Analysis of
Environmental Sensor Station
Deployment Alternatives:
Final Report

Submitted to:

North Dakota Department of Transportation

November 30, 2009

Surface Transportation Weather Research Center
University of North Dakota
Grand Forks, North Dakota

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

EXPERIMENTAL PROJECT REPORT

EXPERIMENTAL PROJECT	EXPERIMENTAL PROJECT NO.							CONSTRUCTION PROJ NO	LOCATION
	1	STATE: UND	YEAR: 2007	-	NUMBER: 01		SURF	SPRR029(003) 8	Grand Forks 28
	EVALUATION FUNDING							NEEP NO.	PROPRIETARY FEATURE?
	48	1 X HP&R	2 CONSTRUCTION	3 DEMONSTRATION	4 IMPLEMENTATION			49	51 X No / Yes
SHORT TITLE	TITLE 52 Analysis of Environmental Sensor Station Deployment Alternatives								
THIS FORM	DATE 140	MO. November	--	YR. 2009	REPORTING 1 INITIAL	2 ANNUAL	3 X FINAL		
KEY WORDS	KEY WORD 1: 145 RWIS Equipment				KEY WORD 2: 167 Pavement Sensors				
	KEY WORD 3: 189 Temperature Sensors				KEY WORD 4: 211 Precipitation Sensors				
	UNIQUE WORD: 233				PROPRIETARY FEATURE NAME: 255				
CHRONOLOGY	Date Work Plan Approved: 277 September 2007	Date Feature Constructed: 281	Evaluation Scheduled Until: 285	Evaluation Extended Until: 289	Date Evaluation Terminated: 293 November 2007				
QUANTITY AND COST	QUANTITY OF UNITS (ROUNDED TO WHOLE NUMBERS) 297	UNITS 305: 1 LIN. FT, 2 SY, 3 SY-IN, 4 CY, 5 TON, 6 LBS, 7 EACH, 8 LUMP SUM			UNIT COST (*Dollars, Cents*) 306				
AVAILABLE EVALUATION REPORTS	CONSTRUCTION 315	PERFORMANCE	FINAL X						
EVALUATION	CONSTRUCTION PROBLEMS 318: 1 NONE, 2 SLIGHT, 3 MODERATE, 4 SIGNIFICANT, 5 SEVERE	PERFORMANCE 319: 1 EXCELLENT, 2 GOOD, 3 SATISFACTORY, 4 MARGINAL, 5 UNSATISFACTORY							
APPLICATION	320: 1 ADOPTED AS PRIMARY STD., 2 PERMITTED ALTERNATIVE, 3 ADOPTED CONDITIONALLY, 4 X PENDING, 5 REJECTED, 6 NOT CONSTRUCTED	*(Explain in remarks if 3, 4, 5, or 6 is checked)*							
REMARKS	321 Recommendations resulting from this study are under consideration by NDDOT for future implementation when considering new RWIS site development or replacement of existing equipment. 700								

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Executive Summary

The North Dakota Department of Transportation (NDDOT) is currently evaluating the restructuring of their present Road Weather Information System (RWIS) to utilize Environmental Sensor Stations (ESS) that utilize low-cost alternatives to the "traditional" road weather pavement sensors. As a further future design consideration, the NDDOT is interested in the technical and cost feasibility of incorporating an open systems approach in their future RWIS/ESS design and deployment.

Under contract to the NDDOT the University of North Dakota Surface Transportation Weather Research Center (UND STWRC) engaged in investigations into the efficacy of low-cost ESS solutions that would support an open systems architecture. This work involved an assessment of the NDDOT current RWIS state-of-practice and an evaluation of agency personnel usage of this RWIS. This evaluation and user-expectations were used to prepare a prototype ESS for NDDOT consideration. This prototype ESS was constructed and demonstrated at the UND STWRC Road Weather Field Research Facility during the winter of 2008-09 to test the use of open systems interfaces to ESS sensors, evaluate the operating characteristics of selected sensors, and to assess the data management and operational needs to support such a system. This information was used to develop a design and management plan for a low-cost, open architecture ESS including a cost estimate to translate the single prototype into a full statewide RWIS.

The research yielded as set of identified opportunities and challenges associated with an alternative ESS deployment. These included:

Opportunities

- Vendor neutral incorporation of atmospheric and pavement sensors that can be selected *a la carte* (to a reasonable extent);
- Realization of a lower cost solution to ESS deployment (described further in Section VII) through in-house installation and configuration of ESS and a statewide RWIS;
- Minimal proprietary issues associated with sensor selection and implementation [Note: a truly open architecture would consist of an open source data acquisition software capability. Such open source software is possible in the near future, but not currently.];
- Scalability of the ESS network for future growth while incorporating new sensor technology as it becomes available;
- Development of in-house agency expertise to craft ESS configurations that best match the needs of the NDDOT;
- Cost reduction of ESS sensor packages through the replacement of pavement condition sensors with non-invasive camera imagery and improved precipitation detection sensors;
- The continued use of legacy ESS that are part of a present proprietary architecture while transitioning to an open architecture over time;

- Tailoring of ESS sensors, data management, and associated program data integration to better aide NDDOT-defined objectives of supporting maintenance personnel (both winter and summer), incorporation in Maintenance Decision Support Systems, improved traffic/incident management, improved road weather forecasting, and support for agency-related research efforts; and,
- Provide better information to travelers for weather-related decisions, through integration into 511 traveler information resources.

Challenges:

- The design and deployment, including sensor installation, data communications, and calibration, of the ESS becomes an agency responsibility requiring higher manpower commitments [Note: this can be mitigated by procurement of these services much as they are currently done with proprietary architectures];
- Development of in-house expertise will take time and an agency investment to understand the intricacies of configuration of sensors within an open architecture, including developing software expertise to work efficiently with ESS sensor data;
- Sustainability of agency budgeting for a long-term RWIS commitment can be difficult during periods of great economic pressure leading to possible loss of critical mass in agency ESS open architecture knowledge and expertise; and,
- Transition of current proprietary RWIS architecture to an open architecture with data integration of legacy ESS will require the development of an interface layer of software to merge the capabilities of the two systems.

The findings indicate that such a low-cost and open architecture ESS is feasible, both in terms of design/development and relative costs to expand/enhance the current proprietary RWIS configuration. However, to optimize benefit to the NDDOT and its stakeholders, it is recommended that a data management plan that will ensure the quality of the data and its accessibility to all operations and services be established and emphasized.

To support procurement of open system components consistent with the construction of an integrated, low-cost ESS configuration, specific ESS sensor component characteristics and a list of qualified vendors who provide these components was compiled.

I. Introduction

Over the past decade substantial debate has occurred regarding the future direction of environmental sensor stations (ESS) and the corresponding operations of Road Weather Information Systems (RWIS) within state departments of transportation. This debate often has centered on three central issues. The first involves the appropriate architecture for interfaces to ESS components, and how these are managed relative to the data collection and management. The second issue relates to the quality of data derived from the ESS, focusing primarily on the reliability and cost effectiveness of the surface condition and chemical concentration parameters reported by in-pavement sensors. The third issue relates to cost constraints associated with the installation and maintenance of sensors. This includes the frequency of replacement of sensors destroyed due to pavement maintenance and/or construction that limits the expansion potential of the statewide road weather network.

As the North Dakota Department of Transportation (NDDOT) is considering the use of low-cost alternatives to the "traditional" road weather pavement sensors as part of their future deployments, it is important to understand the availability of these sensors and how best to utilize the resulting systems to satisfy user needs and minimize costs, both long- and short-term. Hence, the transition to a new ESS paradigm requires consideration of various factors including:

- Value of ESS data delivered to end-user community;
- Cost;
- Quality of the data received from the sensors;
- Comparability of sensors provided from various vendors;
- Integration of additional non-vendor specific sensors in the existing ESS sites and road weather information system data management infrastructure; and,
- Potential impact on the data management requirements to collect and utilize these data.

The quality of data is an issue of paramount importance. Quality must be addressed by selecting sensors that provide reliability and accuracy levels along with sufficient lifetimes desired by the NDDOT to support their operations, while potentially providing a lower cost alternative to present ESS deployments. Knowing which vendors provide acceptable quality sensors at a reasonable price is important in NDDOT procurement decisions. Central to these decisions is understanding the needs and requirements for which the data are to be used.

The present NDDOT vendor-specific RWIS architecture dictates the types of sensors that can be managed by the remote processor unit (RPU) (i.e., an in-field data logger supporting on-site processing), field data storage, and communications protocols. Often, the addition of new sensors must be provided by the original vendor or from an approved list of equipment the vendor's RPU will support. However, this might not provide the best solution for the NDDOT in achieving their goal of a lower cost and more reliable RWIS. As part of an effort to develop a plan for their future ESS deployments, the NDDOT is exploring the possible transition to an open architecture for their ESS deployment. Before implementing such a transition plan it is important to evaluate the most economical path to achieve the desired

outcomes. This includes a cost analysis of the use of commercial, off-the-shelf (COTS) equipment to support this transition relative to the use of an integrated vendor ESS solution. Of particular potential benefit is the use of an open architecture that provides the opportunity to utilize a more diverse set of potential sensor solutions.

Important to future RWIS plans is developing an understanding of the level of data management required to support an evolving RWIS, and how this data management should support end-user access of the data. While national standards for conveying ESS data from field locations to a central data collection/processing center have greatly reduced the compatibility issues within RWIS configurations, the presence of legacy ESS continue to restrict evolution of existing systems. However, the overall issues associated with management and quality checking/control of data volumes resulting from the wider use of fixed and mobile sensors, the frequency of data collection, and how the data are utilized once they have been collected, are still issues requiring investigation. Hence, understanding the information technology support requirements and the communications methodologies are important system costs in the long-term use and operating cost of the system.

II. Background

First generation RWIS networks were not designed to conform to the National Transportation Communications for Intelligent Transportation System (ITS) Protocol Environmental Sensor Station Interface Standard (NTCIP 1204)[1] and were not supportive of an open architecture concept. As a result, state departments of transportation (DOTs) and other transportation agencies were required to use a single vendor for their systems to maintain component compatibility. In the past decade, the trend within the surface transportation community has been towards RWIS networks and their ESS component becoming standardized (i.e., NTCIP compliant). The increasing reach of the Internet and wireless communications has spurred interest by transportation agencies to restructure their networks towards an open architecture. Open architectures further widens the opportunities for ESS component vendor diversity and broader use of the Internet. The premise of standardization and of open architecture is they will allow agencies to utilize multiple vendors for equipment and sensors and have more control over their data and its management. These flexibilities come with some constraints. Uncertainties, may, include

- Potential conflicts that might arise between the flexibility of an open architecture and the constraints from the NTCIP 1204 standards conformance; and
- Increased maintenance costs necessary to manage a larger diversity of sensors.

The following are examples of how the road maintenance community has begun to adopt standardization as well as a more open architecture in RWIS network design.

[1] The National Transportation Communications for ITS Protocol Environmental Sensor Station Interface Standard (NTCIP 1204) defines objects that are specific to environmental sensor stations and object groups that can be used for conformance across sensor manufacturers. The standard describes methods for non-vendor specific communication between central processing units and ESS through the use of a NTCIP application layer services to convey requests to access or modify values of ESS objects The NTCIP is a joint standardization project of AASHTO, ITE, and NEMA, with funding from the RITA ITS JPO. Reference: http://www.standards.its.dot.gov/StdsSummary.asp?ID=348

When Sweden decided it wanted to implement Road Weather Information Systems (RWIS) there were several key requirements that had to be satisfied[2]. These were internal marketing, multi-source input, thermal mapping, open system architecture, and training. Of these five requirements, the open system architecture is most relevant to this research project. The Swedish RWIS is considered an open system architecture in that they are able to utilize sensors and equipment from multiple vendors.

Ontario's Ministry of Transportation (MTO) invested in RWIS with its first station being established in 1991[3]. Between 2001 and 2004, the MTO expanded its RWIS by 85 sites. This process was advertised so that multiple vendors could bid on the acquisition and installation of the stations per specifications set by the MTO. Among the specifications were the technical specifications "…in accordance with the requirements of the national standards…" and based on an open architecture and conforming to NTCIP. Ontario's RWIS stations have five vendors: Surface Systems Inc. (SSI), Lufft, Boschung, Vaisala, and Campbell Scientific.

In 2003, the Ohio Department of Transportation (ODOT) decided to expand its Road Weather Information System (RWIS) from 72 stations to 158[4]. New stations were required to support wireless communications and be NTCIP compliant. The 72 older stations were not NTCIP compliant. ODOT did a cost analysis on what it would cost to upgrade the older stations to NTCIP compliance and to establish a system that would be NTCIP compliant but with an open architecture. Station upgrade for just the NTCIP compliance would be roughly $288,000 (for all 72 stations), while establishment of NTCIP compliant open architecture would be $780,000. The $500,000 difference between the upgrade and open architecture is largely attributable to the difference between using existing equipment within an ESS for the upgrade and using entirely new equipment to support the open architecture system. The resulting costs do not provide a true one-to-one comparison; however, the equivalent cost to replace the entire RWIS network with a non-NTCIP compliant configuration is greater than the open architecture solution due to the higher cost of the integrated proprietary system. This study did not provide information on the future on-going costs to maintain the systems.

[2] Development and Use of the Swedish Road Weather Information System, Axelson, Lennart, Director at the International Secretariat Swedish National Road Administration, (http://www.twncs.com/PDFs/development_and_use_of_RWIS.pdf)

[3] Road Weather Information Systems at the Ministry of Transportation, Ontario, Buchanan, Finlay, and Gwartz, S.E., Ministry of Transportation, Ontario, Road Weather Information as a Decision-making Tool in Winter Maintenance Operations Session of the 2005 Annual Conference of the Transportation Association of Canada, Calgary, Alberta (http://www.tac-atc.ca/English/pdf/conf2005/s3/buchanen.pdf)

[4] Ohio DOT Roadway Weather Information System (RWIS) Expansion, Technology Aids ODOT, Motorists During Winter News release, December 2003, and correspondence with Mr. Abner Johnson, ODOT RWIS Coordinator, Office of Maintenance Administration, February 2003, Ohio DOT (http://www.itscosts.its.dot.gov/its/benecost.nsf/ID/ED80CCA32A9685DB85256E4E0066BA96

Alberta Transportation started a project in 2003 to develop and deploy an RWIS network over the course of three years[5]. During this time, ITS Canada had been trying to develop a universally accepted standard and architecture, recommending the NTCIP standard. Not all vendors had software and hardware that was NTCIP compliant. Environment Canada had a way of incorporating multiple vendors' data but did not have the capability to archive large amounts of data. It was suggested in the short-term Alberta Transportation should develop their own NTCIP compliant server, user interface, and data management server. This would allow them to have full control over the system, any upgrades, and how and when data were gathered and displayed.

III. Project Scope

The purpose of this study is to evaluate the technical and cost feasibility of transitioning the environmental sensor stations (ESS) across North Dakota to an open architecture paradigm incorporating commercial, off-the-shelf (COTS) technologies. The objectives and scope of this project were developed during a series of discussions with NDDOT maintenance management personnel who had expressed a desire to explore low-cost alternative to the current high costs for proprietary ESS installations, and the possibilities of satisfying the agency's road weather needs through the use of non-typical sensor arrays.

The scope of work performed in this research was divided into five tasks reflecting the interests of the North Dakota Department of Transportation. The tasks performed included:

1) User needs assessment to understand the perspective of rank-and-file NDDOT maintenance personnel on ESS usage and expectations;
2) Instrumentation evaluation in an open architecture arrangement to determine RWIS upgrade potentials that responded to NDDOT management and personnel expectations;
3) Formulation of an open architecture ESS system design, data management plan, and system maintenance to provide guidance to NDDOT on possible directions and challenges in adopting open architecture for its future RWIS;
4) Cost analysis of transitioning to an open architecture ESS (including the required maintenance of the system); and,
5) Reporting project findings in a final report and executive summary presentation.

The following sections provide the description of research methods and findings resulting from work conducted under this study.

IV. ESS User Needs Assessment

The overarching purpose of the NDDOT RWIS is to support local maintenance actions conducted in each maintenance district across North Dakota. This operational level of use of

[5] Development of a Road Weather Information System (RWIS) Network for Alberta's National Highway System, Pinet, Mark F. & Associates Limited, Alberta Transportation, 2003 (http://www.tac-atc.ca/English/pdf/conf2003/pinet.pdf

ESS data requires the emphasis in assessing *user needs* be focused on interviews with field personnel actively using ESS data to support their decision-making. This resulted in ESS needs assessment interviews being conducted in all eight NDDOT Districts from March through October 2008. NDDOT personnel were interviewed to determine how present ESS data are used in supporting operations and to understand what limitations these personnel felt existed. This included a discussion of the expectations of ESS data by agency personnel, ways in which ESS can better satisfy agency operational needs, and the acquisition of insight regarding what these individuals saw as opportunities for using ESS.

Across all eight districts, the primary uses of ESS data were:

- To assist in determining the appropriate timing of snow and ice road treatments;
- When to plow the roads;
- To observe conditions at other locations, both within the state and in other states;
- To see what weather is approaching; and,
- For determining spring frost thaw and load restrictions.

Other uses included summer construction weather reports, scheduling of personnel for incoming winter storms, and verification of the forecast and projected conditions with actual conditions. The districts also use the system-wide collection of ESS, i.e., the road weather information system (RWIS) network, in conjunction with area forecasts from a road weather service provider as well as the Maintenance Decision Support System (MDSS).

Based on the interviews, personnel in the maintenance districts indicate they use most of the sensor data in the current ESS configuration. The most commonly used sensors were air temperature and pavement (pavement temperature and condition), along with cameras (when available), sometimes used to determine what treatment, if any, should be applied to a given segment of road. NDDOT personnel stated the air and pavement temperatures are used to determine if the treatment should be sand/salt, only sand, or a liquid chemical. The next most commonly used sensors were wind and pavement subsurface. Blowing snow was mentioned as a significant problem in many of the districts and is a concern for personnel in their decision-making. Some personnel indicated they have been with NDDOT long enough to know that in a given location, if certain conditions exist, they are going to have problems with blowing snow. Many will use wind speed and direction to determine if a given stretch of road will have blowing snow and then decide whether or not to pull the plows or deploy them to plow the roads.

