversal Time	hours minutes	
Segment #8 Pavement Structure	Pavement Layer	Material	Thickness (inches)
	1 (Top)	(Select Material Type)	
	2	(Select Material Type)	
	3	(Select Material Type)	
	4	(Select Material Type)	
	Subgrade	(Select Subgrade Type)	

Figure 1: Contact and Route Information Form

questionnaire was constructed. The focus of the questionnaire was information needed to support the winter demonstration field test of the MDSS. The initial form was directed toward gathering a core set of information needed to operate the MDSS in a forthcoming winter demonstration test. The form was circulated to several members of the Technical Panel as well as a few selected field participants. Based upon the responses, the form was modified and a Frequently Asked Questions (FAQ) section was attached to the end of the form.

This final version of the questionnaire was distributed via e-mail to the project's Technical Panel on October 14, 2004 as an "MDSS Test Route Information Form." The Technical Panel recipients were provided with instructions to redistribute as appropriate to test participants within their individual states.

The form (Figure 1 through Figure 3) requested the following types of information from the respondent:

- contact information;

- route information, including construction, segmentation, traffic, and traversal time information;

- maintenance practices information, including maintenance goals during and after different types of events and information about hours of operation and dead times;

- materials information, including chemicals and mixtures commonly applied, maximum and minimum rates, and unit costs for materials;

- vehicle information, including identification numbers, plow and spreader types, and capacities;

- computing information, including CPU speed, RAM, operating system, and screen resolution.

Maintenance Practices				
	Route Traversal Time (all segments)	hours	minutes	
	Route Cycle Time	hours	minutes	
	Dead Times (if any)			
	Hours of Operation (Normal)			
	Hours of Operation (Heavy Event)			
	Are anti-icing practices used on this route?	YES ☐ NO ☐		
	Specified Service Level Maintenance Goal During an Event for Chemical Application (check only one)	☐	to burn off all ice whenever physically possible	
		☐	to maintain a wet slushy mixture on top of the road that can be plowed off after the event is finished	
		☐	to sustain just enough liquid to prevent ice bonding, to permit effective plowing at the end of the event	
		☐	to maintain the best state possible using only a combination of plowing operations and grit applications	
		☐	Other (please define):	
	Maintenance Goal After a Typical Winter Storm Event is Finished and Little or No Wind is Expected (check only one)	☐	to burn off all ice not removed by the plow whenever possible	
		☐	to prevent refreeze by still allow a shall, slushy mixture on the top of the road that may later be removed by natural processes	
		☐	to maintain the best state possible using only a combination of plowing operations and grit applications	
		☐	Other (please define):	
	Maintenance Goal After a Typical Winter Storm Event is Finished and Moderate to Strong Wind is Expected (check only one)	☐	to burn off all ice not removed by the plow whenever possible	
		☐	to prevent refreeze by still allow a shall, slushy mixture on the top of the road that may later be removed by natural processes	
		☐	to maintain the best state possible using only a combination of plowing operations and grit applications	
		☐	Other (please define):	

Maintenance Materials	Chemical	Grit	Form	% Chemical	Units	Min Rate (units/mile)	Max Rate (units/mile)	Typical Rate (units/mile)	Unit Cost ($ per unit)
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				
	(select type)	☐	(select form)	%	(select units)				

Maintenance Vehicles					
	Primary Truck	Truck ID			
		Plows	☐ One-Way / Rev.	☐ V-Plow	☐ Underbody ☐ Wing
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
	Alternate Truck	Truck ID			
		Plows	☐ One-Way / Rev.	☐ V-Plow	☐ Underbody ☐ Wing
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
	Alternate Truck	Truck ID			
		Plows	☐ One-Way / Rev.	☐ V-Plow	☐ Underbody ☐ Wing
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)
		Spreader	Material Form: (select form)	Capacity:	Units: (select units)

Computing Resources	Operating System (select operating system)	Processor Speed GHz	RAM MB	Monitor Resolution (Select Resolution)	Network Connection Dial-Up

Figure 2: Maintenance Information Form

FAQ Section
Question: What is a 'segment' of a maintenance route? Answer: A segment is defined by a stretch of highway between two natural breakpoints in the maintenance route. In many cases, segments will be defined by turns. For example, a simple out-and-back route would have two segments: "Eastbound on Hwy 19 to Jct Hwy 43, then westbound on Hwy 19 to garage". An out-and-back route that begins at the midway point of the route might have 3 segments: "Eastbound on Hwy 19 to Jct Hwy 43, westbound on Hwy 19 to Jct I-99, then return eastbound on Hwy 19 to garage". An 'L' route would be broken into 4 segments: "Eastbound on Hwy 19 to Jct Hwy 43, south on Hwy 43 to Sometown, back up north on Hwy 43 to Jct Hwy 19, and westbound on Hwy 19 to garage". In other cases even a straight stretch of highway might be broken into two or more segments if there was a significant break in the highway characteristics along that stretch. For example, "Eastbound on Hwy 19 to end of asphalt, continue eastbound on Hwy 19 to Jct 43, westbound on Hwy 19 back to beginning of asphalt, then continue westbound on Hwy 19 to garage." However, I'd encourage you to avoid using this type of segmentation unless it is a major issue for maintenance along the route, as the more segments a route has the more complex the user interface becomes (at least for the initial release).
Question: What if we have more than three maintenance vehicles that operate on this route? Answer: This is a difficult question. The problem isn't so much with the MDSS modeling as it is with the reporting difficulties that come along with this situation. For the demonstration test we'd encourage you limit the number of trucks that participate in the demonstration test on a particular route, then have those trucks consistently work on the same lane(s) of that route and take care of all the reporting. Accepting maintenance reports for multiple lanes of a given test route or too many trucks operating on the same test route is going to make the reporting process more complex for everyone on the simpler routes. We do need to be thinking about how to address these complex routes, however, so we don't necessarily advocate changing a test route just because it is complex. The best advice may be to contact us if you think one of the test routes may present unique difficulties and we'll work through it on a case-by-case basis.
Question: What is 'traversal time', and why is it requested on both a segment and route basis? Answer: Traversal time is the time it takes you to drive the truck from one end of a segment or route to the other during a 'normal' maintenance operation. It is requested on both a segment and whole-route basis in order to check for consistency. In a perfect world the traversal times from all segments on a route would sum up to the traversal time for the route as a whole.
Question: What should we use for the route name and the segment descriptions? Answer: Just use the name or description that makes most sense to you. At a later date we'll likely assign a unique identifier to each segment and route, but we'd still like to know how you refer to it so that you can spot it in menu boxes (for example).

Figure 3: Frequently Asked Questions Segment of Form

Colorado became the sixth member of the MDSS Pooled Fund Study in July 2004. In July and October, Meridian provided introductory training sessions for the new CDOT participants at the two test locations selected by Colorado. The training sessions introduced the background and purpose of the MDSS program and discussed the progress of the program up to Colorado's involvement. The questions used in the interview process in the other five states during Phase I served as the foundation for discussions, and the Meridian trainers initiated the process of collecting maintenance practices documents from CDOT to augment the knowledge base.

TASK 4: ASSESS STATES' PROCESSING AND COMMUNICATIONS CAPABILITIES

Assess the participating states' current and near-term capability to report current roadway conditions and track maintenance activities on specific highway routes.

The primary effort under Task 4 was determination of the processing schemes that were acceptable to each of the Information Technology (IT) departments in the six states. This information was collected from the original five states in the MDSS program to support the final design of the LDTI test. Additional information was collected from IT personnel in Colorado during July and August 2004.

The transfer of maintenance information from the field to the central processing facility was one of the key features of the LDTI. Meridian investigated the resources available in the member states to communicate data. Each state has a slightly different communications infrastructure. The interest was to develop, if possible, a common communication process that can use these existing communications infrastructures. Meridian participated in several discussions with representatives from ThomTech and Iwapi regarding their capabilities to monitor and communicate maintenance data collected on and within maintenance vehicles. Work was done to coordinate the AVL efforts within four of the states with the objectives of the MDSS program in order to facilitate an automated collection of maintenance data to support MDSS processing. Meridian provided guidance on the touch screen menus for the Iwapi in-vehicle, touch screen maintenance data collection systems to be used in Colorado for the 2004–05 MDSS demonstration test and worked with ThomTech in evaluating the wireless transfer of data from data collection loggers on moving vehicles to stationary data receivers adjacent to the highway.

TASK 7: CONSTRUCT PROTOTYPE MDSS

Upon approval of the panel, construct a limited deployment prototype MDSS incorporating those requirements that can be immediately satisfied.

Meridian has been engaged in maintenance weather forecasting and pavement modeling since its inception. As such, Meridian possessed core infrastructure capabilities upon which a limited function MDSS prototype could almost immediately be constructed. Modifications were initiated during Phase I and continued early in Phase II to implement the following enhancements to the Limited Deployment Tactical Integration (LDTI) program:

- The addition of a solution modeling module that could be linked with Meridian's HiCAPS^{TM} pavement model to provide assessments of the effects of freeze point depressants upon the contaminant layer. In the LDTI prototype test this solution modeling capability was limited strictly to NaCl in dry, prewet, or brine form.