Common challenges mentioned in nearly all the interviews were spring thaw and load restrictions decision-making. Some districts use Falling Weight Deflectometer (FWD) data either alone or in conjunction with ESS pavement and subsurface temperatures to make decisions on sub-grade conditions. It was noted a delay in receiving FWD data can sometimes be lengthy such that personnel will incorporate alternate decision support methods such as experience, subsurface temperatures, or the extent of load restriction in other districts south and west of them. Other districts look solely at the ESS pavement and subsurface temperatures to determine when to implement the load restrictions.

Even though ESS pavement sensor data are regarded as important, the district personnel question the reliability of the conditions reported. Of the observations available from a pavement sensor (temperature, conditions, freeze point temperature and sub-pavement temperature), many rank high in the data's importance to conducting winter operations. Individuals were asked to rank on a Likert scale of one to ten (one being the least important and ten being the most important) the importance of ESS pavement-related information they could receive to assist their operational use. In general, all of the pavement-related ESS data were considered to be of importance, with the results being:

- pavement temperature: 9
- pavement conditions: 8
- pavement freeze point: 7
- sub-pavement temperature: 8 (seasonally dependent).

The importance of pavement freeze point temperature varied most among districts. While most districts looked at freeze point temperature as being somewhat important, one rated the importance with a two and another does not use the value, citing questionable values and unreliability of the observations.

Personnel from all districts commented that the reliability of the pavement condition sensor data has been in question for some time. Not many districts expressed confidence in the pavement condition or freeze point temperature that is reported, and two districts do not look at freeze point temperature because of the lack of trust in its reported value. This reliability of the data presents a persistent problem, as frequently personnel are deployed to check on the actual condition of a road segment, depending on what the pavement condition/freeze point temperature sensor is reporting due to the mistrust of the sensor readings. Personnel from two districts expressed concerns regarding the added expense incurred to perform this manual validation of the ESS-sensed road conditions and the negative impact on their effectiveness determining whether to perform treatments. One district went as far as conducting its own test with the pavement sensor and chemical, placing chemical on a sensor then calling back to the office to obtain the observation. After driving over the sensor, the reported value was far from where it should have been for what was spread on the sensor. As a result, they have largely discontinued using the ESS pavement condition sensor.

The solution seen by NDDOT district maintenance personnel to counter the lack of trust in the ESS in-pavement sensor reported pavement condition is the use of video cameras at the ESS. Cameras are seen as a verification tool for pavement sensors as well as giving the districts a visual assessment of the road conditions. Cameras are believed by these personnel to be an invaluable asset, though they are not present at most of the locations. Personnel also indicated the use of camera images to view incoming weather. Many personnel will view camera images outside of their area to observe weather that may be moving their way. This includes ESS in the state, as well as those in South Dakota and Montana.

District personnel were satisfied with the accessibility of data, but had varying opinions on the frequency of data updates. All districts are able to access the North Dakota ESS data via

their intranet, which takes them to the NDDOT ScanWeb[6] page. Currently, the data are also accessible through MDSS; however, MDSS is currently used more as a forecasting tool than examining data from ESS locations. Maintenance personnel opinions varied on how frequently they would like the ESS data made available to them. Some were content with the current set up of polling times, while others were looking for more frequent updates.

Personnel in all districts expressed a need for more ESS data locations. These could be within their respective districts, in another district, or even a different state. Additional sites would provide data for identifying weather conditions potentially moving their way, providing them a better understanding of current conditions, and enabling them to better prepare for possible winter storms. Many agreed that with the large district coverage and differing weather elements possible within a district, the weather in one location could be completely different from the weather in another. Some locations given by NDDOT personnel as possible additional ESS locations include:

- Hersfield
- Peace Gardens
- Along the ND/Canadian border
- South of Devils Lake
- Northwest corner of ND
- Minot Air Base
- Berthold (bridge to the west)
- Petersburg
- Oaks
- Foreman
- Thompson or Merrifield
- Hwy 13 and Hwy 1(Verona and Oaks)
- Washburn

When asked to recommend an ESS configuration and/or sensor packages that would better aid in their planning and deployments, district maintenance personnel provided the following recommendations:

- Precipitation sensors reporting winter precipitation type, rate, intensity, and amount;
- Visibility sensors or visibility monitoring capability for low visibility and blowing snow conditions;
- Deep soil probes for monitoring frost front movement in the spring (sometimes in the fall) and to aid with the timing of seasonal load restrictions;
- More video cameras, preferably with pan/tilt/zoom capabilities with more frequent updates or live streaming;
- More accurate pavement sensors, specifically regarding pavement condition and chemical concentration measurements;
- Incorporation of dynamic signs with ESS for notifying travelers of adverse conditions; and,

[6] Scan Web is a registered product of Surface Systems, Incorporated.

- Infrared pavement sensors for determining the thickness of slush, snow, and ice (particularly on remote, high volume roads and interstate highways).

The most resounding requests from each district were a desire for more video cameras. It was generally noted that maintenance personnel struggle more with remote ESS that do not have a camera. As mentioned earlier, maintenance personnel noted plows often are deployed to a given ESS location based on what the pavement sensor is reporting. Too frequently, these situations result in actual conditions being different than what was reported by the sensors. The districts report that with the amount of money involved with man-hours and fuel, it is expensive to send a driver to a location if they are not needed. Lack of trust has resulted in the pavement condition and chemical concentration sensors such that many find these sensors of little value for the cost. On the other hand, a camera would eliminate unnecessary trips by allowing the individuals responsible for the maintenance routes supported to view the conditions via camera. The district personnel, however, do realize there are communication bandwidth limitations and commercial power limitations at remote sites.

When open architecture configurations were described to NDDOT personnel, many were in favor of such an option in hopes of reducing the cost of supporting/installing ESS and the potential for allowing for the installation of more sites. Given the use of the overall RWIS network, some district personnel mentioned not all ESS need to have the full suite of sensors. In some remote locations, either a camera and wind sensor or a camera and pavement temperature sensor would suffice. The configuration would depend on the area and what the district personnel would deem to be appropriate. For example, in areas where blowing snow is a concern a wind sensor and camera would be appropriate. In some locations, it was expressed that a camera alone would suffice. In most situations, however, it was believed that having at a minimum a camera and pavement temperature sensor was needed.

As ESS data, along with MDSS forecasts, are used more by NDDOT supervisors for scheduling of maintenance personnel for winter operations, determining if and when to treat and/or plow, and (if treating) what chemicals to use, agency personnel are looking for more accurate information. These supervisors are looking for more reliable sensors and more locations to collect weather and pavement information. In summary, the RWIS/ESS user needs identified in the user assessments were:

- Increased number of ESS across North Dakota, including video cameras
- More frequent access to ESS data, particularly from video cameras
- Improved reliability of pavement condition sensing
- Expanded sensor capabilities for:
    - Precipitation
    - Visibility
    - Deep soil temperature and moisture conditions
    - Blowing Snow
- Increased capabilities for camera images
    - Infrared
    - Pan/Tilt/Zoom
    - More frequent image updates

Given the needs summarized above, the district maintenance personnel did realize that there are budgetary limitations to what can be done to increase the coverage and accuracy of ESS data. Many expressed optimism that an open architecture approach to the RWIS/ESS would permit more long-term options and a lower cost to the agency.

V. Instrumentation Assessment and Evaluation

Significant project effort was directed at the establishment of a comprehensive list of ESS sensors relevant to the NDDOT project interest and of ESS sensor characteristics, including, performance characteristics, vendor, interface method (e.g. NTCIP 1204, proprietary), data volumes, accessibility (e.g., telephone, IP addressable, etc), accuracy, reliability, life expectancy, and cost. Part of this activity included the acquisition and testing of selected ESS sensors to conduct an evaluation of sensor configuration and relevance towards establishing a low-cost, open architecture alternative for future NDDOT RWIS/ESS configurations. The timeframe for the sensor testing and evaluation was 15 December 2008 through 31 March 2009. This effort included the installation of sensors, development of data integration and management methods, and testing and evaluation of pavement-related sensors.

The instrumentation assessment effort utilized new and existing road weather instrumentation resources of the University of North Dakota's (UND) Surface Transportation Weather Research Center (STWRC) Road Weather Field Research Facility (RWFRF). This facility is located along and adjacent to Interstate 29 (I-29) twenty-one miles south of Grand Forks, North Dakota. The RWFRF had pre-existing pavement and atmospheric sensors that were utilized in the study as well as a newly installed 35-foot tower instrumented adjacent to I-29. The latter included various atmospheric sensors, as well as a pavement sensors installed in the active driving lanes of I-29. The purpose of the new instrumented tower was to construct a prototype ESS configuration to test the efficacy of open architecture design and to support the assessment of pavement sensors. The sensor array assigned to this tower and the adjacent I-29 roadway included:

- Lufft Radar Rain Precipitation Sensor (R2S)
- RM Young 81000 Ultrasonic Wind Sensor (3D)
- Campbell Scientific HMP45C Temperature/Relative Humidity Sensor
- Met One Instruments 50.5H Sonic Anemometer (2D)
- Campbell Scientific SR50 Sonic Ranging Sensor (Snow Depth)
- Kipp and Zonen CNR1 Net Radiometer
- Lufft IRS31 Pavement Sensor
- Zydax Active Passive Surface Sensor (ZAPSS) with a Drop Down Temperature Sensor (DDTS)
- Zydax Temperature Sensor (ZTS).
- Axis 233D Network Dome Pan/Tilt/Zoom Camera
- Wavetronix Smart Sensor HD model 125 traffic monitor

The installation of the Wavetronix Smart Sensor HD model 125 traffic monitor was not part of the original tower design, but became available as part of other research being conducted at the RWFRF. This Wavetronix sensor provides vehicle information such as speed, class, and volume, and its addition was utilized in evaluating the coupling of camera pavement images and pavement sensor data to monitor existing road conditions.

The Lufft R2S precipitation sensor is a radar-based sensor (operating with a 24-GHz Doppler radar) to detect precipitation type, rate, and accumulation through microwave measurements of backscatter cross-section of vertically falling precipitation particles. Due to the inherent difficulty associated with obtaining wintertime precipitation measurements across North Dakota where blowing snow can quickly contaminate precipitation samples, the vertical sensing direction of the R2S sensor was selected to evaluate its potential to overcome this contamination and provide a more realistic and reliable measurement of snowfall. Precipitation indicator types include: none, rain, snow, hail, freezing rain, and sleet. Accumulation can be set to a resolution of 1 mm, 0.1 mm, or 0.01 mm. The sensor can be configured as Internet Protocol (IP) addressable in binary or ASCII format.

The Zydax ZAPSS sensor is an intelligent pavement sensor that reports the following measurements:

- Surface temperature,
- Pavement temperature at a depth of 1.75 inches (4.5 cm),
- Surface conditions (wet, dry, chemical wet, trace),
- The last 5 surface conditions since the last data poll,
- Time the last active cycle was completed,
- Date the last active cycle was completed,
- Freeze point temperature (active cycle),
- Current surface condition (reported from last active cycle),
- Depth of liquid on surface of the sensor.

Along with the above, the ZAPSS has an attached Drop Down Temperature Sensor (DDTS) with 5 feet of cable that can be installed at any depth in the pavement or materials beneath the pavement. The active pavement conditions cycle on the sensor includes measurements of the freeze point temperature and a current surface condition. This active cycle component can be set to run once an hour or at a maximum of twice an hour.

As part of an evaluation of 'low-cost' alternatives for ESS design, the stand alone thermistor-based temperature Zydax Temperature Sensors (ZTS) was evaluated. Besides being lower in cost, these sensors have the capability of being placed anywhere in the pavement and are not attached to the ZAPSS intelligent pavement sensor. They allow for lower unit costs along with the potential for monitoring multiple locations in the roadway. The Zydax sensors (ZAPSS and ZTS) can be configured for data hookup via telephone line, serial connection, or can be made IP addressable. In the prototype sensor integration plan for this effort, the IP addressable and serial connection to a datalogger were each configured for testing of the open architecture design. The operational temperature range for both the ZAPSS and the ZTS is -50°C to +85°C (-58°F to + 185°F).

Another pavement sensor evaluated was the Lufft IRS31 intelligent pavement sensor. This passive sensor measures:

- Road surface temperature,
- Liquid film height,
- Freeze point temperature (inferred),
- Road condition (dry, damp, wet, ice, or snow, residual salt, freezing rain),
- Chemical concentration (%) of liquid component,
- Chemical content (g/m^2) within liquid component,
- Additional temperature sensors (one for pavement temp and one to be placed deeper in the pavement as specified by the user).

The range of temperatures measured with the IRS31 is -30°C to +70°C. Its range for the freeze point temperature is -20°C to + 0°C. The IRS31 was used as part of the open architecture design using a serial data connection, but the sensor can also be converted into an IP addressable unit.

Additional sensors utilized during this project were included from the existing suite of STWRC RWFRF sensors. The primary existing research sensors utilized were two Geonor Vibrating Wire Precipitation Gauges. Both gauges were equipped with a single windshield with the two gauges arranged in a side-by-side configuration for the purpose of measuring the localized variability in precipitation amounts.

Winter Sensor Evaluation

The following sections detail the efforts conducted during winter testing to evaluate the performance of the precipitation and pavement sensors that were part of the open architecture evaluation.

Winter Precipitation Events – Lufft R2S Precipitation Sensor

Given the high priority expressed by NDDOT for reliable wintertime precipitation measures, efforts were focused on identifying a precipitation sensor that provided such reliability in addition to supporting an open architecture design. While various precipitation sensors satisfied the latter criteria, finding a sensor that produced a reliable estimation of wintertime precipitation proved problematic. UND STWRC experience with advanced precipitation measuring system in the past, particularly with the Yankee Hotplate Total Precipitation Sensor (model TPS-3100) and the Geonor Vibrating Wire Precipitation Gauge (T-200B), indicated that both of these sensors could suffer from serious inaccuracies under certain conditions. Based upon discussions with other state DOT personnel on the apparent successes experienced during winter conditions, the Lufft R2S precipitation sensor was selected for use during the evaluation process. The R2S was located atop the tower adjacent to I-29 at a height of approximately 10-meters (~33 feet). Using published sensor design and communications protocols, data communications were established with the sensor and appropriate data acquisition methods were developed to access the data directly from the sensor. A series of winter events were subsequently evaluated to assess the effectiveness of the sensor.

Total snowfall amounts for the event from both R2S sensors were compared against the two Geonor vibrating wire precipitation gauges and National Weather Service (NWS) radar-estimated precipitation. Efforts to use the Yankee Hotplate precipitation sensor were unsuccessful as the unit was undergoing re-calibration by the manufacturer throughout the entire winter season and thus was not available for comparison.

The Geonor precipitation gauges, which are research-quality high-precision precipitation gauges that have been successfully deployed for measuring liquid precipitation, were used for observational comparison. However, as they represent the class of orifice gauges most commonly used within the weather community, they are prone to underrepresentation of wintertime precipitation. They are included in this study as a benchmark of *commonly accepted practice* for comparison to the R2S precipitation measurements. The NWS estimated precipitation is a radar-derived precipitation amount that is quality controlled by the NWS using routine analyses of regional surface and satellite-based observations. This product is generated as "a byproduct of National Weather Service (NWS) operations at the 12 CONUS River Forecast Centers (RFCs), and is displayed as a gridded field with a spatial resolution of roughly 4x4 km"[7]. The NWS-reported precipitation amounts are valid at 12 UTC for a 24-hour period.

December 30, 2008

On December 30, 2008 snow fell at the STWRC RWFRF starting at approximately 0822 UTC and ending around 1351 UTC. Snowfall amounts in this five and one-half hour period for the I-29 R2S sensor was 8.85 mm. For comparative purposes the precipitation amounts for the period of 1200 UTC December 29 to 1200 UTC December 30 reported by the R2S, both Geonor gauges, and the NWS estimated precipitation are shown in Table 1. Winds during this weather event were from the north with speeds early in the period from 1 to 2 m/s but they quickly increased in speed to 4 to 8 m/s. A graph of precipitation intensity measured by the R2S sensor (Figure 1) indicates that the snow occurred in three bands about an hour apart from 0830 UTC to 1030 UTC, mostly during the period of lighter winds. The image of the NWS observed precipitation (Figure 2) indicates the estimated snowfall amounts decreased from 2.5 mm to the south of the RWFRF site toward 0.25 mm north of Grand Forks, ND. A rough estimate of the gradient yields an estimated total precipitation ending at 1200 UTC of 1.9 to 2.0 mm. The Geonor values fit more closely with the NWS radar-estimated values and suggest that the R2S values, which are almost an order of magnitude larger, are suspect. The reasonably low wind speeds would suggest the under catch of snowfall issue inherent with the Geonor precipitation gauges in stronger winds is not an issue in this situation. Thus, in this situation it appears that the R2S measured precipitation amount in excess of what the other sensors reported.

Table 1 Precipitation amounts for the reporting time period of 1200 UTC December 29 to 1200 UTC December 30, 2008. Amounts are shown for the Interstate 29 R2S precipitation sensor, both Geonor precipitation gauges, and the NWS radar estimated precipitation.