- The development of a system for collecting maintenance actions reports from DOT personnel. For the LDTI test a two-pronged approach to maintenance data collection was implemented. First, a web interface was developed that allowed maintenance personnel or radio operators to enter information into the MDSS system via a computer. In addition, a computer-telephony, interactive voice response (IVR) system was developed and deployed that allowed maintenance activities to be reported via a cellular telephone directly from the maintenance vehicle. The conceptual layout of the computer telephony system application is shown below in Figure 4. The information collected via the web interface was similar in nature. In order to maximize the expediency with which maintenance actions could be reported users were allowed to configure their truck, after which each subsequent report required only a truck number, route number, and a single key press to submit. Since the maintenance personnel were also deemed to be a potentially valuable resource for road condition and weather reporting, the menu also contained options for making these types of reports. In addition to being ingested and utilized to support the MDSS processing, the information collected was stored in a database and made available to MDSS test participants via a web interface.

- The development of a module for the LDTI test that permitted users to specify candidate maintenance actions and then view the results expected from those actions. Simulations from this module, termed the "what-if" tool, integrated information on both performed and proposed maintenance activities, observed and expected weather conditions, road condition reports, and RWIS observations in order to simulate the state of the contaminant layer atop the roadway.

- The development of user interfaces to test display and control concepts planned for eventual integration into the client-side Graphical User Interface (GUI) of the PFS MDSS. The interfaces tested in the LDTI were strictly web browser based, primarily because of the short time frame within which the interfaces needed to be deployed. These interfaces included a Geographical Information Systems dynamic mapping and display tool based on the open source Java OpenMap^{TM} application, and a tool for specifying candidate maintenance actions and viewing the results expected from those actions in consideration of past weather conditions and maintenance actions and forecast weather conditions.
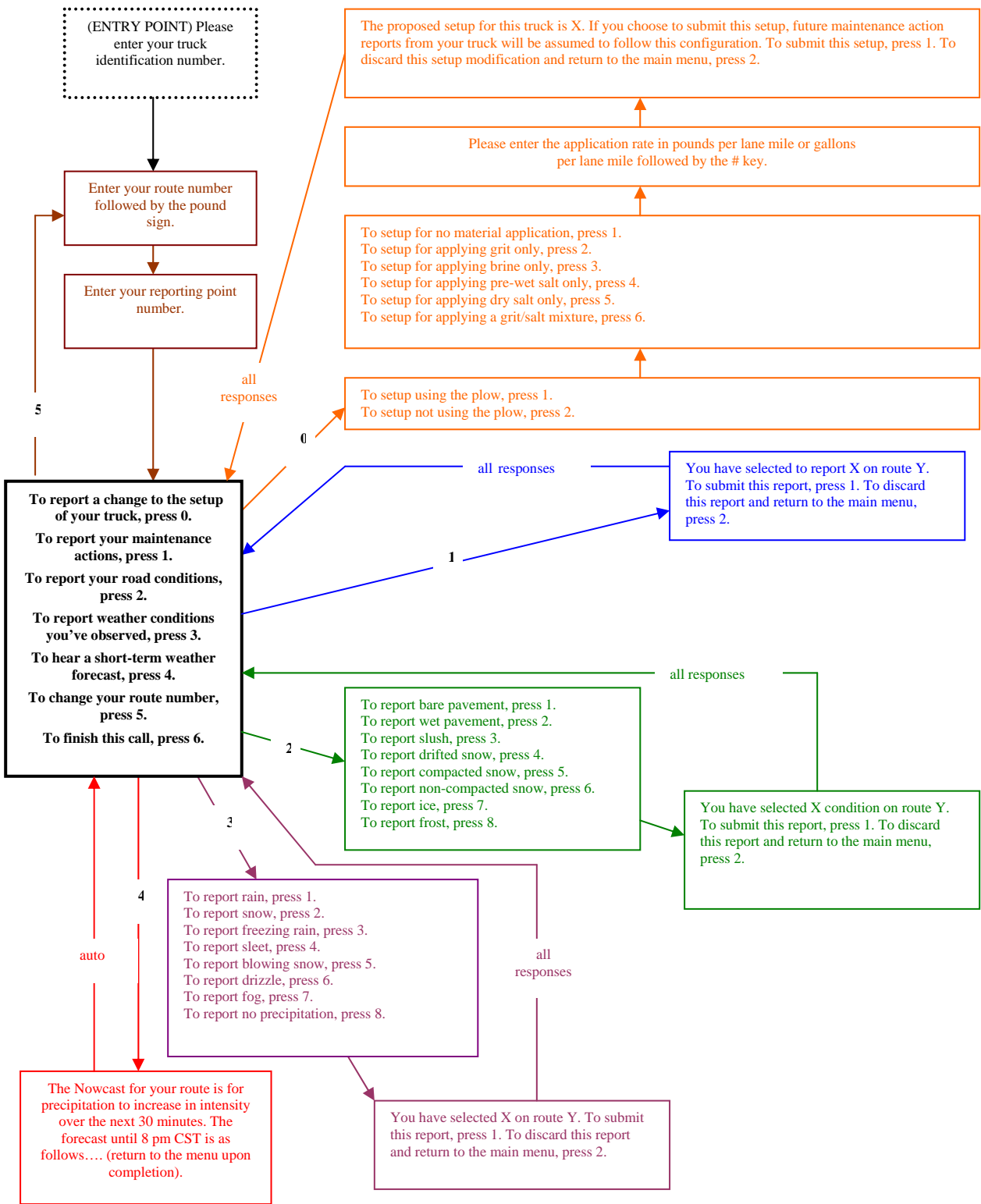
Figure 4: Telephony System Conceptual Layout for the LDTI Test

TASK 8: PREPARE DEPLOYMENT & EVALUATION PLAN

Prepare, for approval of the project's technical panel, a plan for pilot deployment and evaluation of the basic prototype MDSS in a multi-state test region spanning portions of North Dakota, South Dakota, Minnesota, Indiana, and Iowa.

A formal plan was developed to transfer the prototype LDTI test program into an actual demonstration project. The plan addressed the necessary components of the LDTI test and indicated the details necessary to assure the prototype could be successfully deployed in the five member states as well as Colorado, the sixth state. The primary components of the test described in the plan included:

- Level I and Level II tests;
- schedule and duration of the test;
- description of the Interactive Voice Response data collection project;
- the graphical user interface;
- description of the test route in each state;
- the training program;
- contact information;
- support processes for the test.

The formal plan was published and circulated to the Technical Panel on March 3, 2004 as the Limited Deployment Tactical Integration Field Test Implementation Plan. During the subsequent training sessions the route structures and personnel information were clarified further and confirmed for the tests. These modifications became part of the plan.

TASK 9: DEPLOY THE PROTOTYPE MDSS & EVALUATE PERFORMANCE

Upon approval of the technical panel, deploy the basic prototype MDSS in state agency offices in the designated test regions and evaluate its performance in actual winter conditions during 2004.

The LDTI deployment plan was presented formally to the Technical Panel on March 3, 2004 along with the schedule for the LDTI test and the agreed times for the training in each of the states. During this meeting the graphical user interface for the LDTI test was unveiled and used for a live demonstration. The test was defined as fully operational on March 10, although Meridian commenced training in Indiana on March 8 using a version of the LDTI software which contained all but a couple of the remaining modifications. Meridian used four trainers to complete the training at 10 sites in the five states. The training took roughly a week and a half with the last training occurring in Fergus Falls, MN on March 19. The training sessions were designed to provide an overview of the LDTI test program and to explain the mechanics of entering field information into the LDTI decision support system. The sessions also provided guidance on the graphical user interface and the presentation formats designed for LDTI. Each session demonstrated the actual input of maintenance information for a local route and the display of the maintenance information that was just entered. On March 10, a minor weather event occurred over the Monticello, Indiana site and the LDTI display screens during that event were captured and put into a

PowerPoint presentation. This example was used at all of the subsequent training sessions to illustrate the performance of the LDTI system and the display pages generated in conjunction with the event. The presentation illustrated a series of alternative maintenance actions and the effects that these actions would have on the forecasted pavement conditions. The training sessions lasted from 2½ hours to over 4 hours, depending upon the depth of the discussions.

Based upon user input during these training sessions, subsequent phone conversations after the training, and written recommendations from DOT participants, Meridian made several adjustments to the graphical user interface to make the interface more user-friendly and to correct a few minor inconsistencies in the road condition processing technique. Test participants found the interface acceptable but made several recommendations that they felt would make their interaction with the system more efficient. Meridian did a follow-up visit in Iowa to review procedures and assess user acceptance. Additional trips were planned; but after the conclusion of the training sessions there was limited weather activity and the visits did not materialize. All states had an opportunity to do some minimal testing before winter ended. Indiana and Iowa had the best situations for the test and both provided considerable input.

TASK 10: DEVELOP & TEST NEW SYSTEM COMPONENTS

Develop and test new system components that satisfy those requirements requiring fundamental research, incorporating ongoing and emerging technology improvements associated with weather forecasting and maintenance practices.

An initial list of technological enhancements requiring additional research was developed in Phase I, Task 10.1 of the MDSS PFS project. For reference, this list is reproduced in Table 1. This list of research needs was initially presented in the Phase I report and shown again to the Technical Panel during the March 2004 meeting. The reasoning behind the identification of each of these needs was discussed during the March meeting and the list was given informal approval by the Technical Panel at that point.

Background research and development of initial modules to meet these required technological needs was ongoing throughout the entire Phase II research and development effort. Partial completion of components or phases of the research within several of the defined research areas was critical to the performance of the demonstration test. The specifics and status of this research and associated development efforts are addressed below.

CHEMICAL CONCENTRATION–FREEZE POINT COMPUTATION

Meridian added support for solution modeling to the MDSS infrastructure in preparation of the LDTI test in the late winter of 2003-2004. Only dry, prewet, and brine NaCl were supported during the LDTI test. Support of $CaCl_2$ and $MgCl_2$ has since been added to the MDSS solution modeling library. The equations for calculation of the concentration required to maintain a purely liquid solution at a given temperature were drawn primarily from the FHWA's MDSS Functional Prototype (FP) code. These equation sets were then inverted to arrive at equations for the calculation of the freeze point of a solution at a given concentration. These two equation sets serve as the basis for the PFS MDSS solution modeling.

Table 1: Initial List of Research Needs Developed in Phase I of the Study

Need	Description	Priority
Chemical Concentration–Freeze Point Computation	Computation of chemical concentration of the liquid component of slush for all routinely used chemicals and chemical admixtures. Module needs to compute the freeze point of the mixture of chemicals.	1
Percent Ice In Slush Mixture	Computation of the ice percent of the mixture of ice and dissolved chemical solution for all routinely used chemicals and chemical admixtures	1
Traction Index	Develop an index based upon the "effective" coefficient of friction caused by the state of the contaminant layer	2
Latent Heat Effects Of Chemical Application	Develop a simulation of the heat of fusion required as salt induces the state change from ice to water over time and how this heat flux affects the pavement temperature; output from this simulation needs to loop back into freeze point and percent ice computation modules	3
Chemical Residue	Create a simulation of the bonding process of different chemicals or chemical admixtures on various types of pavement as the solvent (water) evaporates from the highway surface; simulate the residual bond over time for different traffic volumes and speeds; simulate the dissolution of this bonded chemical once moisture is added to contaminant layer due to dew, frost, absorption, or some form of precipitation	3
Plowing Techniques	Simulate the plowing action of the spectrum of plow types with the intent to output the residual material after plowing is complete; consider the effects of different road surface types and their interaction with the plow action	3
Blowing Snow	Simulate the effects of blowing snow due to topography, local wind patterns, construction factors, vegetative cover, and snow fences; simulate the amount of snow within the contaminant layer caused by a variety of wind conditions under differing snow densities; simulate the effect of traffic on the snow blowing or moving across the highway	3
Frost	Develop an improved model to simulate the formation of frost on bridges or highways	3
Road Condition Reporting	Develop a module to capture and transmit road conditions along a stretch of highway and relatively short time intervals (on the order of once an hour or less); module needs to store and display road conditions along any segment of highway	4
Material Application Estimator	For each type of material spreader, create an algorithm or simulation package to determine the effective amount of material placed on the road surface	4
Chemical Migration And Dissolution In Slush	Develop a simulation process that mimics the movement of chemical through a contaminant layer and approximates the process of chemical dissolving and/or mixing in a snow or slush layer	5
Chemical Mixing As A Function Of Traffic Volumes	Develop a simulation of traffic's effect on the contaminant layer at varying degrees of slush consistency; part of the module should also determine how much material is removed from the contaminant layer at different traffic volumes and speeds	5
Grit Migration	Simulate the positioning and movement of grit materials within the contaminant layer; simulate the amount of residual grit material over time and determine where and how it migrates under different traffic situations	6
Long Wave Radiation Balance	Perform research to determine what factors impact the energy balance equations in the long wave portion of the spectrum; observations indicate the temperature of the lower atmosphere influences the net long wave radiation; this parameter is not currently considered in the long wave radiation flux	6
Traffic Simulation	Create a simulation model that estimates the traffic volume and speeds as a function of time and special events; simulation should estimate the same traffic flows under varying weather and contaminant layer situations; output from the simulation becomes input into nearly all modules addressing contaminant layer values	7
Research The Bonding Of Snow To Pavement Surfaces	Develop and understanding of the bonding process and determine what conditions are needed at the threshold point and how the process occurs as conditions change; evaluate the influence of different types of pavement and characterize the critical bonding conditions	7
Contaminant Layer Composition During Precipitation	Simulate the state of the contaminant layer during precipitation events such as snowfall; determine how snow melt occurs and how the concentration changes with time through the layer	8

PERCENT ICE IN SLUSH MIXTURE

Unlike the FP, the PFS MDSS maintains individual masses of liquid, ice, frost, and snow within the contaminant layer. As freeze point depressants are applied to and removed from the road the balance between these moisture states is shifted in a manner that is consistent with the phase diagram curves of the solution and the energy balances acting upon the contaminant layer. As such, the PFS MDSS is able to maintain assessments of the 'slushiness' of the contaminant layer that are used to recommend actions

that prevent compaction and maintain mobility without the unrealistic requirement of melting all the ice present.

TRACTION INDEX

Meridian determined that the algorithm supporting the Mobility Index used during the LDTI test was not sophisticated enough to provide good guidance on the level of safety and mobility. Several alternative approaches were investigated to define a "Highway Safety Index", a combined measure of how varying compositions of the contaminant layer affect safety and mobility. Potential candidate options address both traction and rolling friction. Once the index is developed it is anticipated that it will become a centerpiece metric by which contaminant layer states are described within the PFS MDSS.

LATENT HEAT EFFECTS OF CHEMICAL APPLICATION

The HiCAPS^{TM} pavement model, which serves as the core model of the PFS MDSS, already had functions for modeling the latent heat exchanged with the road as moisture freezes and thaws. Therefore, in order to address these processes as they relate to chemical applications Meridian modified the model from a fixed freezing point to one that floats along the phase diagram curve of the chemicals present in the contaminant layer.

CHEMICAL RESIDUE

The modeling of chemical residues takes place throughout the PFS MDSS rather than in any one particular module. The effects of chemical removal by traffic are handled within the traffic module. Chemical removal with runoff is handled within the runoff calculations of the pavement model. Chemical applications, immediate loss, and removal by subsequent plowing operations are modeled within the maintenance actions module.

PLOWING TECHNIQUES

Plow specifications were added to the PFS MDSS and are configurable; however, at this juncture the plowing operation is treated in a relatively simplistic manner. Materials removed from the roadway were assumed to be both permanently removed and removed from the entire width of the lane. Note, however, that some material was assumed to be left behind the plow and the depth of this material was made configurable. Liquid was assumed to preferentially lie near the road surface relative to ice (because of density considerations) and was therefore removed at a lesser rate than frozen materials. Soluble and insoluble chemicals in the contaminant layer were assumed to be removed by the plow at the same fractional rate that liquid / total moisture mass was removed from the road.

BLOWING SNOW

Development work was done on a blowing snow module by the University of North Dakota with some consultation with Meridian regarding potential integration into the PFS MDSS application. The research is not complete and remains ongoing, but the existing model at the time of the demonstration test will be integrated into the PFS MDSS to evaluate its performance. Feedback from the test will be used to guide modifications and future direction of the research effort.

FROST

The prediction of frost is a notoriously difficult problem. The difficulties arise more from the sensitivity of the actual field situation rather than from poorly understood processes. Small errors in either forecasted road/bridge or dew point temperatures can make the difference between no frost and a major frost event. Therefore the best way to improve frost predictions is simply to improve the forecasts. Unfortunately this improvement may take years to realize. However, a few fundamental research issues were addressed in the PFS MDSS that should help improve the usefulness of frost forecasts, such as chemical residue, radiation balance, and depth of the frost layer.

ROAD CONDITION REPORTING

Accurate forecasts of pavement conditions require a good understanding of the initial state of the road conditions. Unfortunately road conditions are not routinely recorded or communicated to a processing site. During the LDTI the PFS MDSS utilized electronic and computer telephony based forms for reporting road conditions and maintenance actions along maintenance routes. These technologies will continue to be supported during the 2004-2005 winter demonstration test. In addition, efforts were taken by most of the states participating in the PFS MDSS to install automated maintenance data collection capabilities or move existing vehicles into the test areas. These vehicles are being included in the 2004-2005 demonstration test to determine what options offer the greatest potential for future MDSS maintenance data collection and communications.

MATERIAL APPLICATION ESTIMATOR

The distribution of chemicals and grit onto the road during the application process is dependent upon numerous things, including the material form (dry, prewet, brine), the spreader type, and the vehicle speed. However, at this point the PFS MDSS estimates immediate application losses based only upon the material form. Provisions were made in the PFS MDSS infrastructure to model these processes in a more refined manner in future releases.

CHEMICAL/GRIT MIGRATION, MIXING, AND DISSOLUTION

Chemical and grit migration, mixing, and dissolution in slush and as a function of traffic volume is a very complex set of processes that have been addressed very little by the research community. However, since traffic has a substantial influence on the migration and mixing of contaminant layer materials, these processes were addressed within the traffic module of the PFS MDSS. The initial parameterizations were relatively simple.

LONG WAVE RADIATION BALANCE

This research need was discussed earlier under frost research. The long wave radiation balance is a subtle yet important process, as it plays a fundamental role in regulating the pavement temperatures (especially bridge temperatures). Although the down-welling radiation from the atmosphere and the upwelling radiation from the road are certainly important on the top surface of the roadway, the radiation balance at the bottom surface of the bridge is also of fundamental importance and has long been neglected. The PFS MDSS explored several options to address this research need and is coordinating the efforts to purchase and install radiation sensors at a couple of test sites within the PFS MDSS states.