Reporting Period	R2S Interstate 29	Geonor 1	Geonor 2	NWS Estimated Precipitation
1200 UTC	8.02 mm	1.6 mm	1.4 mm	0.25 – 2.5 mm

[7] Advanced Hydrologic Prediction Service; http://water.weather.gov/about.php

Dec. 29 to 1200 UTC Dec. 30				

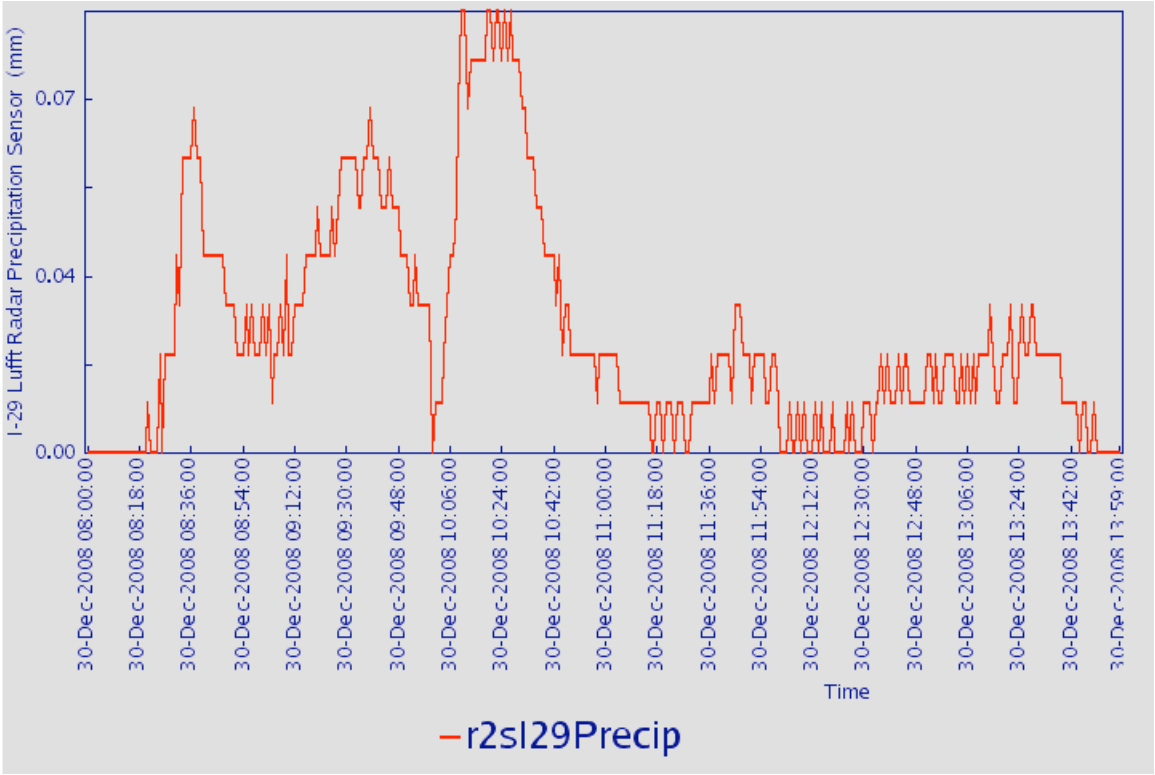

Figure 1 R2S precipitation sensor one-minute liquid equivalent precipitation amounts (in millimeters) for December 20, 2008. Reporting period 0800 UTC to 1359 UTC.

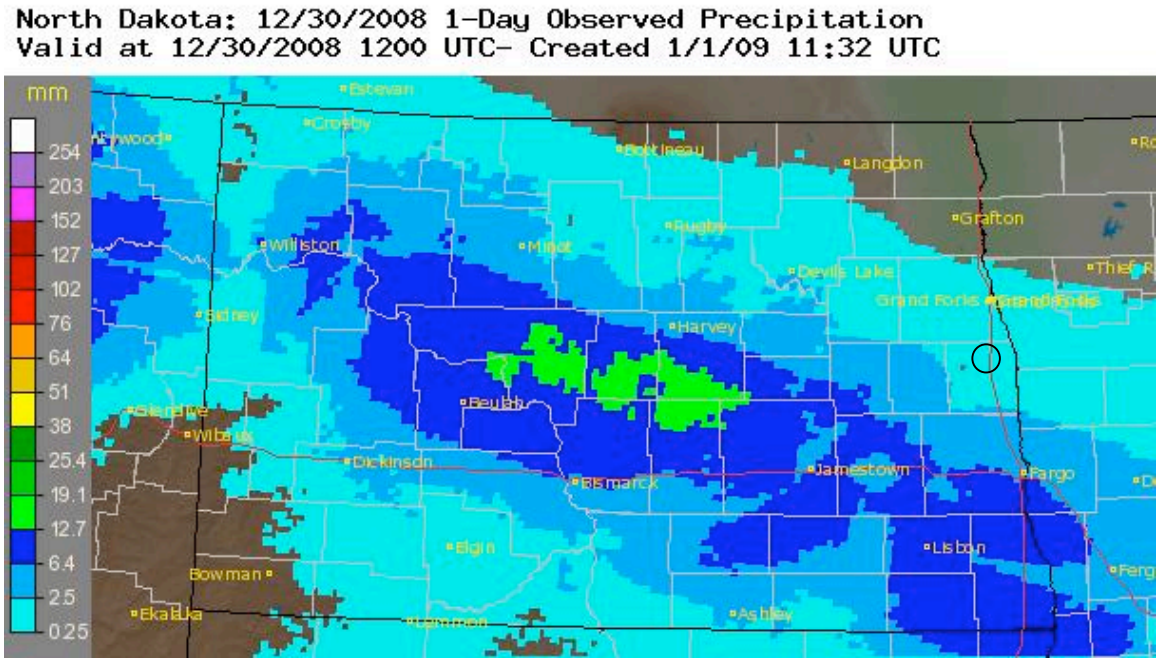

Figure 2 National Weather Service radar estimated precipitation for the reporting period valid 1200 UTC December 30, 2008. The RWFRF site (designated by the black circle) is located in the area that was estimated to have received 0.25 mm to 2.5 mm of precipitation.

February 26, 2009

Snow fell at the STWRC RWFRF site on February 26, 2009. Figure 3 provides the graphical display of precipitation intensity observed using the R2S sensor on this date. Two camera images (Fig. 4) verify the presence of snowfall during the day. The winds during this event were from the north and ranged in speed from 7 m/s to 21 m/s. Although this weather event was one continuous event, it occurred within two separate 24-hour reporting periods; the first being 1200 UTC February 25 to 1200 UTC February 26 and the second from 1200 UTC February 26 to 1200 UTC February 27. The NWS radar precipitation estimation graphics for the two 24-hour periods are show in Figure 5. Precipitation started around 0817 UTC February 26 and was intermittent before increasing in intensity and ending at 1932 UTC February 26. The RWFRF (Buxton, ND) circled on the top image of Figure 5 is located in the band of NWS radar estimated precipitation that ranges from 0.25 to 2.5 mm during the first reporting period. The RWFRF location on the second image shows the site in the 2.5 to 6.4 mm precipitation during the second reporting period. Table 2 details the breakdown of snowfall totals as reported by all precipitation sensors at the RWFRF and the NWS. The R2S and NWS radar estimated precipitation amounts have a reasonable correlation; however, they both estimate more snow than was captured by the Geonors, especially during the second period.

Table 2 Precipitation amounts from the R2S and Geonor sensors and the NWS radar estimated precipitation for the February 26, 2009 snowfall event. The precipitation amounts are divided into two reporting periods: 1200 UTC February 25 to 12 UTC February 26, and 12 UTC February 26 to 12 UTC February 27.

Time Period	R2S (Interstate 29)	Geonor 1	Geonor 2	NWS Estimaged Precipitation
1200 UTC Feb. 25 – 1200 UTC Feb. 26	1.83 mm	1.7 mm	1.1 mm	0.25 mm – 2.5 mm
1200 UTC Feb. 26 – 1200 UTC Feb. 27	6.29 mm	1.9 mm	1.0 mm	2.5 mm – 6.4 mm

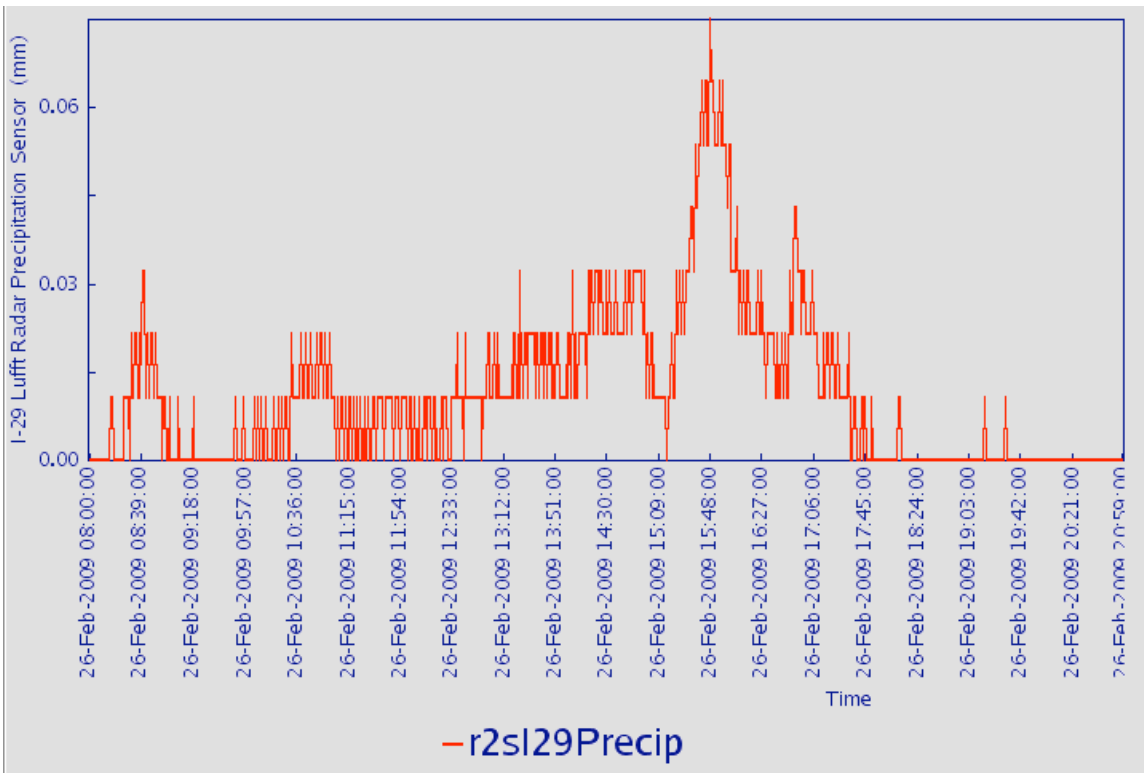

Figure 3 R2S precipitation sensor graphical display of one-minute precipitation accumulation on February 26, 2009. Time period for the reported precipitation was 0800 UTC to 2059 UTC. Accumulation was measured in millimeters.

Figure 4 STWRC RWFRF camera images showing snowfall on February 26, 2009. The top image is a downward facing camera on the RWFRF access road adjacent to I-29. The red circle outlines falling snowflakes picked up by the camera. The bottom image is a south facing view from the RWFRF facility's west 20 foot tower. Reduced visibility in the bottom image is due to falling snow.

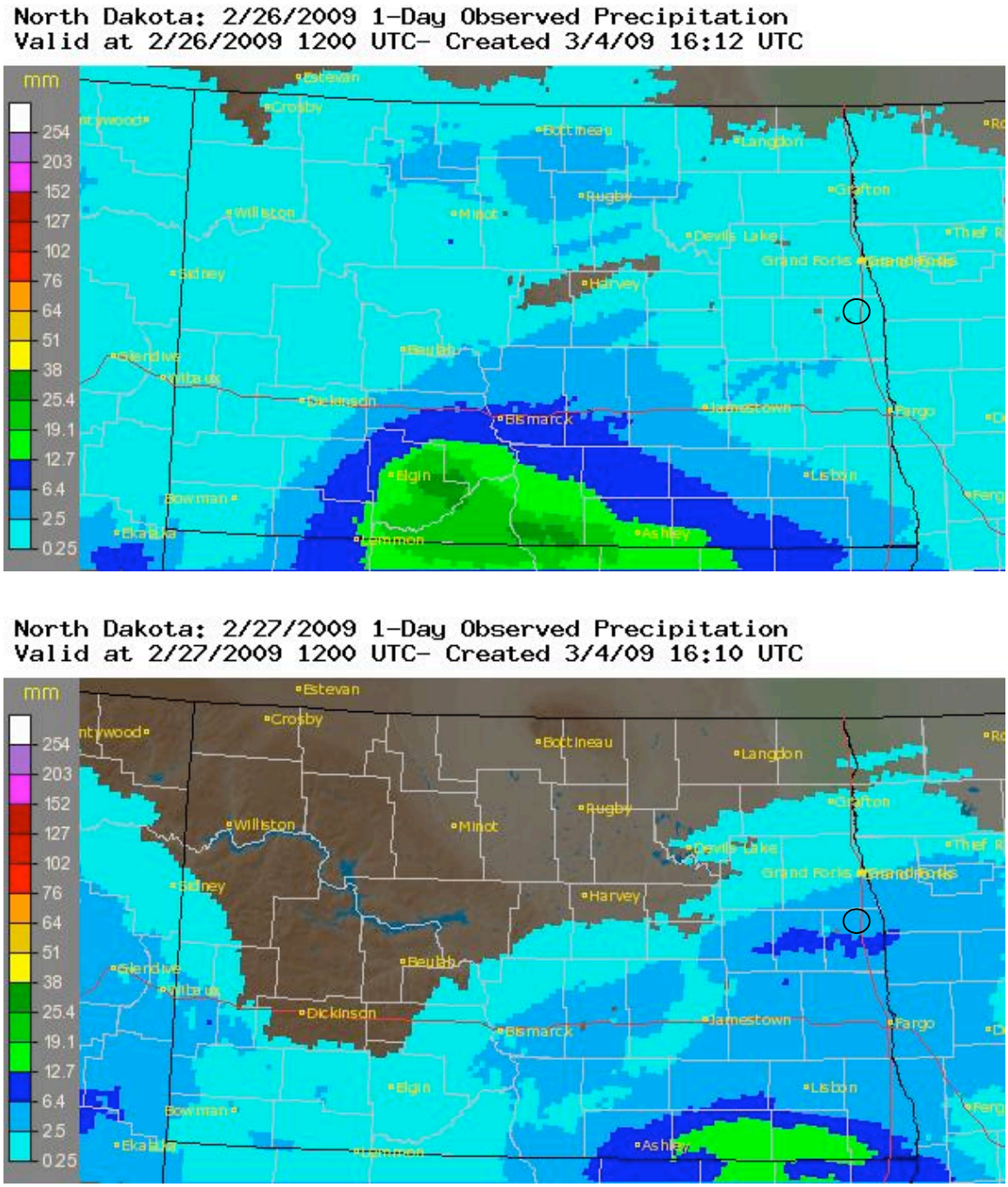

Figure 5 National Weather Service (NWS) radar estimated precipitation. The top image is valid for 1200 UTC on February 26, 2009 and the bottom image is valid for 1200 UTC February 27, 2009. The precipitation totals ranged from 0.25mm to 2.5mm in the top image and between 2.5mm and 6.4mm in the bottom image.

March 31, 2009

On March 31, 2009 the R2S sensor detected snowfall beginning around 1315 UTC (8:15 am local), which can be seen in the graph of the snowfall intensity data (Figure 8). Camera images of Interstate 29 (Figure 7) verify the observed snowfall occurrence. Total precipitation amounts for the event (Table 3) indicate that the R2S sensor recorded snowfall water equivalent amounts within the range given by the NWS radar. A careful review of the NWS radar estimated observed precipitation map (Figure 9) shows that close to the RWFRF there was a heavier band of snow that fell during the sample period and the NWS radar estimate was just above the 2.5 mm lower limit for the snowfall accumulation band of 2.5 to 6.4 mm. Thus, an estimated snowfall of 2.5 to 3 mm is consistent with higher amount reported by the R2S sensor, which was higher than the snowfall amounts reported by the Geonors. Wind speeds during the event ranged from 10 m/s (22.4 mph) to just over 18 m/s (40 mph). The high speed was a brief extreme value that was more likely a wind gust captured during the time frame. Wind speeds were high enough to produce under catch of snow with the Geonor precipitation sensors.

Table 3 Precipitation amounts from the R2S and Geonor precipitations sensors and the NWS radar estimated precipitation data for March 31, 2009.

Time UTC	R2S Interstate 29 (mm)	Geonor 1 (mm)	Geonor 2 (mm)	NWS Radar Estimated (mm)
13UTC to 20UTC	3.83 mm	1.4 mm	0.7 mm	2.5 mm -6.4 mm

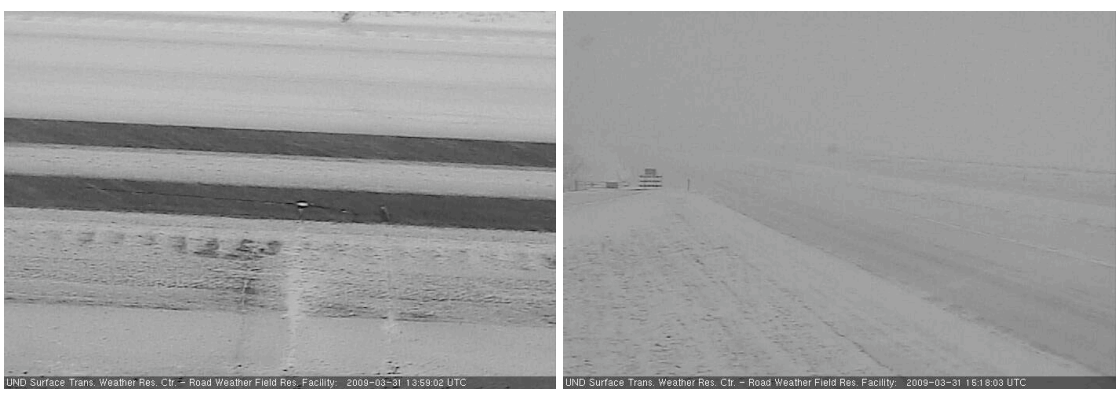

Figure 6 STWRC RWFRF camera images of Interstate 29 at MM 120 in North Dakota. Both images show falling snow.