TRAFFIC SIMULATION

The research that does exist on the effects of traffic is limited and largely subjective in nature. Several attempts have been made to measure the effects of traffic on removal of chemicals from the roadway. However, these experiments have led to wide ranging and largely unexplainable discrepancies even within the same study. As such, Meridian chose to model the effects of traffic on what was perceived to be a more tractable vehicle-by-vehicle basis, based upon personal observations of the effects that one's own and surrounding vehicles have on the contaminant layer. This modification was integrated into the traffic module of the MDSS PFS.

BONDING OF SNOW TO PAVEMENT SURFACES

Intuitively it seems clear that the likelihood for bonding increases as the percentage of liquid in the contaminant layer decreases. However, Meridian found very little research for modeling this relationship. Reference was made in a number of publications to 15-30% liquid within the mixture being critical for preventing ice bonding, but the source of the original research has yet to be verified. Unfortunately this is a very critical piece of information, so if scientifically sound research data cannot be located, the PFS MDSS or related research efforts will likely need to address this problem in an experimental setting.

CONTAMINANT LAYER COMPOSITION DURING PRECIPITATION

The ability to model and display the ice, snow, and liquid components of the contaminant layer along with the impact of varying amounts of chemical permitted Meridian scientists to evaluate a number of potential situations. There are a number of complex interactions between the existing state of the road and its impact on new snow and its relative movement across the pavement surface. Meridian was able to review a couple of events during the LDTI test and has investigated how the model deals with certain scenarios, such as wet surfaces capturing additional snow. The installation of Geonor precipitation gauges and ultrasonic snow depth sensors at test sites within each of the PFS MDSS member states will help to provide a better understanding of the precipitation processes associated with the modeled and observed pavement conditions.

Most of the modules and processes discussed here were included in the MDSS Version 1.0 release at the end of the Phase II project. Due to a lack of research quality observational data, the performance assessment for many of these modules has been subjective in nature. Data collected from the various field site installations and from maintenance personnel during the 2004-2005 winter demonstration will be used to support more objective evaluations of module performance as the winter demonstration test evolves. The research program is an ongoing task that will apply to enhancements that are developed in Phase 3 of the project. Where an enhancement is expected to have an effect upon the performance of the system that will be significant and discernable by users of the system, those users will be asked to provide feedback on the enhancement. This feedback will be taken into account when considering whether to accept, refine, or reject the enhancements. The MDSS GUI provides a tool by which feedback from users can be collected directly through the interface, allowing for capture of feedback while it is fresh in the user's mind and with minimal inconvenience to the user.

TASK 11: RECOMMEND NEEDED IMPROVEMENTS

Based on the results of the evaluation and development of new system components, recommend needed improvements and design modifications and identify operational limitations requiring additional research and development.

Although some of the research projects addressed in Task 10 have been integrated into various portions of the MDSS code, none have been thoroughly tested as part of an operational system. The demonstration test planned for the winter of 2004–05 will provide the first opportunity to evaluate the performance of those modules developed out of the research done during 2004.

TASK 12: DEPLOY AN IMPROVED PROTOTYPE

Upon approval of the technical panel, make system improvements, deploy an improved prototype MDSS in state agency offices in individual and multi-state test regions as determined by the Technical Panel, and evaluate its performance in actual conditions during the 2004–2005 winter with expanded deployment during the 2005–2006 winter.

Design and development of Version 1.0 of the PFS MDSS software has been ongoing since the inception of Phase I of the project. Limited portions of this software, including the solution modeling, maintenance activities reporting, and 'what-if' capabilities as well as certain concepts under consideration for the eventual MDSS client application were prepared for operational testing during the LDTI test in the late winter of 2003-2004 (discussed under Tasks 7-9 above). The LDTI test period yielded valuable information concerning components in need of further scientific development as well as information on the practicality and user acceptance of a number of interface, display, and reporting concepts.

Efforts to develop Version 1.0 of the PFS MDSS software were accelerated upon completion of the LDTI test. The initial design of the MDSS client application (the Graphical User Interface, or GUI) was refined based upon lessons learned in the LDTI. On August 13, 2004 a functional description (including screenshots) of the MDSS client application was released to members of the project's GUI evaluation team for review and comment. The first functional release of the PFS MDSS software was demonstrated at the mid-September 2004 Technical Panel meeting, and was released to Technical Panel members for comment and evaluation on September 22, 2004. This release was functional in that it was fed with live data from an MDSS server located at Meridian. A second evaluation release was made available to the project's Technical Panel on October 14, 2004. Meridian received a number of useful comments based on both evaluation releases. Several of the suggestions as well as additional enhancements were released in Version 1.0 of the software on November 15, 2004. The design and functionality of the Version 1.0 PFS MDSS software is discussed in the "Findings" section of this document.

TASK 3: EXPAND MDSS KNOWLEDGE BASE

The final definition of routes for the LDTI showed that there was a distinct difference between the Meridian perception of a route and the true operational perspective used by maintenance agencies. From work done for the Manual of Practice and Functional Prototype, routes had been defined as distinct stretches of highway treated in a uniform manner. The simplest approach to address this route definition would be to utilize one vehicle for the route and perform the maintenance activity in a redundant, simple loop scenario. The reality is that multiple trucks may operate on the same route, each performing maintenance actions at different times. Routes may also be spatially defined, but only part of the route is affected by any one maintenance cycle. Traffic or local environmental factors may require that different parts of a designated route require more attention than other parts. On multilane roads, the driving lanes may receive different treatments than the passing lane and multiple trucks may handle these multiple lane roads either in tandem or at separate times. Irregularities in treatment patterns were more dominant than simple "out and back" scenarios. The importance of this finding is that MDSS needs to segment roads or routes and apply treatment recommendations to relatively short segments of roadway or assess treatment options by lane rather than by route.

The form in Appendix A illustrates the detail that is necessary to properly define the segments for the MDSS demonstration field test. The form is obviously oriented toward better characterizations of shorter segments than originally proposed. Based upon the processing and display techniques of MDSS and the operational practices, Meridian is aware that the MDSS program will need to gravitate toward shorter and shorter segments and develop a mechanism to recommend both local treatments and a general averaged route treatment. The segment approach is a necessity to effectively handle the maintenance treatments affected by more than one vehicle on the pavement.

One factor the form does not handle yet is the method used to apply materials. Feedback during the LDTI test, and through subsequent discussions in preparation for the demonstration field test, indicate a number of different application patterns or approaches are used by different local maintenance units. Some applications are broadcast, some focus on wheel tracks only; some places the application in a furrow and allow traffic or gravity flow to spread solid and dissolved chemicals across the road. In addition, maintenance personnel emphasized the impact traffic has on the loss of granular chemical and abrasives and the need to assess that loss as part of the MDSS program. The traffic module of the MDSS program attempts to handle part of this issue by addressing spray and splatter patterns related to different vehicular speeds and pavement surface conditions.

In the initial meetings with Colorado, the state selected two locations for the MDSS demonstration test, I-29 from north of Monument to Colorado Springs and a corridor along I-70 west of Glenwood Springs and then south on State Route 82 to Aspen. During the introductory meetings and initial interviews with personnel at these two locations, it was determined that the core maintenance practices in Colorado were similar to the practices found in other states except that Colorado uses magnesium chloride as its chemical of choice. Wind and blowing snow are more often the dominant maintenance concerns along with locally enhanced snowfalls associated with topography. Colorado has a strong interest in automating the

collection of maintenance data from their trucks and shortly after their entry into the MDSS program initiated efforts to acquire the appropriate logging and communications equipment to facilitate this process for the Demonstration Field Test.

TASK 4: ASSESS STATES' PROCESSING AND COMMUNICATIONS CAPABILITIES

During the selection of the optimal processing approach for MDSS, the best software configuration for the user interface was determined to be a client side application coupled with a centralized decision support system located at Meridian. This approach placed all of the weather, pavement condition analyses, and decision logic at the central site but gave the MDSS user the maximum control over interaction with the large volume of decision support data. Initial discussions suggested that four of the five states utilized Citrix or a similar centralized terminal management package to support client based software packages such as MDSS. Upon further analysis, it was found that only South Dakota was positioned to use this approach and that the other states had varying levels of IT involvement in the management of software upgrades and direct software installation on state-owned computers. Technical Panel members and/or key members of the demonstration test team within the states have assumed responsibility to assure that the software is loaded and works properly on computers not served by a centralized system.

Each state has a number of communications options that could potentially support the transfer of information from mobile maintenance data collection platforms to a central site. As the assessment progressed and the states worked with two Maintenance Data Collection (MDC) vendors to determine the appropriate communications interface, the states in consort with the vendors determined that different communications options were appropriate at different locations within a state. The dominant communications solution is a wireless interaction between the truck and a receiver at specified collection points (or "drop" points). The most common drop point selected was a maintenance facility and in particular the location where trucks routinely loaded materials. Minnesota has equipped a portion of its trucks with cellular communications capabilities, especially along the Interstate corridors and in metropolitan areas. Some of the AVL/MDC equipment procured for the demonstration test within the participating states does not have a communications interface, thus forcing the exchange to be done manually. Where this manual approach is the selected interface for this research program, the data transfer will be done by dumping the data to a memory stick or card, and then transferring the data to a PC at the maintenance facility.