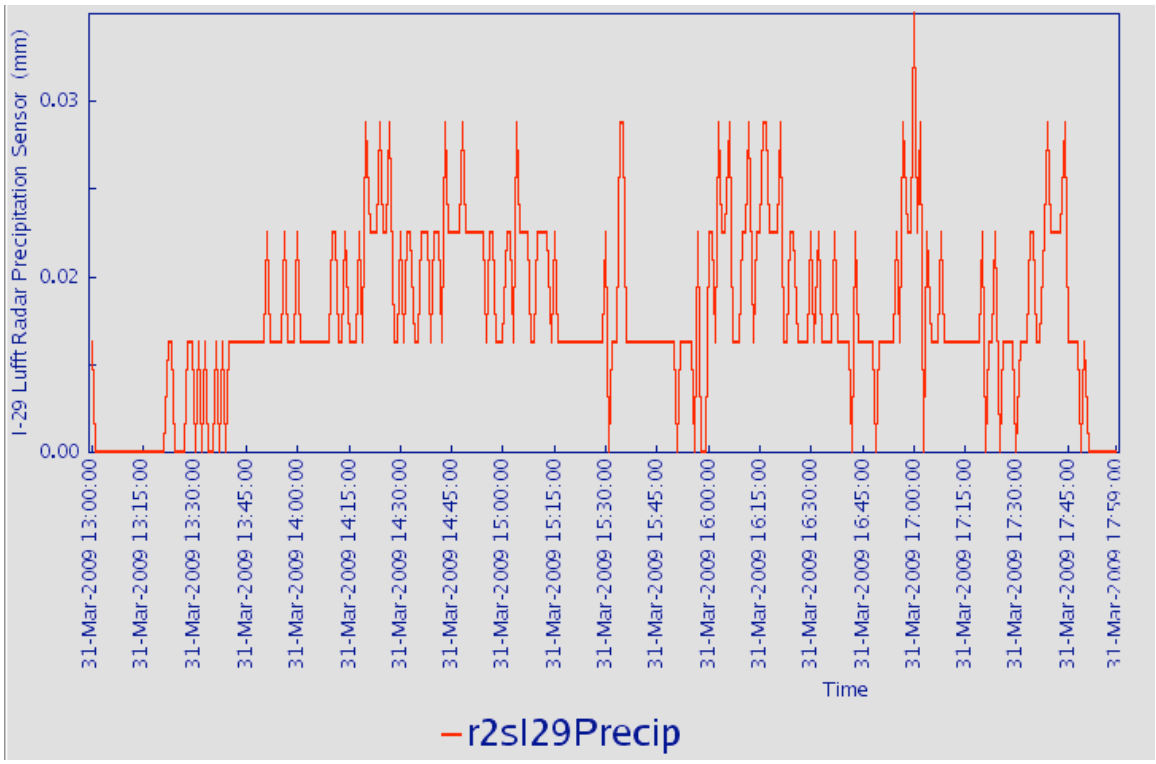

Figure 7 Lufft R2S graphical display of one-minute precipitation on March 31, 2009. The graph shows precipitation accumulation for the time period of 1300 UTC to 1759 UTC. Precipitation is in millimeters.

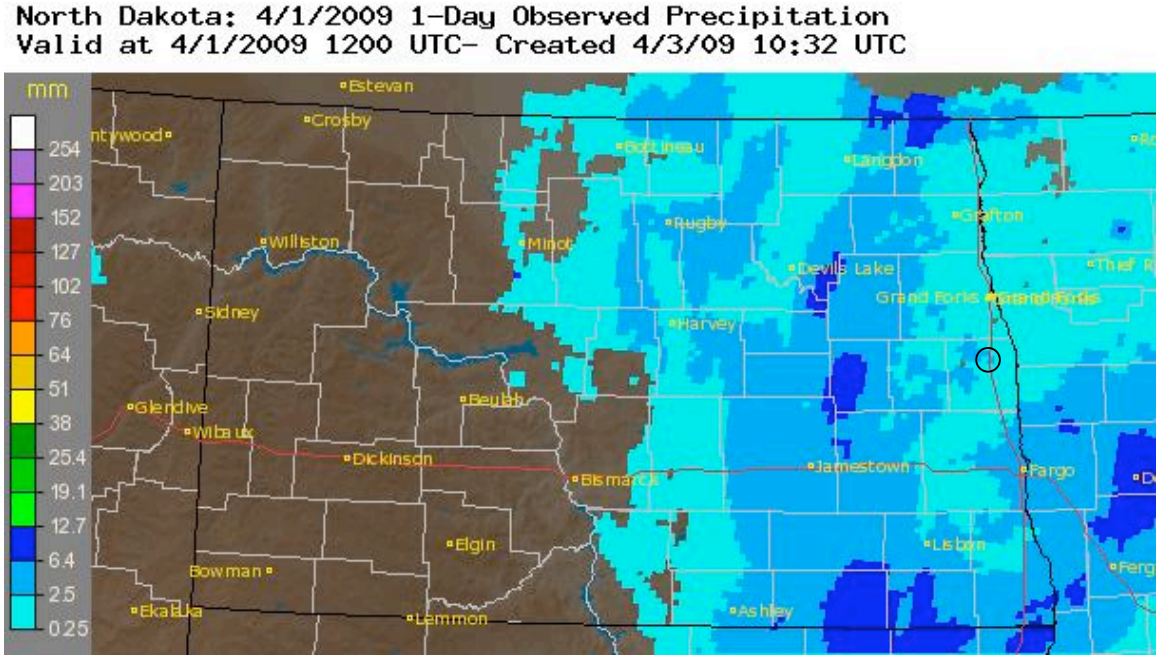

Figure 8 The National Weather Service observed precipitation data for a 24 hour period valid 1200 UTC April 1, 2009. The black circle indicates the location of the RWFRF. Precipitation amounts within that circle range from 2.5 mm to 6.4 mm.

Low-Cost Pavement Temperature Sensor Evaluation

NDDOT maintenance personnel expressed that the use of pavement temperature for monitoring current conditions and for determining potential treatment materials was one of the primary uses of ESS. Therefore, consideration of low-cost thermistor-based sensors and their applicability to an open architecture framework was an essential part of the field evaluation efforts that were conducted. To evaluate the efficacy of this class of sensor and to assess its ease of configuration within an open architecture, the Zydax Temperature Sensor (ZTS) was used in the winter trials. This is a thermistor-based, stand-alone temperature sensor capable of being buried in different types of pavement at any depth the user wishes to measure temperature.

In addition, a low-cost UND STWRC pavement temperature sensor was included for comparison with the ZTS as a possible sensor concept to further reduce agency costs. The UND pavement temperature probe is an experimental sensor designed by STWRC staff and used in prior field research for pavement and sub-pavement temperature measurements. The probe has six integrated circuit temperature sensors, three external sensors, and three internal sensors. All integrated circuit temperature sensors in the UND temperature probe were bench calibrated to 0°C (32°F) in an ice bath.

Two Zydax sensors were installed by cutting a groove in the asphalt at of depth of approximately one half inch below the surface and then the sensors were covered in a black colored Fabick Joint Seal. Installation of the STWRC pavement temperature sensor used a pre-existing channel cut in the pavement where the external sensors faced upward. Figure 10 shows the installation setup at the RWFRF for both Zydax Temperature Sensors and the UND Temperature sensor.

Data were collected from February 26th and 27th, and March 9th 2009. Averages and standard deviations were calculated for all the data. The data were then graphed along with error bars showing a three standard deviation from the mean to identify outlier observations.

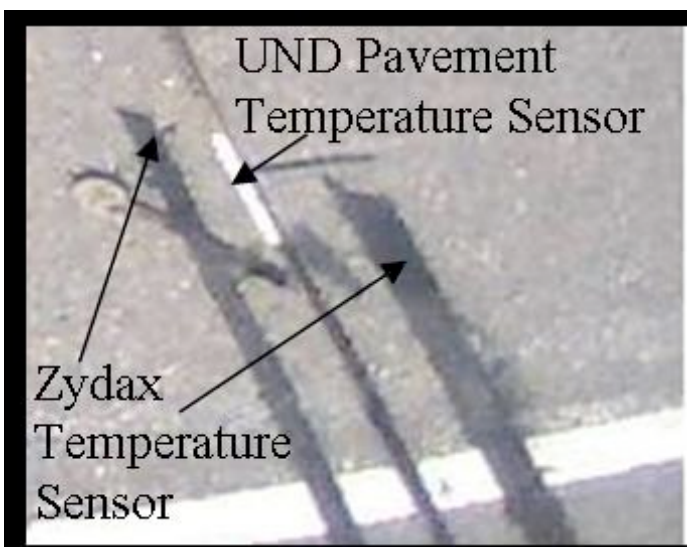

Figure 9 Zydax Temperature Sensor and UND Temperature Sensor installation setup at the UND STWRC RWFRF.

Pavement temperatures from the Zydax sensors compared well with those from the UND sensors on February 26, 2009. The period of evaluation was 1730 UTC to 2250 UTC. Table 4 is a representative data sample during the 1800 UTC hour in 10-minute intervals. The mean temperatures ranged from -12.1375 °C to -11.58375 °C. Both Zydax sensors were reporting slightly lower temperatures than the sensors on the UND probe. The differences between the reported temperatures did not vary more than a degree from the UND sensors that were closest in temperature and did not vary more than two degrees from the UND sensors that reported temperatures a little higher than the rest. Overall the reported temperatures did not deviate too far from sensor to sensor.

Table 4 February 26, 2009 pavement temperature data from two Zydax ZTS sensors and 6 sensors from the UND pavement temperature probe. Also shown are the mean and standard deviation samples.

Time (UTC)	UND1 S1	UND2 S7	UND3 CC4	UND4 HS5	UND5 HS6	UND6 HS12	ZTS 1	ZTS 2	Mean	Standard Deviation
18:00	-11.65	-12.55	-11.15	-12.75	-11.75	-12.1	-12.65	-12.5	-12.1375	0.573679
18:10	-11.55	-12.45	-11.05	-12.65	-11.65	-12	-12.53	-12.43	-12.03875	0.573994
18:20	-11.45	-12.35	-10.85	-12.55	-11.45	-11.9	-12.37	-12.34	-11.9075	0.603152
18:30	-11.35	-12.25	-10.75	-12.35	-11.25	-11.8	-12.31	-12.28	-11.7925	0.609748
18:40	-11.25	-12.15	-10.65	-12.25	-11.25	-11.7	-12.15	-12.09	-11.68625	0.581327
18:50	-11.05	-11.95	-10.55	-12.25	-11.15	-11.6	-12	-12.12	-11.58375	0.607193

The data from the above time period were plotted out with error bars to identify outliers and whether or not the ZTS sensors were within 3 standard deviations of the mean temperatures. Shown is a graph (Figure 10) of plotted temperatures with corresponding error bars for the time of 1800 UTC (1200 UTC). Absolute values were used in this plot since all of the temperatures were below zero.

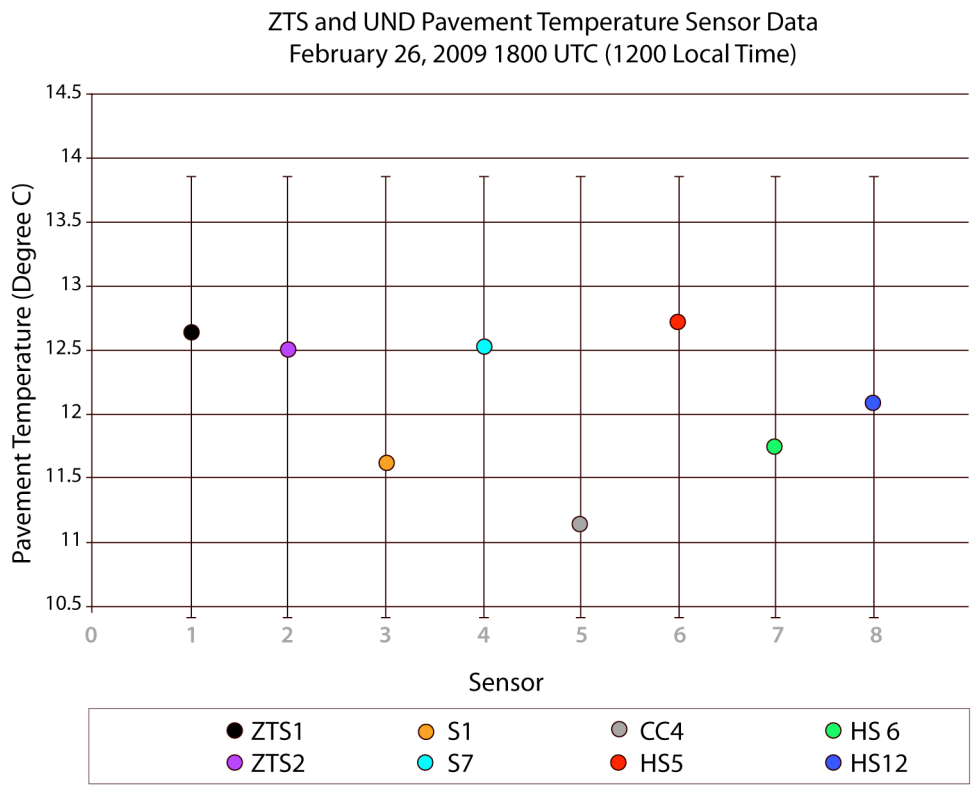

Figure 10 Temperature data, plotted as absolute values, for two ZTS sensors and the UND sensor for 1800 UTC on February 26, 2009. Also shown are the error bars depicting 3 standard deviations from the mean value for the same time period. As shown, the two ZTS sensors are within 3 standard deviations of the mean temperature of all sensors at 1800 UTC.

Data were collected on February 27, 2009 from 0000 UTC to 2050 UTC. Sample data for the period of 1800 UTC to 1850 UTC are shown in Table 5 with temperatures in 10 minute intervals along with the mean and standard deviation values for each 10 minutes of data. Early in the day the ZTS temperature data were within one to two degrees of the UND probe sensors. As the day progressed the UND sensors reported temperatures five to six degrees higher than the ZTS sensors.

Table 5 Pavement temperatures for the time period of 1800 UTC to 1850 UTC. Data shown includes two Zydax Temperature Sensors, six sensors from the UND Pavement Temperature Probe, and the mean and standard deviation values for each 10 minute period.

Time (UTC)	ZTS 1 (°C)	ZTS 2 (°C)	UND1 S1	UND2 S7	UND3 CC4	UND4 HS5	UND5 HS6	UND6 HS12	Mean	Standard Deviation
1800	-21.09	-21.53	-14.9	-16.05	-13.85	-15.55	-14.65	-15.6	-16.6525	2.954487
1810	-20.87	-21.31	-14.7	-15.85	-13.55	-15.35	-14.45	-15.4	-16.435	2.959228
1820	-20.78	-21.12	-14.5	-15.55	-13.35	-15.05	-14.15	-15.1	-16.2	3.008388
1830	-20.53	-20.96	-14.2	-15.35	-13.05	-14.85	-13.85	-14.9	-15.96125	3.038573
1840	-20.34	-20.65	-14	-15.15	-12.85	-14.65	-13.65	-14.7	-15.74875	3.015036
1850	-20.12	-20.46	-13.8	-14.95	-12.75	-14.45	-13.55	-14.5	-15.5725	2.9896

Temperature data (in absolute values) for the above time frame are plotted in the graph below Figure 11 along with the error bars that depict three standard deviations from the mean

temperature for values collected during the time interval. It is clear that the ZTS sensor data falls within three standard deviations of the mean temperature.

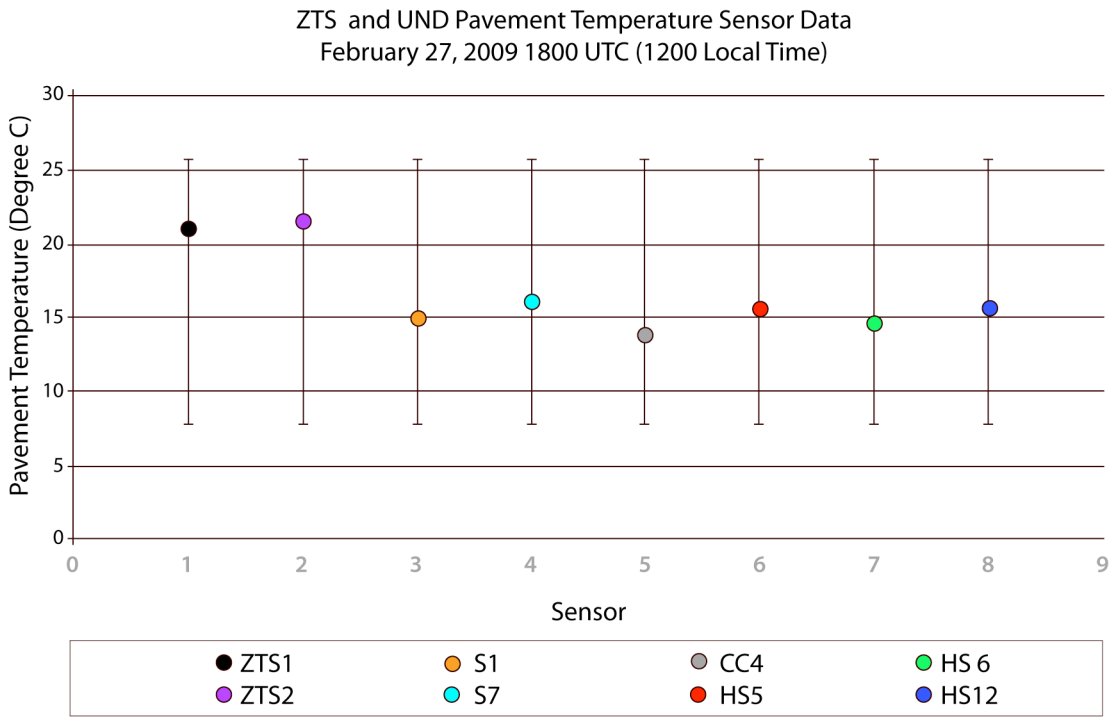

Figure 11 Temperature data, plotted as absolute values, from the two ZTS sensors and the UND probe for 1800 UTC on February 27, 2009. The plot also shows the temperature data for all sensors falling within 3 standard deviations from the mean temperature as seen by the error bars.

Pavement temperatures on March 9, 2009 were evaluated for the time period of 0400 UTC to 2350 UTC. A sample of the pavement temperature data from selected sensors in the UND pavement temperature probe and the two Zydax sensors are shown below (Table 6), along with the mean and standard deviations for the time period of 1800 UTC to 1850 UTC. The Zydax sensor reported temperatures closer to those of UND2, UND4, and UND6. Temperatures reported on this day did not deviate far from the mean temperature during any given time period.

Table 6 March 9, 2009 pavement temperature data for two Zydax ZTS sensors and five sensors from the UND pavement temperature probe for the period of 1800 UTC to 1850 UTC. Also shown are the mean and standard deviation values.

Time (UTC)	ZTS 1	ZTS 2	UND1 S1	UND2 S7	UND4 HS5	UND5 HS6	UND6 HS12	Mean	Standard Deviation
18:00:00	-2.25	-2.12	-1.55	-2.65	-2.55	-1.35	-2.5	-2.138571	0.507032
18:10:00	-2.25	-2.06	-1.55	-2.65	-2.45	-1.25	-2.4	-2.087143	0.510383
18:20:00	-2.21	-2.06	-1.55	-2.65	-2.55	-1.35	-2.4	-2.11	0.49548
18:30:00	-2.18	-1.96	-1.45	-2.55	-2.35	-1.15	-2.3	-1.991429	0.512101
18:40:00	-1.96	-1.9	-1.35	-2.45	-2.25	-1.05	-2.2	-1.88	0.506754
18:50:00	-1.96	-1.84	-1.55	-2.45	-2.45	-1.45	-2.2	-1.985714	0.403272

Absolute values of data from 1800 UTC on March 9 were plotted (Figure 12) along with the error bars depicting three standard deviations from the mean. The two ZTS sensors observed values again within three standard deviations, which was used as a broad measure to identify potential data outliers. This shows that almost all the temperatures (99%) would fall within three standard deviations of the mean.

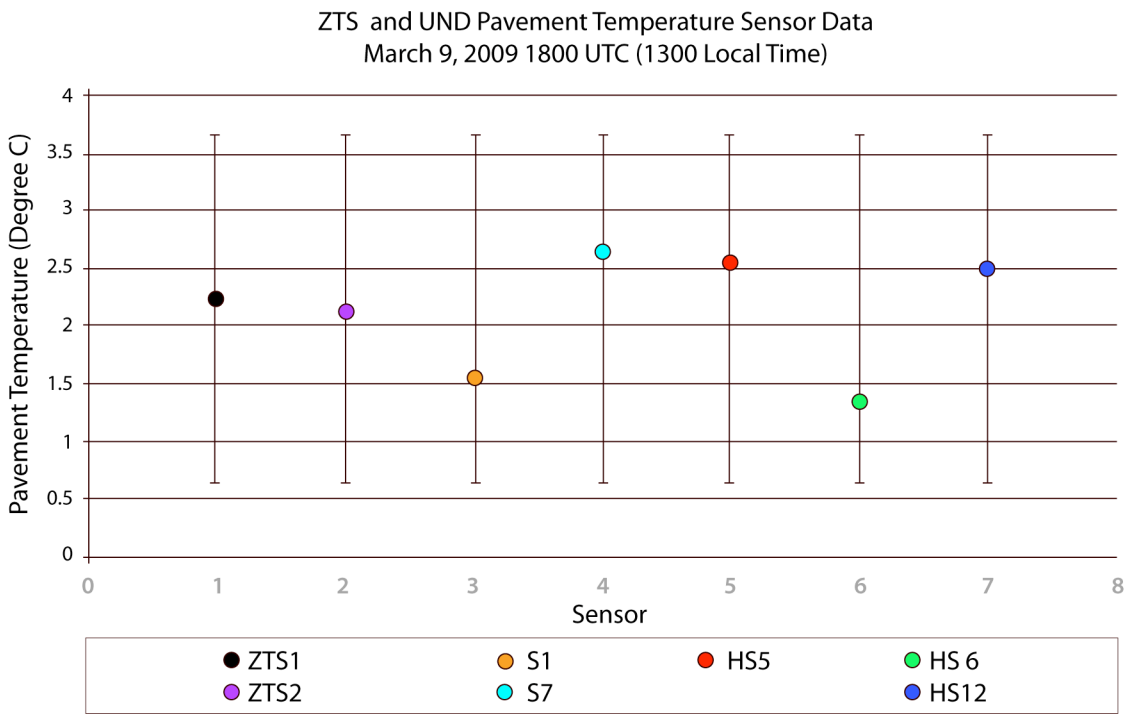

Figure 12 Pavement temperatures, plotted as absolute values, from the two ZTS sensors and five sensors from the UND pavement temperature probe along with the error bars showing the three standard deviation from the observed mean for all data. Data are valid for 1800 UTC on March 9, 2009.

Overall, the Zydax Temperature Sensors and the UND temperature sensors compared well. The differences in temperatures could be calibration offsets in the UND sensors. The Zydax sensors, sealed with a black-colored joint seal, are expected to warm up faster than the UND sensor, which is inside white PVC. Most of the differences in temperatures between the UND sensors and the Zydax sensors stayed within ±1 °C. Some fell out of that range with a difference of no more than ±2 °C. The combined ZTS and UND sensor data were within the

three standard deviation window used throughout the trials to qualify observed values as not being grossly erroneous and valid for comparison.

Applicability of Video Camera Imagery for Pavement Condition Assessment

During field maintenance personnel interviews, the most prominent request for additional pavement and weather monitoring was the desire for camera imagery. The visual awareness of conditions was considered to yield an acceptable surrogate for traditional pavement sensor data, i.e., pavement state and chemical concentration observations. Further, the remote visual recognition of ongoing weather and pavement conditions was believed to represent a cost savings over deploying personnel to conduct an *in situ* patrols of the maintenance segment. Challenges noted by these field personnel as to limitation during nighttime hours were not considered sufficient to warrant a limitation in camera imagery use.

The test of the integration of a camera system into the ESS open architecture utilized an Axis Pan/Tilt/Zoom (PTZ) (Model Axis 233D) camera system mounted near the top of the RWFRF instrumented ESS tower adjacent to Interstate 29. This camera is a programmable, IP addressable camera providing the capture of a user-determinable number of images from any desired camera orientation at preset time intervals. In the configuration used to test the ESS open architecture, three camera orientations were established. Two were oriented to capture images in the oncoming and downstream traffic directions relative to the I-29 southbound lanes and one image capture was oriented to observe the pavement closest to the camera. This latter image was also zoomed to provide a closer visual inspection of the pavement conditions centered on a mid-point between the southbound passing and driving lanes. The image capture initiated a data transfer over an Internet connection to the ESS system remote processing unit where the images were subsequently delivered to the central processing unit located on the UND campus. Image size for each captured image was approximately 35 kilobytes, which permitted rapid transfer to occur. The sampling interval was set at three minutes, which provided an adequate sampling rate to capture relatively rapid variations in traffic flows and transient weather features (i.e., snow squalls and temporary visibility reductions due to blowing snow during sustained wind gusts).

To evaluate the applicability of video camera imagery to determine pavement conditions, two analysis methods were used. The first involved establishing a data acquisition protocol for capturing a variety of camera images to depict the visually observed pavement condition and to capture the broader weather conditions within the roadway environment. Assessment of information representativeness was conducted by comparison of variations in the physical state of the pavement during winter weather conditions as observed from camera imagery.

The second method utilized an experimental method of traffic speed monitoring to compare with visual-estimated pavement conditions determined from the camera imagery. This latter method utilized a traffic monitoring system, manufactured by Traffic Control Corporation (a subsidiary of Wavetronix) (Model SS125 Smart Sensor HD), to compare vehicle speeds to road conditions. The SS125 is capable of recording interval data and per-vehicle data. Interval data reports:

- Traffic lane observed,
- Volume (shows the number of vehicles detected during the interval),

- Occupancy (gives the percentage of time during the interval that the detection zone was occupied),
- Speed (indicates the average lane speed during the interval),
- 85th percentile speed (85% of the vehicles in the interval were traveling at this speed or slower),
- Classes (refers to length-based bins; shows the number of cars from each length class that were detected during the interval),
- Headway (displays the average time separation between vehicles detected during the interval, measured from the front bumper to the front bumper of the following car), and
- Gap (shows the average time separation between vehicles detected during the interval, measured from back bumper of the first car to the front bumper of the second).

Per vehicle data reports:

- Lane (the lane in which the vehicle was detected),
- Timestamp (time at which the vehicle was detected),
- Speed (the speed of the vehicle in miles per hour), and
- Length (the length of the vehicle in feet).

In the analytical comparison the lane, volume, occupancy, speed, and 85th percentile speed were used in conjunction with the visual data. Two storms where weather and pavement conditions warranted reduced traffic speeds were used in the evaluation of camera images.

March 24-25, 2009

On the evening of March 24, 2009 road conditions on Interstate 29 at the RWFRF were good. Driving speeds averaged near the posted limit of 75 mph. A few hours later, travel conditions deteriorated due to snow, blowing snow, and worsening pavement conditions. During the height of the event, speeds dropped to an average of 40 – 55 mph. These conditions persisted into the overnight hours and through midday on March 25th. Driving conditions improved by early evening on March 25th with speeds returning to the 65-75 mph range. Table 7 shows the diminished traffic speeds due to the deteriorating pavement conditions that are visually illustrated in Figure 13. Figure 13 shows snow blowing across the road as well as snow and compacted snow sticking to the road.

Table 7 Traffic information for Interstate 29 on March 25, 2009 from 03:33 UTC to 03:36 UTC. When lane volume is zero, the last known average speed for that lane is reported.

Date	Time (UTC)	Lane	Volume	Occupancy (%)	Average Speed (MPH)	85%
3/25/2009	3:33:00	SB-Driving	6	8.7	56.1	58
3/25/2009	3:33:00	SB-Passing	1	0	52.8	53
3/25/2009	3:33:00	NB-Passing	0	0	54.7	55
3/25/2009	3:33:00	NB-Driving	0	0	59.8	60
3/25/2009	3:35:00	SB-Driving	0	0	56.1	58
3/25/2009	3:35:00	SB-Passing	0	0	52.8	53
3/25/2009	3:35:00	NB-Passing	0	0	54.7	55

3/25/2009	3:35:00	NB-Driving	1	0.6	54.4	55
3/25/2009	3:36:00	SB-Driving	4	3.7	42.6	43
3/25/2009	3:36:00	SB-Passing	0	0	52.8	53
3/25/2009	3:36:00	NB-Passing	0	0	54.7	55
3/25/2009	3:36:00	NB-Driving	1	0.6	46.3	47

Figure 13 Camera image showing the condition of Interstate 29 on March 25, 2009 at 03:35 UTC (March 24 at 10:35pm local time). The light shining from a vehicle shows deteriorating pavement conditions due to blowing snow.

Table 8 and Figure 14 depict traffic information and road conditions, respectively, for March 25, 2009 during the hour of 14:00 UTC. Average vehicle speeds during that time indicate poor pavement conditions. This is visually obvious in Figure 14.

Table 8 Traffic data on March 25, 2009 for the time period of 14:31 UTC to 14:33 UTC. Traffic speeds averaged between 42 and 57 MPH. When lane volume is zero the last known average speed for that lane is reported.

Date	Time (UTC)	Lane	Volume	Occupancy (%)	Average Speed (MPH)	85%
3/25/2009	14:31:00	SB-Driving	0	0	48.8	49
3/25/2009	14:31:00	SB-Passing	0	0	49.7	50
3/25/2009	14:31:00	NB-Passing	1	1.9	47	48
3/25/2009	14:31:00	NB-Driving	2	2	42.9	54
3/25/2009	14:32:00	SB-Driving	1	1.5	58.9	59
3/25/2009	14:32:00	SB-Passing	0	0	49.7	50
3/25/2009	14:32:00	NB-Passing	0	0	47	48
3/25/2009	14:32:00	NB-Driving	1	1.6	55.1	56

3/25/2009	14:33:00	SB-Driving	4	4.4	52.8	52
3/25/2009	14:33:00	SB-Passing	0	0	49.7	50
3/25/2009	14:33:00	NB-Passing	0	0	47	48
3/25/2009	14:33:00	NB-Driving	0	0	55.1	56

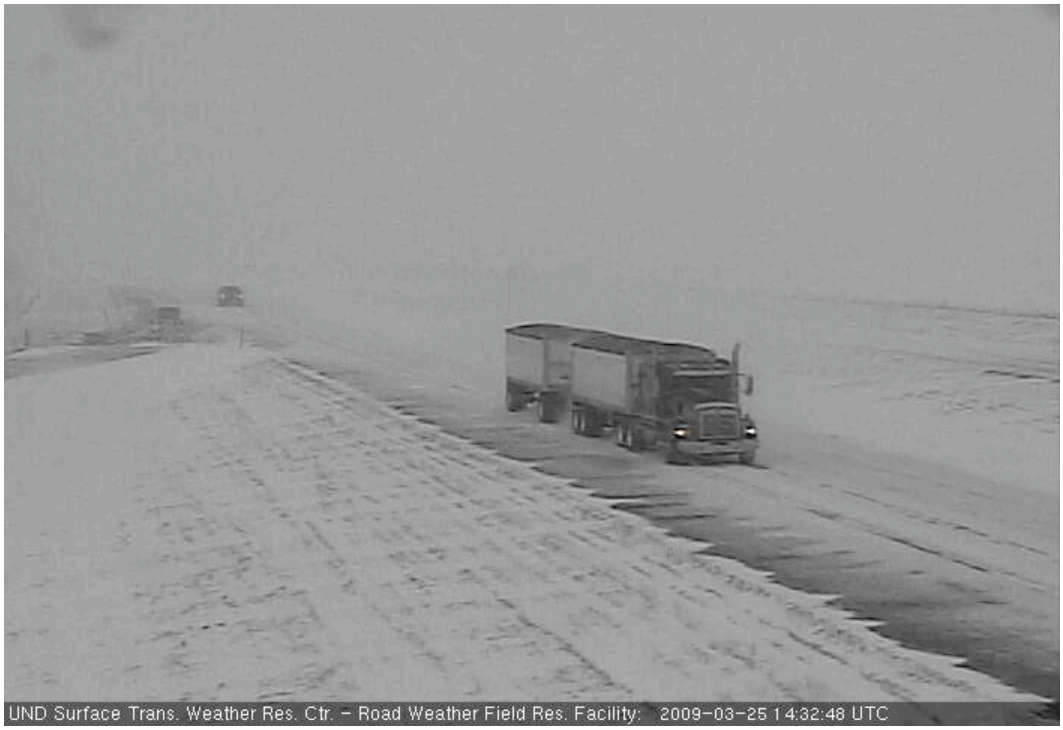

Figure 14 Camera image on Interstate 29 on March 25, 2009 at 14:32 UTC (9:32 am local time). The image shows snow covered pavement and reduced visibility due to snow and blowing snow.

By 2300 UTC on March 25th traffic speeds were returning towards the posted speed limit of 75 mph on the interstate. Even though the number of vehicles during the time shown in Table 9 is low, it still shows an increase in speed. These data compare well with the improving pavement conditions depicted in Figure 15.

Table 9 Traffic information for March 25, 2009 from 23:55 UTC to 23:57 UTC. The data indicates vehicle speeds are nearing the posted speed limit of 75 MPH for the interstate. When lanes volumes is zero, the last known average speed is reported.

Date	Time (UTC)	Lane	Volume	Occupancy (%)	Average Speed (MPH)	85%
3/25/2009	23:55:00	SB-Driving	1	1.4	76	76
3/25/2009	23:55:00	SB-Passing	0	0	66.2	67
3/25/2009	23:55:00	NB-Passing	0	0	73.4	74
3/25/2009	23:55:00	NB-Driving	0	0	71.5	81
3/25/2009	23:56:00	SB-Driving	0	0	76	76
3/25/2009	23:56:00	SB-Passing	0	0	66.2	67
3/25/2009	23:56:00	NB-Passing	0	0	73.4	74
3/25/2009	23:56:00	NB-Driving	1	0.9	61	61
3/25/2009	23:57:00	SB-Driving	0	0	76	76

3/25/2009	23:57:00	SB-Passing	0	0	66.2	67
3/25/2009	23:57:00	NB-Passing	1	1.2	72.2	73
3/25/2009	23:57:00	NB-Driving	0	0	61	61

Figure 15 Camera image showing the condition of Interstate 29 on March 25, 2009 at 23:56 UTC. Conditions of the road have improved compared to the previously presented images for the same date and location.

March 31, 2009

On March 31, snow had fallen and subsequently accumulated on the road. Atmospheric and pavement conditions at the start of the snowfall included a pavement temperature of -0.8°C (30.6°F), an air temperature of -1.5°C (29.3°F), and the presence of light snowfall. Monitored average traffic speeds were in the 50 to 70 mph range. As the event progressed the temperature of the pavement increased to 0.5°C (32.9°F) at 18:01 UTC, with an air temperature of -0.9°C (30.4°F). Precipitation was still occurring but was decreasing in intensity. The corresponding average traffic speeds were reduced to a range of 38 to 66 mph. Tables 10 and 11 indicate the average speeds during the period of 15:29 UTC to 16:09 UTC. Figures 16 and 17 show the camera images of the pavement conditions at 15:48 UTC and 16:09 UTC.

Table 10 Traffic monitoring information for March 31, 2009 from 15:29 UTC to 15:48 UTC. Data shown in the table include the name of the lane, vehicle volume, occupancy, average speed (mph), and the 85%. When lane volume is zero, the last known average speed for the given lane is reported.

Date	Time (UTC)	Lane	Volume	Occupancy (%)	Average Speed (MPH)	85%
3/31/2009	15:29:00	NB - Driving	1	1.8	54.7	55
3/31/2009	15:32:00	NB - Driving	1	0.7	44.6	45
3/31/2009	15:34:00	NB - Driving	1	0.5	58.2	59

3/31/2009	15:35:00	NB - Driving	1	0.5	67.8	68
3/31/2009	15:39:00	NB - Driving	1	1.4	58.5	59
3/31/2009	15:42:00	NB - Driving	1	1.8	49.9	50
3/31/2009	15:48:00	SB - Driving	0	0	58.5	59
3/31/2009	15:48:00	SB - Passing	0	0	66.2	67
3/31/2009	15:48:00	NB - Passing	0	0	48	49
3/31/2009	15:48:00	NB - Driving	0	0	49.9	50

Figure 16 Interstate 29 pavement conditions at 15:48 UTC on March 31, 2009. The camera image indicates that the pavement is snow covered.