TASKS 7–9: LIMITED DEPLOYMENT TACTICAL INTEGRATION TEST

The LDTI test started with the initiation of the onsite training sessions in each of the five states. These sessions provided an opportunity for the field participants and the Meridian trainers to address the details necessary to make the field test work. Once the discussion focused on specific routes and the responsibilities of individual drivers, the level of detail escalated considerably over what had been accomplished in the interview sessions held during Phase I. Route patterns, operational variations, sharing maintenance responsibilities with drivers on other routes, and specific problem areas on the test routes were primary topics. The MDSS design of specific routes handled by a single truck in an out and back manner evaporated. The early route specifications were changed in a number of areas based upon the actual route patterns run by specific drivers. It was obvious that although snow routes were typically the

designated responsibility of a given driver the methodology of maintaining this "route" could not be defined in a simple maintenance scenario. Routes were treated more as a series of operational segments. The level of treatment was dependent upon the required level of service of the road, the traffic volume, interactions with cross roads, the characteristics of major intersections, and the need to maintain ramps, rest areas, and other secondary elements. Further, the maintenance pattern was influenced by the type of weather situation that occurred. Certain segments created problem areas when specific events occurred. Blowing snow and refreeze situations were critical weather situations. The key finding from these training sessions was the route segmentation process had to be addressed in a different manner for the Demonstration Field Test.

Maintenance information is of critical import to MDSS processing. Meridian provided two mechanisms for field personnel to enter maintenance activity reports into the MDSS processing scheme: the use of interactive voice recognition (IVR) software via a cell phone and direct entry of maintenance information via a web interface. The test of these technologies had varying degrees of success. The direct web entry worked well in Indiana because INDOT drivers maintain a radio interface with dispatchers who are on duty 24/7. The test participants were able to verbally share their maintenance entries with the dispatchers who then entered the data via the MDSS web entry page. The dispatchers found that the web entry required minimal time and was simple to perform. The other states did not have this operational configuration and found web entry to be inconvenient. The IVR techniques worked in Iowa with some degree of success; however, the performance was somewhat dependent upon cellular coverage. The remaining states did not get significant weather after the training sessions and were not able to test either method sufficiently to make an assessment.

The LDTI user interface received both positive and negative responses. The positive responses focused on the level of information available on the site view displays and the ability to see and comprehend how maintenance actions had or were affecting conditions on pavement surfaces. There was particular interest in the ability to adjust maintenance practices to visually assess the impact of different treatment options on the same situation. The primary complaint was the layout of the web pages and the difficulty users experienced in finding their way around the MDSS website. The one web interface page that was well accepted was the maintenance input page.

During the LDTI test a couple of issues arose because of the timing of maintenance activity reports and how the road condition reports were integrated into the contaminant layer computations. Sequentially, road condition reports were entered after the maintenance activity of plowing. The model was performing the plowing and then adjusting the contaminant layer depths to handle the road condition reports. Some strange jumps in the contaminant layer occurred; the code was changed and the issue disappeared. Meridian found the Mobility Index algorithm was an extremely simple approach that would generate unusual responses when the contaminant layer vacillated between more snow and more water in the mixture. The obvious conclusion from watching the mobility index was that a more robust index was needed for the Demonstration Field Test.

In discussions during the training sessions, follow-up phone conversations, and the follow-up visit to Iowa the accuracy of the weather forecast was a common thread within the discussion. Both supervisors and the truck drivers indicated that accurate weather and pavement condition forecasts were essential for allowing maintainers to perform their jobs more effectively. DOT personnel indicated they would like to receive reliable guidance regarding weather and pavement conditions either prior to starting their route or

while they are on their route in order to have a better understanding of where and how they need to respond.

The LDTI demonstrated that there was considerable interest in the MDSS program. Several participants in the program indicated they were disappointed—in a way—that winter had ended too soon for them to fully evaluate the capabilities of MDSS.

TASKS 10–11: RESEARCH

Much of the research accomplished during Phase II may be described as background research or the literature review portion of a more extensive research program. Preparation of the MDSS program for the LDTI and Demonstration Field Tests required the integration of a number of technologies that had not been previously integrated into a decision support package. What was accomplished during Phase II was to integrate the algorithms into the MDSS software to make the software more robust for the Demonstration Field Test. The findings associated with much of the integration of the background research efforts must await the performance of the MDSS software during the winter of 2004–05. However, some initial results did accrue from the LDTI test and internal tests the development team did during the research integration process. The initial findings from Phase II research follow.

LATENT HEAT EFFECTS OF CHEMICAL APPLICATION

A fundamental requirement associated with latent heat transfer was that the MDSS should be able to replicate the temporary drop in pavement temperatures that typically occurs immediately after freeze point depressants are applied to a contaminant layer containing frozen materials. The PFS MDSS was shown to replicate this behavior quite well during the LDTI test. There is an associated heat exchange that was not addressed in this release that deals with the exothermic and endothermic effects associated with salts going into or coming out of solution. These processes are considered of secondary importance, but they need to be addressed at some point in the future.

FROST

Results from the LDTI test indicated that code modifications associated with the integration of research findings did impact the performance of the forecasted frost potential during the LDTI test. Specifically, the modeling of chemical residues from previous maintenance actions helped determine whether or not sufficient residue was present to prevent frost formation. The MDSS did determine that frost would occur when the pavement temperature dropped to the dew point temperature, but the residual chemical caused any ice crystals that did form to change immediately to a liquid. When residual chemical is present, MDSS will convert frost that forms into liquid until the chemical is diluted to the point where further melting of ice crystals ceases.

Different paving materials influence tire traction differently. In frost situations the character of the surface influences how ice crystallization affects the loss of traction. The MDSS code considers the pavement type and assigns the depth of frost necessary to reach the point where additional ice crystallization starts to significantly reduce traction. The frost depth factor is in the code but it will require close observation during the demonstration test to assess the impact of the loss of traction depth.

Meridian has spent considerable time evaluating the performance of the HiCAPS™ pavement model during frost situations. Close evaluation of the forecasted bridge deck temperatures indicate that the model cools the deck temperatures too much during situations where outgoing long wave radiation dominates over incoming long wave radiation. This cooling bias appears more in the fall and spring when there is no snow cover under the bridge decks. The cold bias has been particularly noticeable this fall and points to the lack of a radiation balance term on the bottom side of the deck structure. Radiation sensors proposed as part of the PFS MDSS and related research efforts should help verify the effects of these radiative transfer processes.

RESEARCH THE BONDING OF SNOW TO PAVEMENT SURFACES

Within the MDSS model the distribution of vehicles along a section of the pavement and across multiple lanes were derived from the average daily traffic and prescribed (but configurable) urban and rural daily traffic patterns. Gaussian random number generators were used to choose random lane positions, vehicle widths, tire widths, and wheel track deviations for each vehicle. Liquid, ice, frost, and snow within the tire tracks is then sprayed, splattered, spread, and/or compacted based upon the liquid saturation ratio of the contaminant layer. The net effect of the semi-random parameters for each vehicle is to either migrate materials laterally off of the roadway over time or to compact them into ice. An ongoing cross-sectional profile of the various forms of moisture on the road is kept by the model and appears plausible based upon subjective evaluation. Observations from the demonstration test will help verify this modeling approach and assist with modifications necessary to enhance this module.

TASK 12: SOFTWARE DESIGN AND IMPLEMENTATION

CODE STRUCTURE

The scientific framework for the PFS MDSS has been coded primarily in two computing languages. The scripts that orchestrate the data processing are generally written in Perl. The compiled code is written in C. In order to facilitate plug-and-play capabilities, the vast majority of the compiled code has been placed in a core MDSS library. At present this library contains the files shown in Table 2.

In addition, the PFS MDSS relies heavily upon the HiCAPS™ pavement model to perform the actual pavement simulations. HiCAPS™ is a proprietary pavement model that is not considered to be part of the MDSS code infrastructure. However, a number of enhancements to HiCAPS™ were required in order to support MDSS activities, including functions for modeling aqueous chemical solutions in the contaminant layer, maintenance activities, and the effects of traffic. As such, the functions within which these enhancements are provided have been included in the MDSS library so that they can be accessed by any other pavement model that may eventually be operated within the PFS MDSS framework.

The PFS MDSS is highly configurable. All memory allocation within the code is dynamic, meaning the code automatically sizes itself to fit the problem at hand. The configurability of the PFS MDSS is accomplished through heavy application of the Capability Database functions with the C programming language. Separate configuration files are maintained for configuring the physical properties and locations of the roads, the properties of the ambient environment surrounding each road, the maintenance activities normally practiced within an institution, the materials and material mixtures normally available for application and their physical properties, traffic characteristics, etc.

Table 2: MDSS Software Library

File	Function
arraytostring.c	functions to write mathematical arrays to strings for file storage
configs.c	generic functions for retrieving information from the MDSS configuration files
dimalloc.c	function for allocating multi-dimensional arrays in a single allocation step
error_exit.c	functions for handling error messages and program return codes
events.c	functions for locating and defining storm events
interp.c	functions for interpolating data
lkup.c	functions for reading generic lookup files
maintenance.c	functions for modeling and suggesting maintenance activities
materials.c	functions for modeling and characterizing maintenance materials
misc.c	miscellaneous functions
observations.c	functions for reading and applying observational data
segment_config.c	functions for configuring road segments for simulation
segment_state.c	functions for handling segment state objects
segment_wx.c	functions for handling weather objects
solution_model.c	functions for modeling solutions in the contaminant layer
stringparse.c	functions for parsing string data into arrays
stringtotime.c	functions for converting strings to Unix timestamps
sun.c	functions for handling various calculations related to the sun
traffic.c	functions for modeling the effects of traffic
wx_functions.c	miscellaneous weather-related functions
wx_snapshot.c	function for returning time-interpolated weather data.

Most data exchange with the graphical user interface (GUI) is accomplished through an index file maintained on the server. A simple directory hierarchy is in place on the server into which data is placed by information vendors. At regular intervals a script scans this directory hierarchy, compresses and logs new files, and creates an updated index file that maps from data type and time (as indicated by a time slider on the GUI) to the appropriate file. The GUI retrieves this index file and compares it against the data files it has stored locally on the client computer. Where there are discrepancies client software supporting that GUI then proceeds to download new or replacement files and updates its internal mappings between data types, times, and files. The data download process occurs automatically so the information is immediately available to the user upon user request. This entire data synchronization process occurs in an ordered fashion where files associated with times closest to the present position of the time slider are retrieved first. Therefore, if the user opts to look into the past or future the GUI will intelligently shift its resources toward gathering the data for the selected time.

The exception to this data exchange rule occurs within what is called the "Route View" of the PFS MDSS GUI. This view within the GUI presents the toolset through which maintenance personnel can view the effects of past and proposed maintenance activities upon the roadway. The nature of the datasets required to support these simulations is such that a more responsive system can be achieved by offloading the associated processing back to the central server. As such, the GUI handles the process of establishing the parameters within which these simulations will run, sending the request back to the server, and then processing the data that is returned into a user-friendly visualization format. However, the actual simulations are done on the server side.

The PFS MDSS approach focuses upon simulation of the 'contaminant layer' atop the pavement. Analyses of past weather conditions (including precipitation and radiation budgets) are integrated with RWIS observations as well as road condition and maintenance activities reports to provide an ongoing assessment of the past and present states of the roadway. These assessed roadway states serve both as a real-time information source as well as the initial conditions from which the pavement forecasts that underpin the PFS MDSS maintenance recommendations are generated.

The integration of weather, road, and maintenance information in the PFS MDSS presently occurs within the HiCAPS^{TM} pavement model and supporting MDSS libraries. HiCAPS^{TM} is a mass and energy balance pavement model that simulates the evolution of the roadway and its contaminant layer by modeling the combined effects of the individual fluxes and processes active on that layer. Sensible and latent heat fluxes are modeled using bulk aerodynamic formulations, while ground heat flux is modeled using the unsteady heat flow equation. The HiCAPS^{TM} latent heat flux module accounts for energy and mass exchanges due to precipitation, evaporation, sublimation, condensation, deposition, conduction, and phase changes.

A new chemical solution module was developed to support modeling the effects of freeze point depressants on the state of the roadway. However, the structure of the HiCAPS^{TM} model was such that the transition to solution modeling required only that a simple fixed freeze point temperature be calculated dynamically based upon the chemicals present (all of the associated phase change processes were already handled by the model). In addition to these dynamic freeze points, solution support also required the handling of absorption processes (salts absorbing humidity directly from the air), evaporation reduction due to reduced vapor pressure in solutions, and removal of the chemicals by runoff, traffic, and additional maintenance activities. Some of these processes will be discussed again shortly. At present, the PFS MDSS supports NaCl, CaCl$_2$, and MgCl$_2$ solutions.

As mentioned earlier, the ongoing assessment of the initial state of the contaminant layer is used in concert with weather forecast and available maintenance resources information to construct an initial/boundary value problem. Standard minimization techniques are used to find candidate maintenance actions that will maintain the required level of service in the most economical manner given available human, equipment, and material resources. Resource and service level information is preconfigured for each maintenance route based upon information collected from local maintenance personnel, but can be adjusted by the user as resource availability and practical maintenance limitations change during a storm situation. Parameters that can be adjusted as needed include the maintenance practices to be considered (materials, minimum and maximum rates, and material costs), the windows of time during which maintenance activities must be completed, the maintenance route traversal and cycle times, and the within-event and nominal service levels desired for the maintenance route. The system also supports contaminant layer simulation for user-defined maintenance actions in a 'what-if?' virtual scenario mode. The simplest of these is a no-action scenario. However, the user can specify multiple maintenance actions and view the expected results of those maintenance actions in a virtual setting, and can compare the results against those expected from the MDSS' recommended maintenance plan.

For simulated plowing operations, the system estimates the depth of snow and ice remaining behind the plow based upon plow type and the road surface roughness. Immediate material loss during the

application process is configurable and dependent upon the form of the material (e.g., dry, prewet, or brine). The depth of materials remaining behind the plow is configurable based upon plow type. Previously applied soluble / insoluble chemicals and grit are removed at the same fractional rate as the liquid / total moisture mass in the contaminant layer. Due to density considerations, liquid is assumed to preferentially reside near the bottom of the contaminant layer and is therefore generally removed at a lesser rate than frozen materials within the mixture. Moisture and maintenance materials are also removed by runoff and by the effects of traffic.

Due to the lack of reliable and consistent research data on the cumulative effects of hundreds or thousands of vehicles upon the contaminant layer, the PFS MDSS instead models the effects of traffic on a more tractable vehicle-by-vehicle basis. Based upon average daily auto and truck traffic counts, the MDSS distributes vehicles across the contaminant layer at a rate that varies according to a configurable pattern throughout the day. Each vehicle is assigned a random lane, track and vehicle width, and moisture within the tire tracks is splattered, sprayed, spread, or compacted depending upon the composition of the contaminant layer. Moisture and materials are moved laterally atop the roadway, and are also removed from the roadway depending upon the splatter, spray, and spread widths relative to the distance of the tire locations from the edge of the roadway.

Decision support in the PFS MDSS is provided on a maintenance route, segment, or tile basis. A maintenance route is made up of one or more discrete segments of highway that are to be treated contiguously by a single maintenance vehicle. Each segment within a maintenance route possesses unique weather, construction, traffic, and environmental information. Maintenance needs within a single route can therefore vary considerably. However, the MDSS will only present maintenance action recommendations on the different segments of a given route that can be practiced with a single vehicle configuration and that can be performed at contiguous times with traversal, cycle, and dead times that are physically realistic. Note that although the materials recommended will (necessarily) be the same on all segments of a route, the recommended rates can vary substantially between segments based upon the modeled needs. Roadway information in the MDSS is generally displayed on a segment by segment basis. The smallest road subunit in the MDSS is the tile. A tile possesses no specific location within a segment, but is intended for modeling generalized variations in conditions along a segment (such as a sheltered area verses an open area). At this juncture information that is available at the tile level is hidden from the user.

Data is generally exchanged using simple and self describing text file formats. As previously discussed, a central MDSS library has been developed for all IO function of the MDSS. Data is therefore accessed and written to the system using simple library calls. Most data is stored on a segment or tile basis.

GRAPHICAL USER INTERFACE / CLIENT APPLICATION DESIGN

The primary mode of user interaction with the MDSS is through a Graphical User Interface (GUI) that is installed either on the client computer or on a central state server. The PFS MDSS also supports use of computer telephony technologies for both data gathering and information distribution.

The PFS MDSS graphical user interface (GUI) is written in Java™ and is distributed to the participating states as self-contained compiled executable. It has been constructed to meet the stringent criteria of state information technology divisions, including the ability to run the graphical user interface at remote locations from a central server.