Table 11 Traffic monitoring information for March 31, 2009 from 15:57 UTC to 16:09 UTC. Data reported were name of the lane, vehicle volume per lane, occupancy, average speed (mph), and 85% traffic speed. When lane volume is zero the known average speed for that lane is reported.

Date	Time	Lane	Volume	Occupancy	Average Speed	85%
3/31/2009	15:57:00	NB-Driving	1	1.4	61.4	62
3/31/2009	15:59:00	NB-Driving	6	8	38.4	42
3/31/2009	16:01:00	NB-Driving	1	0.6	43.8	44
3/31/2009	16:02:00	NB-Driving	1	0.5	50.3	51
3/31/2009	16:05:00	NB-Driving	2	1.3	40.8	42
3/31/2009	16:06:00	NB-Driving	2	3.1	42.2	44
3/31/2009	16:08:00	NB-Driving	1	2.4	42	42
3/31/2009	16:09:00	SB-Driving	1	0.4	68.8	69
3/31/2009	16:09:00	SB-Passing	0	0	66.2	67
3/31/2009	16:09:00	NB-Passing	0	0	48	49
3/31/2009	16:09:00	NB-Driving	1	2.2	39.5	40

Figure 17 Interstate 29 pavement conditions at 16:09 UTC on March 31, 2009. Snow covered conditions on the road would warrant slower driving conditions as indicated in Table 11 above.

As indicated in the tables and figures above, the detected traffic speeds matched the conditions of the pavement at the times noted. In all events, the snow had covered the road significantly, which forced traffic to slow down.

Sensor Recommendations

The R2S precipitation sensor was found to be a reasonable and beneficial unit. It is capable of distinguishing precipitation types (rain, snow, sleet, hail, and freezing rain). The sensor also reports precipitation accumulation and rate. This sensor is sensitive enough to provide early indications of snowfall where other sensors are not able to detect measurable snowfall until the rates and amounts increase. The R2S sensors picked up on intermittent snowfall before the Geonor precipitation sensors did. The R2S is able to provide reliable information and was found to be a low-cost, maintenance-free precipitation sensor available in an open architecture format.

An evaluation of a low cost pavement temperature sensor proved quite promising. The Zydax Temperature Sensor (ZTS) can be buried in any pavement type at any depth selected by the DOTs. It can be a part of the ZAPSS or a stand-alone unit with as many as a department would like. When compared to the UND temperature sensors, both ZTS sensors reported similar pavement temperatures. Overall, the average differences between the UND and ZTS sensors were no more than ±1 °C. Plots of temperature data with corresponding error bars for the data revealed the ZTS sensor temperatures for the evaluation period fell within three standard deviations of the mean temperature values.

VI. Open Architecture ESS Design, ESS Data Management, and ESS Maintenance Findings and Summary Report

The transition to an open architecture ESS by the NDDOT will depend on the resulting structure of the consolidation of all ESS into the agency's Road Weather Information System (RWIS). Understanding the nature of the present RWIS was considered an important aspect in establishing the efficacy of transitioning to an open architecture and the management and maintenance of such an architecture. This required establishing as a baseline the characteristics of the existing RWIS.

The existing North Dakota Department of Transportation Road Weather Information System consists of twenty-four (24) fixed Environmental Sensor Stations irregularly distributed across North Dakota (Fig. 18).

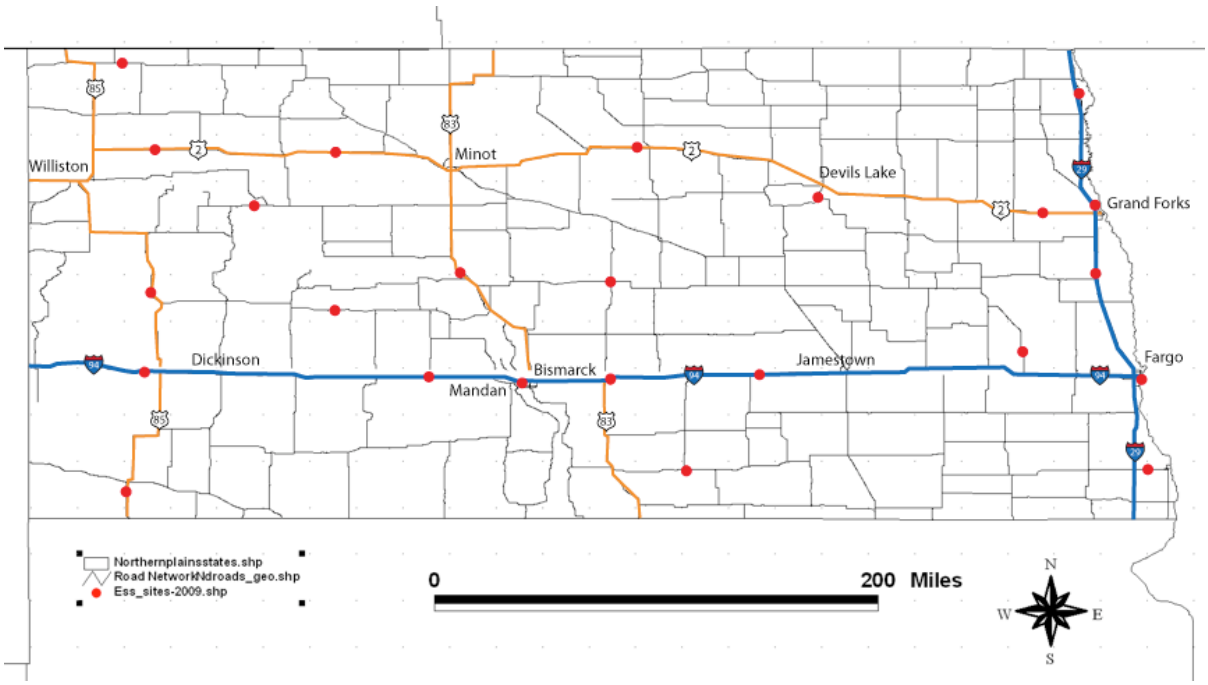

Figure 18. Distribution of Environmental Sensor Stations

The ESS sensor packages are part of a proprietary system (i.e., closed architecture) provided by Surface Systems Incorporated (SSI) (now a part of Quixote Transportation Technologies, Inc.). The typical configuration of the ESS sensor packages includes sensors to observe the following atmospheric parameters:

- Air temperature,
- Relative humidity,
- Wind speed,
- Wind direction,
- Precipitation presence (yes/no indication), and
- A weather indicator/visibility sensor.

Pavement and sub-pavement sensors include pavement temperature, sub-pavement temperature (typically at 17-inches), and pavement condition. Some locations also directly measure the freeze-point temperature of the solution found on the pavement and/or have deep sub-surface temperatures (only at Grand Forks and to a depth of 1.8-meters). The configuration of each current ESS relative to the sensor complement for each location is provided in Appendix A.

While SSI manufactures the majority of the pavement sensors used within each NDDOT ESS, there are instances of sensors from of other manufacturers (e.g., the Combitech AB Frensor Mk II Active Freezing Point Sensor) being incorporated by SSI into their ESS package. The atmospheric (weather) sensors used by SSI in their ESS installation were from other instrumentation providers who, in most situations, provided a non-proprietary interface to their sensors. However, the configuration of the present ESS atmospheric sensor packages installed across North Dakota are part of the current ESS vendor's integrated proprietary package as are the communications methods to acquire the data from the ESS remote processing units (RPU).

The vendor-provided communications/polling software is responsible for data acquisition from each ESS data aggregation RPU module. The present central processing unit (CPU) software in place for communicating with each RPU and to perform overall data management is the SSI ScanWeb[8] version 5.10. The data collection is primarily completed by use of the "Plain Old Telephone System" (POTS) through polling software that is part of the SSI closed architecture. An exception to the POTS communication with the ESS is the use of broadband communications at the Fargo, Denhoff, Wishek, and Ray ESS locations. All of these sites, except for Fargo, are located in rural areas of North Dakota where the use of broadband communications has been a limitation until recently. The use of broadband communications by NDDOT in retrieving ESS data is an important precedent for the DOT, opening greater possibilities for future placement of ESS at locations not dictated by telephone and power line utility presence.

The data management of the acquired data from each RPU is handled by the SSI Central Processing Unit (CPU), which is a host computer located at the North Dakota Information Technology Department (ND-ITD) in Bismarck, North Dakota, and executing the SSI ScanWeb software. ND-ITD works in cooperation with the NDDOT Information Technology Division (NDDOT-ITD) to coordinate the data collection, data management, and delivery of observed and historical ESS data through a publicly accessible web site (http://rwis.dot.nd.gov). RPUs at each ESS location serves as the local electronic processing center, continually acquiring data and conducting limited on-site processing of data from the suite of weather and pavement sensors at the site. The RPU stores the data for subsequent transmittal of the data to the CPU. Data transfer from the RPUs to the CPU is managed by a SSI data collection software application located on the CPU using a polling technique. A scheduler on the CPU initiates calls to the RPU over phone or broadband communications pathways and the CPU then assures that all records not previously communicated are successfully transferred from the RPU memory to the CPU database before termination of

[8] SCAN Web is a registered trademark of Surface Systems, Inc. and the software is a copyrighted product of Surface Systems, Inc.

the connection. Each ESS sensor has an assigned IP address, which is used by the vendor software to identify and acquire a particular sensor's data.

Upon collection of ESS data from the RPU and storage on the CPU database, the information is made available to users. All users of the statewide RWIS are able to access and display the information from the CPU through a vendor-supplied software interface package accessed via the internet. Thus, the data distribution may be envisioned as a statewide distribution network centered on the CPU containing the entire collection of NDDOT ESS data. The predominant utilization of data is by DOT personnel, with additional access by the public through web links located on various North Dakota government web pages. In addition, non-DOT entities, with the approval of the NDDOT, have a secured (i.e., password required) FTP access to the entire ESS database located on data servers in Bismarck. The CPU has one connection port for data access, creating a potential bottleneck during situations where multiple users desire FTP access at the same time.

To gain an understanding of the extent of ESS coverage across North Dakota, an analysis of the ESS distribution across the state was made. In performing this spatial analysis, several considerations and assumptions adopted from the Federal Highway Administration's guidelines for ESS siting[9] were made regarding the representativeness of the ESS data. The FHWA guidelines specify use in identifying 1) local road weather phenomena or 2) regional representation of road weather conditions as the two primary siting considerations for the representativeness of ESS data. The former asserts that the ESS installation is sited at a location to resolve a specific local road and/or weather feature without consideration of a broader spatial context within the data. The latter asserts that the ESS installation is sited such that it provides information for a much wider spatial representativeness of the observed data with less emphasis on resolving a localized discrete situation.

An example of the localized pavement condition phenomena would be the presence of ice conditions on a bridge. In this situation, the unique weather and pavement conditions giving rise to potential ice on the bridge may not reflect the same expected conditions on non-bridge pavement even a short distance away. While the measure of the atmospheric conditions on or near the bridge might provide a reasonable assessment of regional weather conditions, the presence of open water or a sharp terrain change leading to the bridge would likely bias the observation toward the localized weather features and misrepresent the broader atmospheric conditions. Conversely, where an ESS is sited for a more regional representation of both pavement and atmospheric conditions, the terrain type and pavement structure would be more representative of a larger area lending a greater likelihood that similar conditions are within a circular region about the ESS locale. The importance of knowing the siting considerations for an ESS is determining the radius of influence that should be assigned to the data acquired from the ESS.

Determining a reliable radius of influence of a given ESS location is difficult. Factors that complicate this determination include not only the local versus regional intent of the ESS, but

[9] "Road Weather Information System Environmental Sensor Station Siting Guidelines", 2005, Manfredi, J., T. Walters, G. Wilke, L. Osborne, R. Hart, T. Incrocci, and T. Schmit, Federal Highway Administration Office of Transportation Operations, Road Weather Management Program, FHWA-HOP-05-026, 46 p.

also the terrain variation and land-use/land cover variation in the vicinity of the ESS. Further, it must be appreciated that weather systems themselves influence the representativeness of the ESS data over an area. A general rule of thumb is that for ESS sited to reflect regional conditions, the representativeness of the observations increases as the weather conditions improve. Hence, the least representativeness in the data is found when weather and/or pavement conditions are changing rapidly. In the most extreme weather conditions, almost all ESS sites become representative of conditions only within a few miles of their locale. Fortunately, of the above listed constraints, the terrain and land-use/land-cover impacts are largely negligible given the general uniformity of each across North Dakota. Given the desire to resolve finer scales in weather systems, a distance of 30 miles was generally assumed as the greatest distance that ESS data should be used in inclement weather conditions.

In the analysis of the present NDDOT RWIS network, three radii (15-miles, 30-miles, and 50-miles) were used to evaluate the statewide coverage of the network. Figure 19 shows the present NDDOT RWIS network's representative coverage during inclement weather (i.e., radii of influence extending only to 30 miles). It should be noted the present distribution of ESS leaves considerable observational gaps of fine-scale weather features across the state outside the Interstate corridors of I-29 and I-94. Even when a fifty-mile representation of the ESS data is considered (Fig. 20), which is only meaningful during fair weather conditions, considerable gaps remain in the observation network. In the project's initial field interviews, NDDOT maintenance personnel noted they often rely heavily upon the ESS observations upstream of their location during snow fighting preparations.

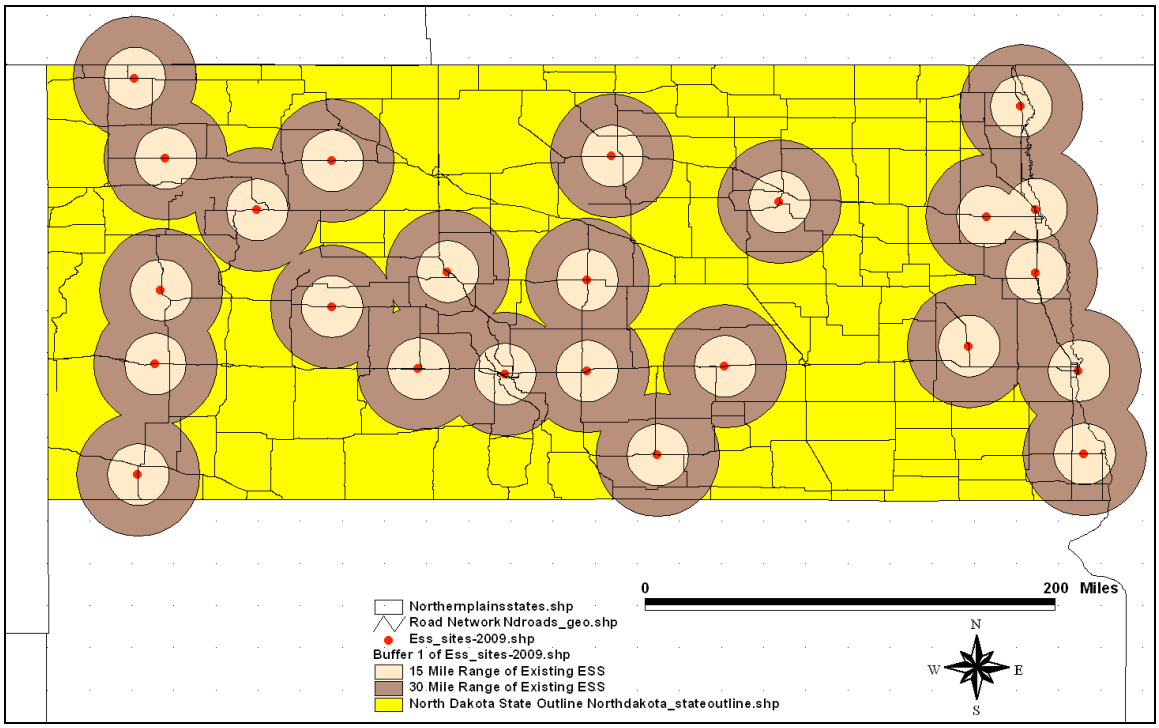

Figure 19. NDDOT RWIS network coverage during inclement weather

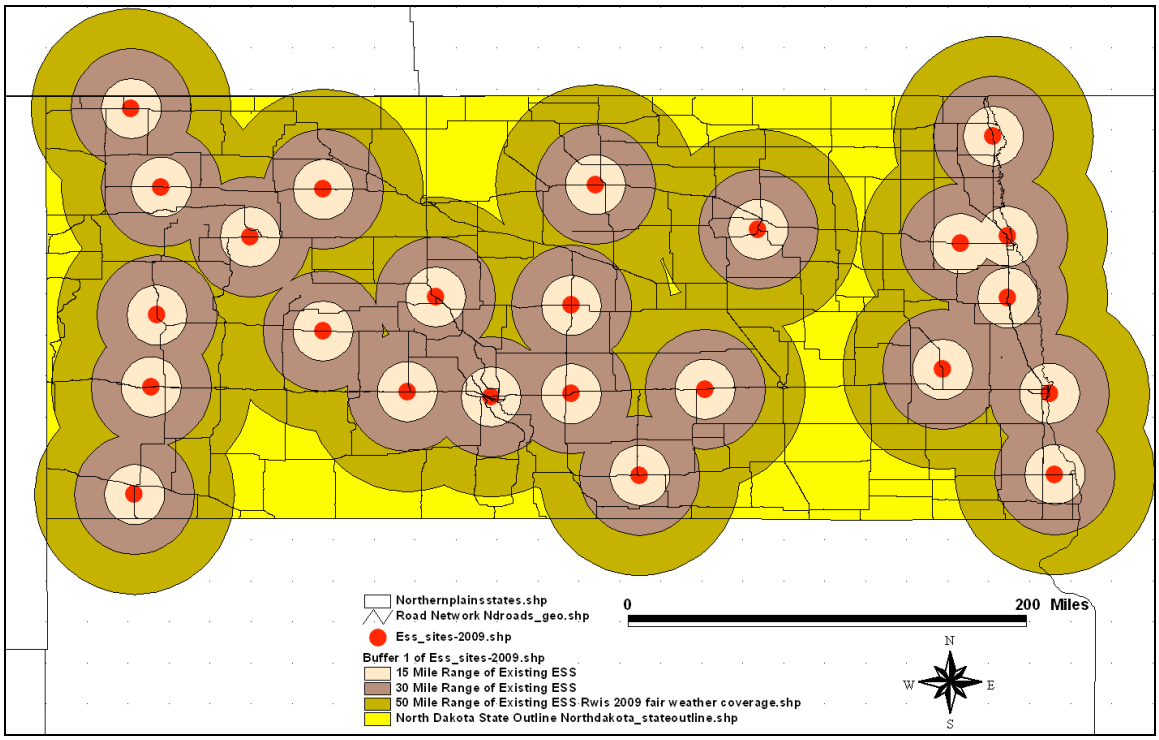

Figure 20. NDDOT RWIS network coverage during fair weather

Thus, the lack of ESS observations off the Interstate highways located along the eastern edge and southern third of the state presents a major limitation in the provision of useful data for decision-making and planning activities. Further, the same limitations in ESS observations present considerable challenges to private sector road weather providers when attempting to forecast road weather and pavement conditions for NDDOT winter maintenance activities. These limitations eventually impact the traveling public who rely upon road maintenance activities to engage in safe travel during winter conditions.