The GUI design is based upon a 3-panel layout. The upper-left panel is a called the "Alert Panel". The lower-left panel is called the "Support Panel". The third "Primary Panel" of the display carries most of the functionality of the MDSS and takes up the right 2/3 of the GUI. In order to function well in all environments the PFS MDSS GUI has been designed to work at 600x800 screen resolution, but can easily be maximized to take advantage of additional screen dimensions when available.
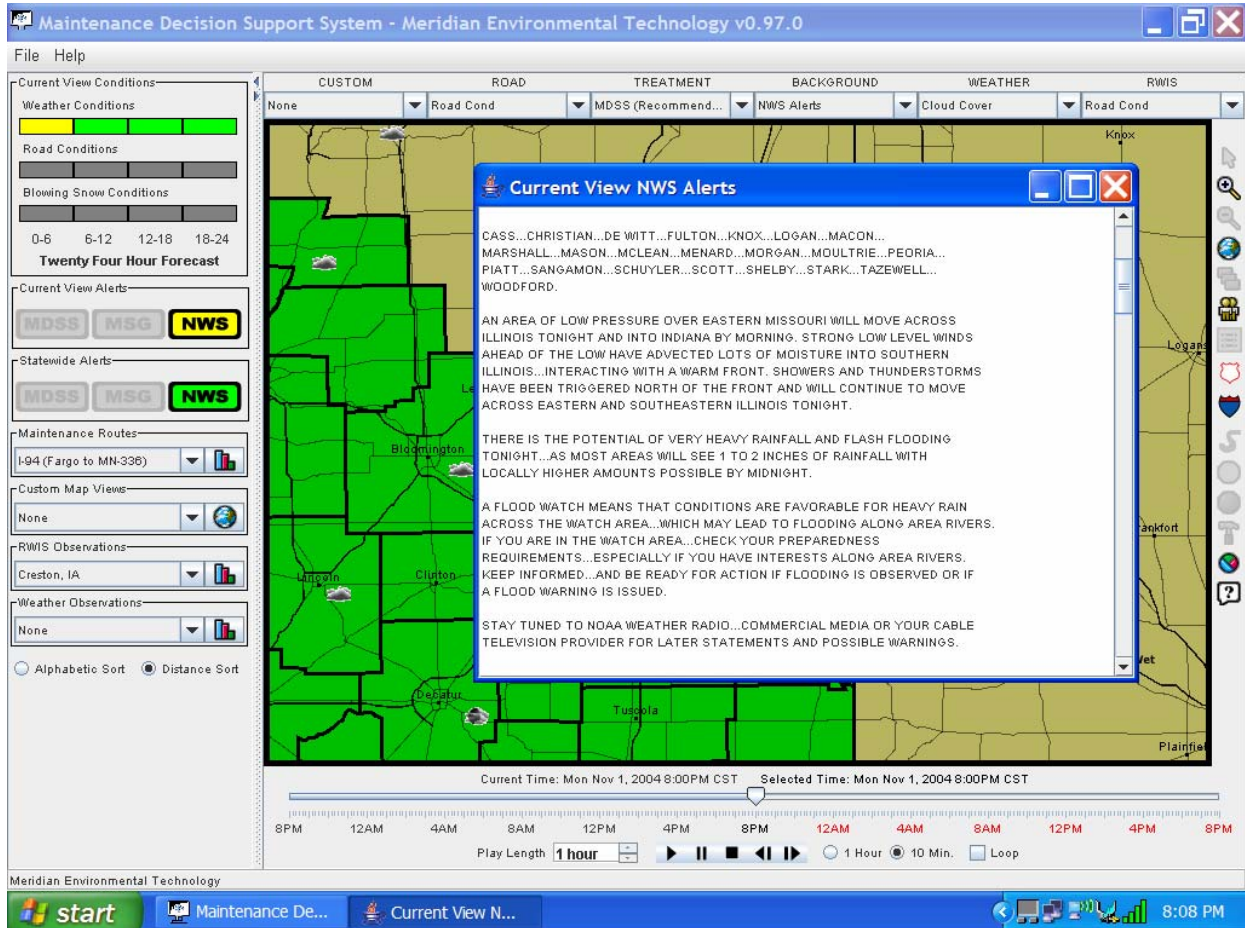

Figure 5: Graphical User Interface Alert Panel

The Alert Panel is present at all times, and conveys information about weather, road, and blowing snow conditions meeting specified alert criteria (Figure 5). This equivalent panel of the FHWA's Functional Prototype (FP) was well received by test users and is thus included in a similar fashion in the PFS MDSS. The alerts for the various conditions are presented using time-series based color bars, where the period in time over which the alert is valid is color coded based upon the perceived severity of the alert. Alerts for road conditions and blowing snow are intended to be provided by the state's meteorological services provider, while the weather conditions alerts are intended to come from both the meteorological service provider and the National Weather Service (NWS). A set of buttons within the alert panel allows the user to retrieve text messages associated with alerts issued by either the meteorological service provider or the NWS. One set of buttons holds information for the user's specific state, while a parallel set of buttons holds information for the user's specific Geographical Information Systems (GIS) 'view' (Figure 6). Standard GIS formats are used for conveying alert information to the MDSS GUI so that the alert notices can be coupled with the user's GIS view even as the user pans into new areas.

The Primary Panel of the GUI holds most of the functionality of the PFS MDSS from the user's perspective. The Primary Panel can host one of four different "views". These views are the "Route View", the "GIS View", the "RWIS View", and the "Weather View". The user selects which view is active in the Primary Panel using selection tools in the Support Panel. Alternatively, when in the GIS View the user can quickly switch to any of the other three views by simply clicking on objects located on the map display of the GIS View.

Figure 6: Graphical User Interface GIS View

The Geographical Information Systems View is the geospatial display component of the GUI. It is based upon the OpenMap^{TM} open source Java GIS toolset. Users are provided a base map with pan, zoom, and static GIS overlay capabilities (e.g., counties, cities, roads, etc.). These static overlays are distributed in the delivered executable and therefore are immediately available and responsive to user requests. In addition, the GUI presently supports four other dynamic overlay types: Road, Background, RWIS, and Weather. These overlays are dynamic in the sense that they change over time. The user is provided a time slider that can be moved forward or backward in time to view past, present, or future data in a geospatial format.

The Road overlays are displayed in the form of selectable and color coded segments in the GIS View. They convey information about the MDSS' analyzed and forecast state for each road. Since the forecast state is dependent upon maintenance actions that have yet to be determined, users are provided the option

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to visualize outcomes with "No Treatment", their "Standard Treatment" (not yet implemented), or the "MDSS Recommended Treatment". The Background overlays primarily comprise raster graphics (e.g., radar, satellite, etc.). The RWIS overlays are presented as point data (text or icons) at the locations of the various RWIS sites and convey information about road and/or weather observations. The Weather overlays are presented in a similar fashion, but display data observed by ASOS and AWOS sites instead.

Features displayed by the Road, RWIS, and Weather overlays in the GIS View are selectable with a single mouse click. This selection brings up an information box giving summary information about the selected item. Within this information box there is an option to "Switch View" by which the user can swap the Road, RWIS, or Weather Views into the Primary Panel of the GUI. As mentioned previously, users can also switch the contents of the Primary Panel using selection tools that are always present in the Support Panel. It is therefore not necessary for the user to return to the GIS panel in order to switch between locations for a particular type of data or even to switch types of data.
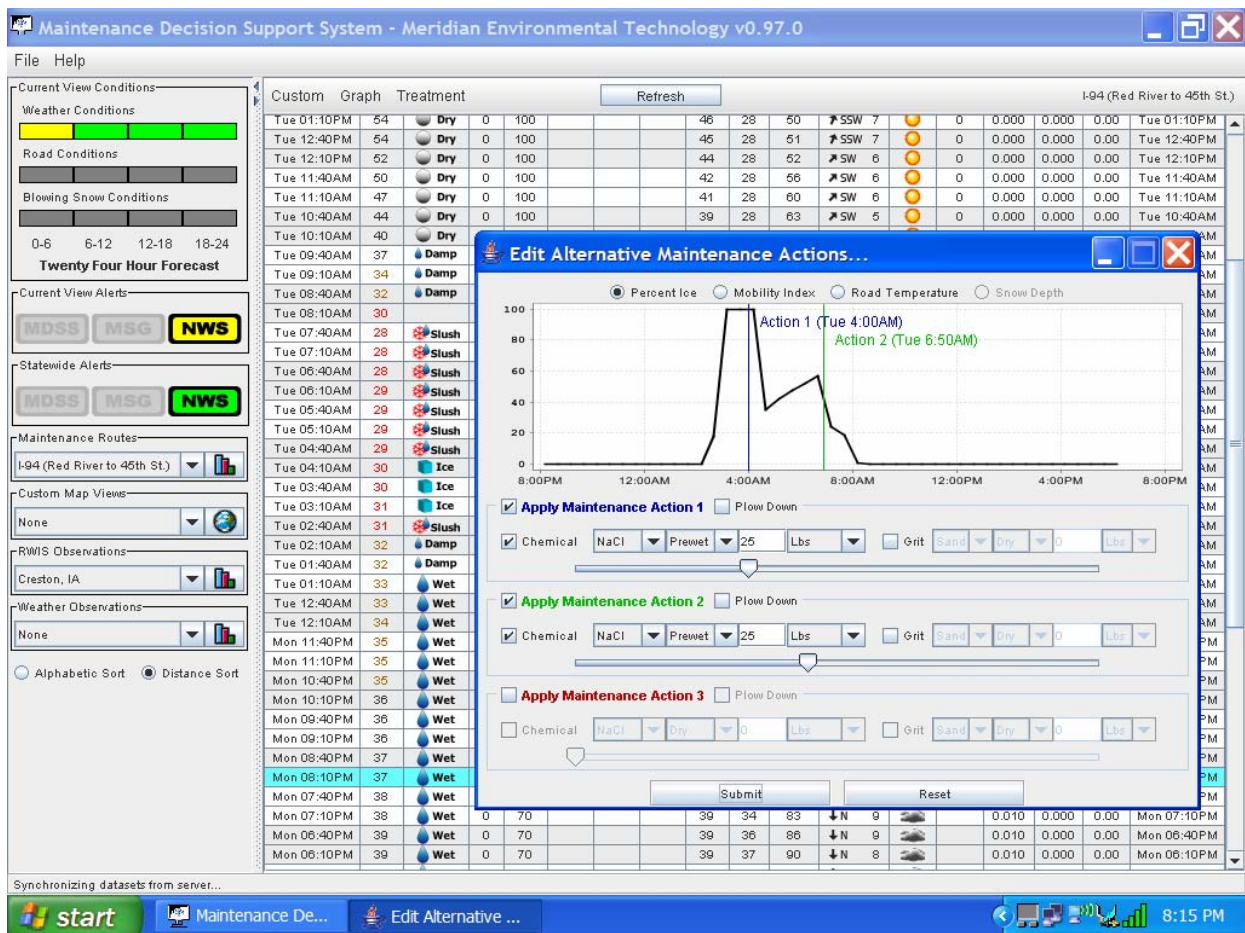
Figure 7: Graphical User Interface Road View