To rectify the deficiency in ESS observation density, additional ESS observations are needed at appropriate locations that would remove the critical data voids. Of particular concern are the data gaps present between Valley City and Jamestown and between New Salem and Fryburg, (along I-94; Fig. 19). These are the most significant gaps along the Interstate highway system and present a challenge relative to understanding the state of the pavement in these areas. Other areas of note exist along US-2 between Rugby and Blaisdell and between Emerado and Devils Lake. The ESS observation gap is even greater at various locations around the state beyond US-2 and the Interstate highways. To achieve a more ubiquitous coverage that would benefit a statewide understanding of current road weather conditions, it is recommended that eighteen (18) additional ESS installations be established at the locations noted in Figure 21 and Table 12.

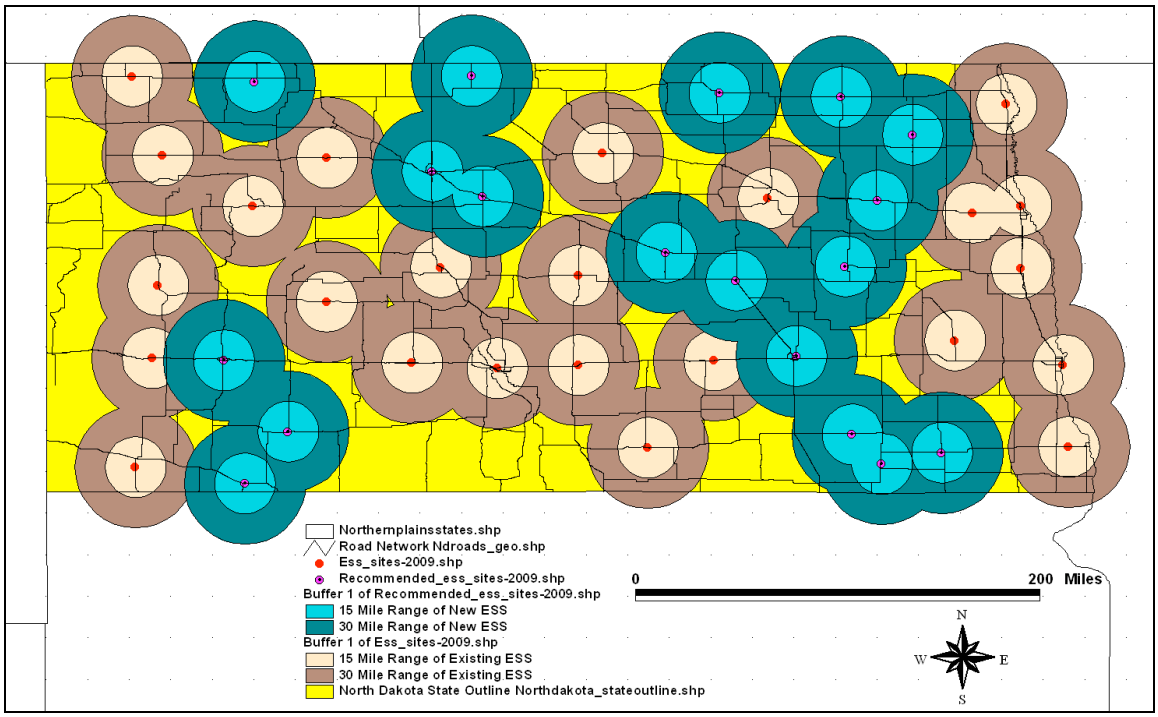

Figure 21. Recommended additional ESS installations

Even with the addition of these eighteen locations, gaps in road weather coverage will remain during inclement weather. However, this addition to the RWIS network would vastly improve coverage, and would provide NDDOT maintenance personnel and private sector road weather forecast providers with adequate coverage to support their current and projected future efforts and activities. Future activities supported would including availability of fixed observations for validating mobile ESS data observations from maintenance vehicles.

Table 12. Specific locations for recommended new ESS installations

Location Name	Highway	Latitude	Longitude
Mott	ND 21	46.37 N	102.32 W
Dickinson	I-94	46.88 N	102.78 W
Velva	US 52	48.05 N	100.93 W
Westhope	US 83	48.91 N	101.01 W
Minot	US 2	48.23 N	101.29 W
Fessenden	US 52	47.65 N	99.62 W
Carrington	US 52	47.45 N	99.12 W
Jamestown	I-94	46.91 N	98.69 W
La Moure	ND 13	46.35 N	98.29 W
Oakes	ND 1	46.14 N	98.08 W
Gwinner	ND 13	46.22 N	97.65 W
Michigan	US 2	48.02 N	98.11 W
Larimore	US 2	48.76 N	98.37 W
Binford	ND 1	47.55 N	98.34 W
Edinburg	ND 32	48.49 N	97.86 W
Rocklake	ND 5	48.79 N	99.24 W
Hettinger	US 12	46.00 N	102.63 W
Lignite	ND 5	48.87 N	102.56 W

Instrumentation required for the additional ESS installations will vary according to local requirements of NDDOT maintenance personnel. From the interviews of expectations and needs of maintenance personnel across the state and to promote a low-cost open architecture, a minimalistic ESS configuration is preferred. This results in a recommended ESS instrumentation suite that should include, at a minimum, sensors to measure:

- Air temperature/relative humidity,
- Wind speed and direction,
- Present weather/visibility,
- Precipitation,
- Pavement temperature,
- Sub-pavement temperature, and
- Camera imagery of roadway/weather conditions.

This complement of instrumentation is approximately the same configuration as the present ESS package installed, with the omission of in-pavement condition sensing. Given the desire by the NDDOT management to minimize the cost of new ESS sites, the elimination of the pavement condition sensor would result in a significant cost savings in excess of $6,000 per site. While pavement temperature and condition were found to be important features, the use of camera images to resolve the latter was becoming a more prominent *de facto* action within the operational environment and supports the field personnel request for greater access to camera imagery.

Using the above recommendations and after conducting a review of the commercial availability and performance characteristics of these systems, a set of performance features

was constructed to assist in development of procurement documentation. The performance features were derived from instrumentation trials conducted at the RWFRF to determine acceptable levels of performance and interface/accessibility characteristics. The list of qualified vendors comes from product literature reviews and discussions with instrumentation vendors who manufacture components and sensors that can be utilized in an open architecture framework and meet the performance characteristics recommended. The list also contains vendors who provide equipment meeting the performance features required. Appendix B provides a complete description of performance features for use in preparing procurement specifications. Appendix C provides a list of qualified vendors who have been determined to meet the performance features described in Appendix B.

Alternate approach to ESS site additions

An alternate approach under consideration by NDDOT is to expand the present ESS coverage through the use of mobile ESS. The observations from these mobile platforms would predominantly come from instrumented maintenance vehicles with a capability of providing near real-time transmission of their data to a central data collection center located in Bismarck. Often referred to as Mobile Data Collection/Automatic Vehicle Location (MDC/AVL), NDDOT has deployed approximately 20 of these units at various locations across the state. Data collected from these mobile platforms, while not equivalent to fixed ESS observations, do provide an interesting alternative to fixed ESS. However, the integration, data quality, and accessibility need further investigation and are outside the scope of this study.

ESS Open Architecture Framework

The growing trend by state DOTs has been to migrate to open systems capable of incorporating multiple vendors and more commercial off-the-shelf components. The South Dakota DOT has recently deployed an open architecture system and expects this system to present much greater flexibility for RWIS to satisfy the growing demands of the data to support maintenance decision making and integration into other support efforts including 511, MDSS, and emergency management. Using information determined in personnel interviews, field trials of representative instrumentation, and studies of open architecture ESS use in other state DOTs, an open architecture design was developed addressing NDDOT's requirements of a lower-cost ESS system with appropriate sensor capabilities to satisfy agency user requirements within a non-proprietary, open architecture ESS configuration. It is likely that some components, primarily atmospheric sensors, within the existing system that are capable of being used in an open architecture ESS can be re-tasked and incorporated into a new NDDOT open architecture RWIS. However, this would be at the discretion of NDDOT as to sensor component re-use considering that technological advances provide more capability with newer sensor components.

The open architecture ESS design was prototyped as part of the field trials described in the previous section. The definition of *open architecture* followed in the ESS open architecture framework was one that embraced both a hardware and software aspect. The open architecture hardware aspect permits adding, upgrading, and swapping ESS sensor components using commercial, off-the-shelf (COTS) sensors permitting vendor neutrality in system development and design. In this framework, the operating characteristics and data

interfaces are a necessary and required feature available from the sensor provider. This information permits communications and processing interfaces for each sensor to be incorporated into an appropriate data logging/data acquisition system. The resulting data logging system is anticipated to be either custom-built by a data interface vendor to support COTS sensors, or a COTS data logging device that can be utilized through agency in-house programming to accommodate the COTS sensors. For this project the latter option was followed in the UND prototype. This decision was based on the ready availability of expertise at UND to construct and deploy such in-house component integrations. It is expected that NDDOT ITD staff have similar software development expertise or that the UND prototype will provide sufficient insight to these agency IT staff to guide them in a successful in-house development. The data interface device used in the UND prototype was a data logger Campbell Scientific CR-3000. An example of the alternate approach to data acquisitions is a vendor provided custom-built data logging system used by the SDDOT. The SDDOT data interface solution was developed by Innovative Dynamics, Inc. (IDI) to permit the use of COTS sensors in the SDDOT RWIS configuration.

The UND-designed open architecture ESS paradigm permits adding, upgrading, and swapping of ESS sensor components, but also extends to the method of data acquisition, data management, and data archival. The open architecture hardware and software come together to support the interface of the ESS sensors to the appropriate data logging systems in use within the architecture design. The additional open architecture software framework extends to the communications protocols used to acquire the data from the data logger, or RPU, and the method by which the data are managed at the central host data server, or CPU. In some situations, the RPU may be by-passed through direct interfacing of the ESS sensor with the CPU. This direct interface refers to Internet Protocol (IP) addressable systems where the CPU "talks" directly to the ESS sensors via the sensor's network address and acquires the sensor data through these direct communications. The advantage of the IP addressable ESS sensors is the capability to poll specific instruments at specific time intervals that might be different from other sensors in the ESS package. This permits the system architecture to address configuration issues where higher frequency of data access may be sought from the ESS without requiring a polling of the full complement of data across all sensors.

The crucial software aspect of the prototype open architecture framework considered was the consistency of the nomenclature and metadata handling of the sensor attributes. Much of the emphasis for this comes from the NTCIP 1204 standard development during the late 1990s and early 2000s. This standard provides a consistent, interagency naming convention to variables supporting a consistent data dictionary of ESS sensor attributes. One of the primary intents of the NTCIP 1204 standard was the promotion of vendor neutrality in ESS sensor array configurations and deployments. While the NTCIP 1204 standard promotes uniformity in component naming and characterization of sensor attributes, it is not a native aspect of the sensor and adds an additional software layer to the construction of in-house ESS open architectures. Thus, the NTCIP 1204 standard, being strongly promoted as a requirement in ESS/RWIS design, must be carefully addressed in the database design of an open architecture ESS framework. Responding to the NTCIP 1204 standard also provides an important step towards collecting and managing ESS sensor metadata. Having a complete set of metadata is considered in the UND open architecture prototype as a necessary and

critical feature of a successful ESS architecture design and data management and utilization plan.

The schematic of the UND prototype ESS open architecture framework (Fig. 22) depicts the hardware and software relationships within the architecture. The hardware and network design of the ESS architecture includes a data logger (serves the role of the RPU relative to the existing NDDOT RWIS design) that integrates an array of atmospheric and pavement sensors each having Ethernet connections between the logger and sensor. Programming of the data logger provided flexibility in determining the nomenclature of the sensor variable (i.e., NTCIP 1204 standard object names), frequency of data collection from each sensor, local processing to generate bulk statistics during set intervals of data collection, and the local storage of the acquired sensor data for later data acquisition and download to the RWIS CPU.

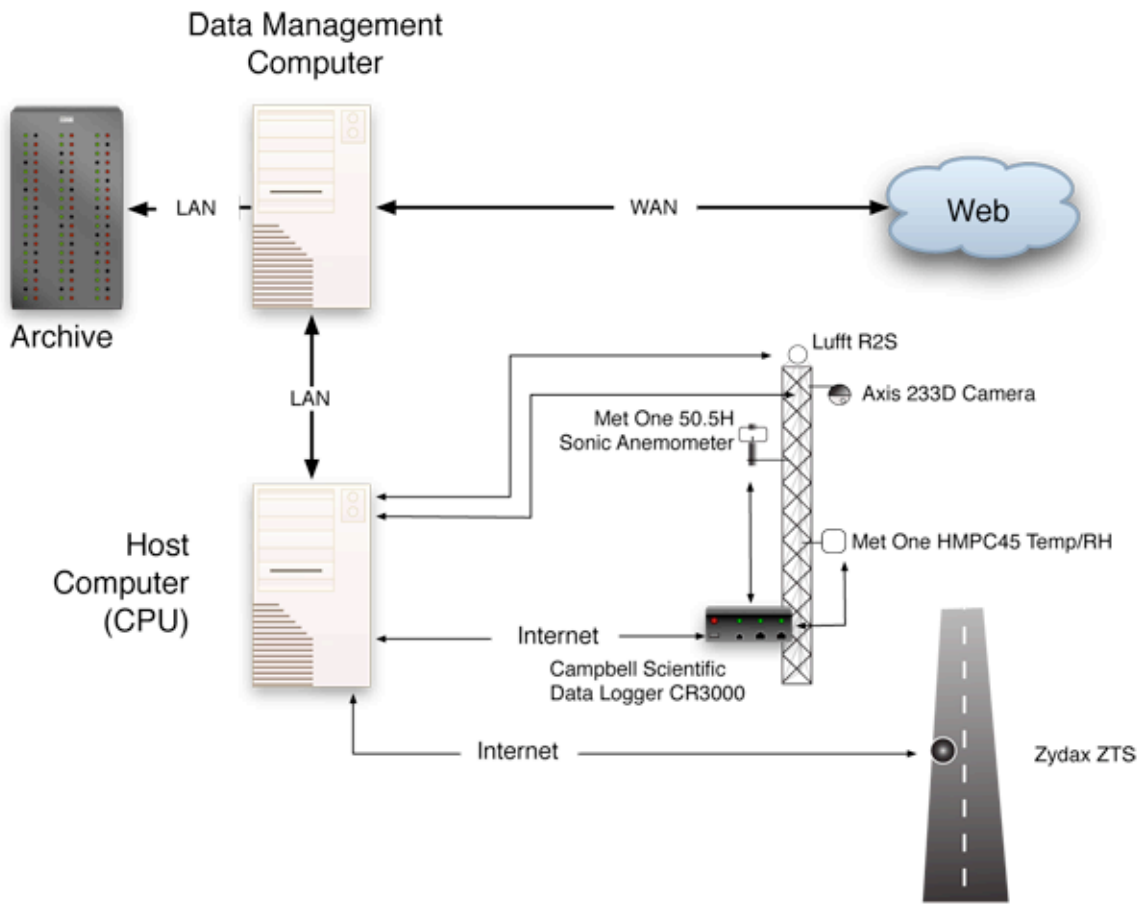

Figure 22. An ESS open architecture framework

In the case of the UND prototype, the communications interface between the sensors and the Campbell data logger were accomplished through hardwire interconnects using sensor wiring screw-down blocks and serial wiring via DB-9 connectors and sockets. These connections, using analog and pulse-length signals, are fed to the data loggers. Communications with sensors without Ethernet capability was possible when connected through serial cables to low-cost (less than $20) Ethernet adapters. All Ethernet wiring was completed using

Category 5e cable with RJ-45 connectors and sockets. The data logger was polled via the Ethernet network by a Microsoft Windows XP host computer located in the STWRC RWFRF data facility (analogous to the CPU in the present NDDOT RWIS configuration). The host computer executed the Campbell Scientific Loggernet software for data polling. This software constitutes the only proprietary portion of the prototype architecture framework. While Campbell Scientific does not provide open source data acquisition software, they do provide the necessary interface specification to develop software drivers to replace the Loggernet software. [Note: Given the personnel limitations in the project, the development of open source software to replace the Campbell Scientific Loggernet software was not attempted but an evaluation of the interface specification suggests that such software would only require several man-months of developer time to complete and that the resulting software could be developed to be software platform independent.]

The prototype ESS open architecture developed also supports an IP addressable interface that integrates sensors directly to the host computer (CPU) via an Internet network connection. As with the sensors connected to the CR-3000 data logger, each sensor manufacturer provided a detailed specification of the interface protocols required to communicate with their sensor and to establish data acquisition methods. Software algorithms were developed by UND staff to complete the Internet access to the IP-addressable sensors, which include the Lufft R2S precipitation sensor, the Lufft IRS31 pavement sensor, Zydax pavement sensors, and the Axis Pan-Tilt-Zoom (PTZ) camera. The design of the software provided the opportunity to specify sensor data nomenclature (i.e., NTCIP 1204 standard object names) and set polling rates and data formats for each sensor. The software design also permitted, where applicable, sensor configuration and testing to optimize the performance of the sensor. While the software developed to support the IP addressable sensors was developed and hosted on a separate computer running under a FreeBSD UNIX operating system, the software could have also been executed on the same host computer used to support the Campbell Scientific Loggernet software. The decision to use a UNIX operating system was for the convenience of UND STWRC personnel. This same UNIX-based computer system was also used as the data management computer for all ESS data acquired during the project.