The Road View is intended to be the most powerful feature of the GUI once fully developed. The Road View presents a time series portrayal of maintenance, weather, and road information for each maintenance route and segment (Figure 7). These time series span from the past into the future, showing what has already occurred (as analyzed by the MDSS processing) as well as what is expected to occur in the future. Since the state of the roadway and the maintenance actions that effect that state are dependent

upon the treatment strategy taken, the user is allowed to compare expected results given no maintenance actions, the MDSS recommended maintenance actions, their standard maintenance actions, or an alternative 'what-if?' action specified by the user. The methodology behind the MDSS guidance recommendations was discussed in the preceding section. The specifics of the 'what-if?' actions are edited by the user via a simple interface. This functionality is intended to allow the user to attempt virtual maintenance actions and gain an understanding of the expected outcomes without the risk of carrying those actions out in reality. Information in the Road View is presented via either tables or graphs. The table format permits drag-and-drop reordering of information, as well as dynamic column resizing. Graphs of multiple parameters can be toggled on or off as well, and variables of similar natures can be overlaid on the same graph.

The RWIS and Weather Views function in substantially similar manners. They present the user with a time series view of RWIS, ASOS, and / or AWOS observations over the past 24 hours. The table and graph display formats used in the Road View are also utilized in the RWIS and Weather Views (Figure 8).
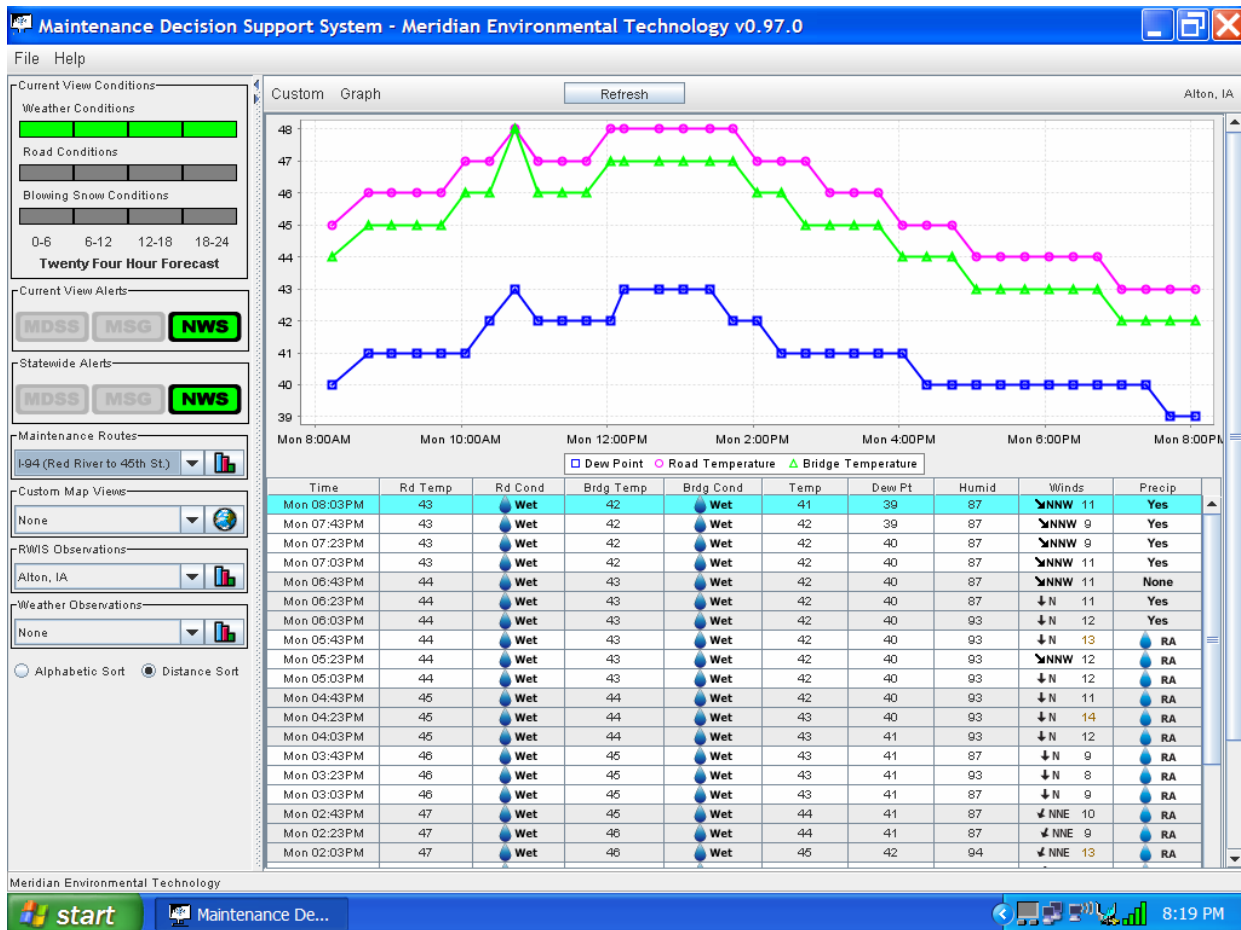

Figure 8: Graphical User Interface RWIS View

In addition to the GUI, the PFS MDSS also relies upon computer telephony technology in order to move information into and out of the maintenance vehicles. A simple menu is provided through which a user can 'configure' a truck by selecting a material, rate, and plow position to be assumed for future

maintenance activity reports. Thereafter the user is asked to call into the system each time the maintenance route is run in order to report the maintenance action to the MDSS processing system (after which it can be incorporated into the ongoing assessment of the road states). The menu system can be circumvented entirely once the user knows its layout, permitting speed dial programming of cellular phones for reporting routine maintenance activities. The menu system also permits the driver to submit road condition and weather reports that are subsequently assimilated into the MDSS system. Through a final option in the telephony system's menu the user can choose to hear the latest projections of weather and road conditions on a given route in light of reported maintenance actions.

Note that although the PFS MDSS supports maintenance activities reports using computer telephony, this is not perceived as a viable long term mechanism for maintenance activities tracking. The need for automated maintenance data collection is widely recognized among the PFS member states. Most have platforms to collect and distribute this information available on only a select few maintenance routes. Where available the PFS MDSS will incorporate these reports in real time, with the hope of learning valuable lessons for future statewide deployments of such systems.

CONCLUSIONS

Phase II set out to transition from the assessment phase of the PFS MDSS research effort to a demonstration that an operational decision support system could be developed and implemented. The Pooled Fund Study members had agreed to a sophisticated decision support system design in Phase I that was a substantially different approach than that taken by the FHWA in the implementation of the Functional Prototype. Phase II provided the opportunity to demonstrate the wisdom of this decision. The Limited Deployment Tactical Integration test demonstrated the detailed processing capabilities of the Road Condition Forecast and Analysis component of MDSS and its ability to interface with the Maintenance Data Collection component. Lessons learned from that test provided the foundation for the development efforts during the remainder of 2004. Software release Version 1.0 of the PFS MDSS represents the result of this development effort; the extensive discussion under Task 12 in the Findings section details the features and functionality of client-based user interface and the associated server based decision support package. The Version 1.0 user interface very effectively resolves the limitations of the LDTI interface. Meanwhile, substantial modifications were made to decision support system software after the LDTI test, particularly through the incorporation of new capabilities derived from the integration of research supported code. Members of the Technical Panel have had the opportunity to "test drive" the software as Version 1.0 came together in the final quarter of Phase II. The objective of transitioning from concept to an operational prototype has been accomplished. The next phase is to implement and evaluate the performance of the PFS MDSS solution.

RECOMMENDATIONS

The culmination of Phase II marks a significant milestone for the PFS MDSS project. The release of Version 1.0 represents an end of the planning stage. But more importantly it signals the beginning of the real objective of the project–the implementation and ongoing refinement of an operational maintenance decision support system. Phase II has highlighted some challenges that the Pooled Fund Study members still have to address. The primary challenge is validation of PFS MDSS Version 1.0 and a determination of how effectively the design and implementation serve the decision support needs of maintenance operations. Attention must also be focused on an effective way to segment highways to best serve the decision support needs of the maintenance community, both as segmentation relates to the physical characteristics of the road environment and the planning around route configurations. The development team, demonstration test participants, and the Technical Panel must work on an effective presentation of the projected state of the contaminant layer in terms which maintainers understand and work with routinely. In particular, the group must develop and evaluate a Highway Safety Index that synthesizes all of the scientific nomenclature into a simple measure of the road surface condition and its related safety and mobility factors.

The integration of maintenance activities is critical to the success of the MDSS and additional work needs to be done to develop effective methods of monitoring field activities and transferring these logged activities into the MDSS processing system. The study must evaluate what level of detail and accuracy are needed in the automated observation of maintenance practices and what effects different field-to-processing-system transfer intervals have on the value of the MDSS projections. Finally, the development effort must continue to integrate more research into the MDSS and evaluate the impact of this integration on the performance of the system.