Although the data communications for the prototype development did not demonstrate the use of wireless communications as a method for data exchange between the RPU and CPU, this method does provide a viable communications method as associated bandwidths have increased and operating costs have decreased in recent years. Specifically, the use of cellular cards within an RPU configuration was investigated and found to be a viable method for data communications across North Dakota. The precedence has already been established by NDDOT for acquisition of data from several existing NDDOT ESS using the present vendor solution. A review of current broadband coverage for each of the eighteen recommended new ESS sites (Table 12) demonstrated that at least one cellular service provider currently supports such services. Given the low data volumes typically acquired from ESS sensors (less than 10 KB), even with the presence of multiple camera images each hour (less than 250 KB for six images each hour), the monthly data volumes acquired from an ESS would permit a low-cost cellular communications solution. Thus, it is recommended that future ESS siting strongly consider the use of cellular communications except where lower cost landline telephone communications capabilities are present.

Data management of the UND open architecture ESS prototype was initially accomplished by creating a standard format data structure using a scientific data format known as netCDF (short for network common data format). This is a self-describing data format frequently used within the scientific community. While not a means to compress the acquired data, this format does provide for near-universal access to the data. After insertion into the netCDF format, the data were placed into an archive as well as interfaced to web display software for presentation via a publicly available web page hosted at UND (http://stwrc.und.edu/timeplot/rwfrf.html). To maintain continuity of data flow through all weather conditions, all data loggers and computer systems were connected to battery backup power units and power conditioning units. Operation of the open architecture ESS was sustained with little difficulty and required only periodic maintenance to manage the archive data volumes. Since the initial field trials, this netCDF data management system has been augmented with a parallel relational database system. Using the database software MySQL, a series of data tables have been established that provide data query capability that has been linked to the UND STWRC web page for ease of data access. At present, the UND prototype ESS open architecture system runs completely unattended with the output from the system available for public access.

Recommended ESS Data Management Plan

The use of ESS/RWIS data in an effective manner requires dependable and readily available data around-the-clock throughout the year. This requires appropriate management of the ESS data not only during routine business hours, but also on-call support during non-routine business hours, including weekends and holidays. Further, as these data are routinely utilized for operational decision-making, road weather forecasting services, and research applications, the support of these data to foster greater reliability in data quality measures suggests that knowledge of the data formats and applications are desired within the data management efforts.

Discussions have been held with the NDDOT Maintenance Division in which numerous reasons for a review of the present ESS Data Management Plan were cited, including the need for greater around-the-clock reliability/availability, improved RWIS data management/quality control, more effective availability of data for integrations into evolving support systems for ongoing operational efforts, and the development of methods to reduce long-term operational costs of RWIS data management.

To address these needs in the future, it is important to satisfy performance outcomes required to provide a comprehensive ESS data management plan. This will ensure the optimal availability and quality of ESS data resources used within NDDOT and beyond. The performance outcomes should include:

- Provide telecommunications capability supporting statewide ESS data retrieval at a frequency no less than once hourly with a provision for higher frequency data retrievals during inclement weather conditions;
- Provide 24/7 operational ESS data management support for network/server maintenance and support issues including holidays and summer;

- Provide routine quality checking and availability of quality check data containing flags of suspect data before ESS data display or delivery to users;
- Provide an effective web-based interface for display and delivery of current and historical ESS data;
- Provide an effective web-based tool for monitoring RWIS network status and supporting trouble ticketing and coordination of problem resolution;
- Provide technical and software support to address user data demands including the integration of data from the legacy proprietary ESS architecture with data from the newer open ESS architecture;
- Provide backup/archival of ESS data including on-line ESS data inventory listings and ESS archived data retrieval;
- Provide database accessibility, albeit with proper security, for routine external access by approved agency and external data users;
- Provide up-to-date ESS sensor and site metadata accessibility on-line; and,
- Provide a repository of all data management operational software including the presence of revision history.

To achieve the performance outcomes above will require implementation of an ESS data management plan that has received the institutional support of the NDDOT and other participating North Dakota agencies, i.e., ND-ITD. It will also require proper staffing to provide the level of user support and technological expertise to quickly resolve problems and to effectively communicate to affected parties the changing status of the RWIS network.

This data management plan is divided into six important components:

1. data acquisition,
2. data processing and data integrity,
3. tracking responses to data issues,
4. data delivery,
5. data archive, and
6. administrative oversight.

<u>Data Acquisition</u>

ESS data acquisition will involve the routine process of communicating with ESS sensors directly using IP addressable methods or via ESS data loggers/RPUs. It is important that the data acquisition be performed in a timely manner such that data are acquired following a pre-determined schedule that is routine, reliable, and meets the ESS data users' needs. Automated processes should be incorporated in the data acquisition, which generate alert notifications when data acquisition issues arise. These alerts should be provided 24/7 to on-duty/on-call information technology personnel whenever an interruption in the data acquisition process occurs. A reasonable, yet short, time limit should be set to respond to data acquisition problems without regard for time of day, day of week, or month of year it is likely that an ESS data flow interruption will have some adverse impact on NDDOT operations. A monitoring and notification process that is tied to the automated data acquisition process should be implemented to provide NDDOT personnel and other high priority ESS data users a means of monitoring the data acquisition status for all ESS in the RWIS network.

Data Processing and Data Integrity

Timely processing of ESS data promotes a quick availability of the data for use by NDDOT and its partners. Data processing should commence immediately upon data acquisition and continue through the identification of the data integrity. The storage of the ESS data as a result of the data processing should be done in a manner that facilitates the most efficient method of data extraction by data users. The method recommended is the use of a relational database that promotes efficient agency IT resource usage through a concise and clear database schema. This database schema should be established to permit future expansion in database tables as new sensor functionality becomes available.

Usefulness of the ESS data will depend upon maintaining an acceptable level of data accuracy as well as appropriate quality check flags useful for identifying ESS data that are suspect or erroneous. The data management plan must include a quality checking process that is sufficiently robust to identify problematic data prior to its incorporation in activities and processes requiring the ESS data. This should be accomplished by applying an automated algorithm for checking data using a combination, at a minimum, of the following methods to identify quality issues:

1. Gross error checks against the sensor valid range;
2. Temporal consistency check against a valid range of change in the time interval between observations;
3. Coarse spatial consistency check through intercomparison with nearest neighbors; and,
4. Fine spatial consistency check resulting from a comparison of observed values with spatial analysis derived from a) all like sensor observed values and b) from a data assimilation of all data and numerical weather prediction and/or pavement condition models as appropriate.

The quality checking process should be performed as a continuous process as data are received. Data not passing the acceptance quality checks listed above should be flagged as not meeting the appropriate quality check flag. These flags should reside as a companion data file to the observed data such that algorithms, data displays, and end-users of the data can respond accordingly to the quality flags for each data element. It is important to note that the success of this data quality checking depends upon the completeness of an up-to-date ESS metadata file. This metadata file must contain the attributes of all ESS sensors including positional information, date the sensor was placed in service, sensor manufacturer, and the complete operating characteristics of the sensor. This metadata should be reviewed at least annually with a complete history of changes maintained in a log that remains for the lifetime of the ESS site. As with the data acquisition, an automated monitoring process should exist that generates alerts to appropriate data management staff when ESS data become flagged for poor quality. Similarly, the results of the monitoring process should be provided in a web-based display that is available to data users for quick determination of data quality issues. It should be noted that the data quality check flags from the *Clarus* System[10] of the Federal Highway Administration could be used as a surrogate for an in-house quality checking process. However, beyond the elimination of the in-house execution of the quality checking

[10] Clarus System Design, http://www.clarusinitiative.org

algorithms through the use of the *Clarus* System, all else described above would still apply towards the ESS data management plan.

Tracking Responses to Data Issues

The presence of problems in data acquisition and/or data integrity requires a technical response to identify and correct the cause of the problems. This could range from visiting an ESS site to verifying the integrity of the sensor installation and communications equipment, to a need to work with telecommunications entities to resolve a data link, to the replacement of a sensor. In all cases this requires human intervention at multiple levels and effective coordination of actions across these levels. Having a trouble ticket system or similar means for providing a status of the problem rectification and resolution assignment is important to maintain an efficient data management program. ESS data management should include a web-based interface to promote a coordinated response to ESS data management issues. This web-based interface should be integrated with the other monitoring and alert notification measures mentioned previously above. Such systems are presently in use by the Minnesota Department of Transportation (MnDOT) for the purpose of providing a clearinghouse of RWIS network vitality and to effectively coordinate the resolution of ESS sensor and data communication problems. The MnDOT system was originally developed, in part, through research activities of the AURORA RWIS Pooled Fund Study.

Data Delivery

The effective use of ESS data depends upon a timely and coherent delivery of the ESS data. The ESS data management should include an appropriate set of data delivery methods to foster the greatest utilization of the NDDOT ESS data. This includes having an interactive web interface that provides both a spatial and temporal depiction of NDDOT ESS data, both current and historical. This web display should provide all relevant information associated with the data including quality check flags. The age and quality of data should be depicted in such a manner as to clearly denote data that are not current or of less than acceptable quality.

In addition to a web display, the ESS data should be accessible in defined and published data formats that facilitate their use in automated data processing systems including such applications as Maintenance Decision Support Systems, road weather forecasting services, and spreadsheet analysis tools. The formats that should be considered include comma-separated values (CSV) and Extensible Markup Language (XML). Access to these data formats of data should be supported either by a web download or an FTP download from a convenient location outside of the NDDOT network firewall.

Data Archive

All data acquired from the NDDOT RWIS network and associated metadata and quality check flags should be routinely archived. These archive files should reside online and be accessible for a period of no less than ten years, at which time they should remain in an offline archive and be accessible for an indefinite period of time by request. The data should reside in a self-describing data format such that changes in the data formatting become noted within the data archived file. The active archival of data should include a searchable inventory providing the sensor types available at each ESS site as a function of time. Access

to the data archive should be provided either through a web-based interface or through a published FTP site outside the NDDOT network firewall.

Administrative Oversight

ESS data users will consist of a non-trivial and diverse number of stakeholders extending beyond the NDDOT. Each of these stakeholders will likely have varying needs for ESS data and accessibility. To promote the maximum use of the ESS data as a public resource, it is important that appropriate administrative oversight be established to foster the ESS data utilization and best practices in data management. A technical advisory panel should be established by the NDDOT to provide consultation and recommendation to the NDDOT for maintaining the NDDOT RWIS network and the appropriate content available from the ESS sensor configuration. This technical panel should report to a NDDOT RWIS Coordinator who has the administrative oversight, including budget recommendation authority, to promote and preserve the greatest benefits of ESS data for the State of North Dakota and the North Dakota Department of Transportation.

As part of the administrative oversight, the RWIS Coordinator should annually review the ESS Data Management Plan in consultation with the RWIS Technical Panel. Appropriate modifications should be made to this plan to respond to changes, needs, and requirements of ESS data in North Dakota.

Open Architecture ESS Maintenance Requirements

To maintain optimal performance for the open architecture ESS, periodic maintenance will be crucial to ensure the data integrity of the sensor array and the accessibility of the sensor data. Routine maintenance will help to minimize downtime of an ESS and will promote data integrity. However, given the often harsh environment of the ESS sensors it is understandable that with time all sensors will experience difficulty and need to be repaired, recalibrated, or replaced.

The recommended maintenance is an annual sensor check that characterizes the operating effectiveness of a given sensor. While it would be preferred that all sensors be recalibrated annually, this would be an expensive activity and in some situations impossible given how a sensor might be installed (e.g., in pavement or sub-pavement sensors). However, using the quality check flag history described for ESS data management, useful indicators would exist to assist in identifying which sensors in the RWIS network are becoming less reliable. These sensors should be identified as the top priority for possible recalibration, repair, and/or replacement.

For some sensors, a performance test can be performed *in situ* following an accepted testing protocol. One such test for pavement sensors was established by NCHRP Project 6-15[11]. It is recommended that pavement sensors be checked following this testing protocol at a minimum of every two years. Pavement sensors (either temperature or condition) not meeting the testing standard for performance should be placed on a list for consideration for replacement and the sensor should be blacklisted as an unusable sensor.

[11] Fleege, E.J., "Testing and Calibration Methods for RWIS Sensors", 2005, National Cooperative Highway Research Program, Transportation Research Board, NCHRP 6-15

For other sensors where testing is difficult, the use of data denial trials with adjacent observations (either from airport, agricultural, or other ESS) should be used to determine if the observations from a given ESS are within acceptable ranges. Care should be exercised in conducting these tests as weather conditions from the sensors involved should be representative for all observation sites involved.

Finally, general maintenance to remove spider webs, dust/dirt on optical surfaces, and checks of communications and data interface connections should be performed every year for all sensors before onset of winter maintenance operations.

A log of all field ESS maintenance should be maintained and available as a historical part of the metadata for each ESS sensor. These metadata should be a part of the ESS data management plan for data archival and metadata distribution.

VII. Cost Analysis of an Open Architecture ESS

A cost analysis was performed to better understand the fiscal impacts of a transition of the current North Dakota Department of Transportation Road Weather Information System to an open architecture. Costs incurred during the development of the UND STWRC open architecture ESS prototype were used in constructing the cost analysis. In conducting the cost analysis, several assumptions and special considerations were made. These assumptions and special consideration were:

- The estimate of monthly data collection and data management costs for the existing statewide RWIS have changed little since 2005 when the per site cost was $300, including phone line costs;
- The total number of new ESS deployed under an open architecture design will be eighteen;
- The cost of new proprietary ESS and the replacement of existing proprietary ESS sensors will not decrease from the present vendor quoted values;
- The open architecture ESS installation will utilize the present UND RWFRF prototype ESS open architecture configuration as the representative model for all new ESS site implementation;
- Personnel costs used in the cost analysis are an approximate representation of the actual loaded rates encumbered by NDDOT-ITD and ND-ITD staff;
- The new ESS site configurations will utilize or be derived from software developed by UND STWRC staff such that new software development will be minimized; and,
- The cost of the open architecture ESS sensors will match the current sensor costs of sensors utilized in the UND STWRC RWFRF prototype ESS.

The assumptions and special considerations above are recognized to be stronger constraints than will be realized in a true implementation. However, they were necessary to form a basis from which to create the cost scenarios as the required data associated with the present NDDOT RWIS were not available. Cost factors for the annual replacement and/or expansion of existing proprietary NDDOT ESS seemed reasonable if not even below the actual costs.

This assumption was made to establish a reasonable basis for comparison in a transition to new open architecture ESS installations. This is balanced in knowing that in all likelihood there will be additional software development needed to implement the required ESS data management requirements of the open architecture ESS in Bismarck.

The present UND ESS data management system is a stable and cost effective system that has been designed to support the RWFRF research and operations activities. The hardware environment and software development and operations environment supporting the UND effort may differ from those within the NDDOT Information Technology Division (NDDOT-ITD) and the North Dakota Information Technology Department (ND-ITD). These differences have not been factored into this analysis.

Salaries selected for use in the cost analysis were considered to be approximate market value salaries for work associated with road weather sensor systems, software development, and database administration. Actual salaries of existing NDDOT, NDDTO-ITD, or ND-ITD personnel were not used; however, broadband salaries available from the North Dakota Office of Management and Budget were employed. The cost analysis did consider that the NDDOT would see a cost benefit from lessons learned and software developed at UND. Thus, it is expected that the implementation costs would be reduced for deployment as many of the costs would be associated with replication of the present UND system to any new State system. Software development costs that are included in the cost scenario are primarily associated with those that will be required to develop a new combined database containing the open architecture ESS data and the data obtained from the legacy proprietary ESS architecture.

The hardware costs associated with an individual open architecture ESS recommended earlier in this study are noted in Table 13. These represent the current list costs of sensors and communications components used to establish the ESS prototype at the UND RWFRF. The proposed open architecture ESS is composed of

- Atmospheric sensors,
- Pavement temperature sensors,
- A pan-tilt-zoom (PTZ) camera, and
- Associated data collection and power supplies.

The instrumentation manufacturers and the sensor model numbers used to construct the UND RWFRF prototype ESS are:

- Lufft Radar Rain Precipitation Sensor (R2S)
- Campbell Scientific HMP45C Temperature/Relative Humidity Sensor
- Met One Instruments 50.5H Sonic Anemometer (2D)
- Zydax Pavement Temperature Sensor (ZTS)
- Axis 233D Network Dome Pan/Tilt/Zoom Camera
- Campbell Scientific CR3000 Data Logger.

Table 14 provides the costs associated with the construction of the tower to host the ESS equipment. These costs are expected to be higher than the similar construction costs that

would be incurred by the NDDOT due to ability of the NDDOT to perform aspects of this construction activity with agency personnel rather than contract labor.

Table 13. Hardware costs associated with the recommended open architecture ESS

Sensor	Manufacturer	Unit Price
Radar Rain Sensor (R2S)	Lufft	$3,365.00
Power Supply 24V/4A		$418.00
Digital Transmitter UMB-ISOCON	Lufft	$502.00
Model 50.5H Sonic Anemometer	Met One Instruments, Inc.	$2,950.00
3188 Mount and Alignment Adapter (for 50.5H)	Met One Instruments, Inc.	$120.00
50.5H Cable Setup and Connector	Met One Instruments, Inc.	50.00
50.5H Heater Power Supply (50.5PS)	Met One Instruments, Inc.	$170.00
HMP45C Temperature/Relative Humidity	Campbell Scientific	$595.00
Radiation Shield for HMP45C	Campbell Scientific	$185.00
Zydax Temperature Sensor	Zydax	$281.95
233D Network Dome Pan/Tilt/Zoom Camera	Axis	$2,299.00
Weatherproof Dome Housing	Axis	$349.00
Wall Mount Bracket	Axis	$98.50
Pole Adapter for Bracket	Axis	$62.40
Internal Camera Adaptor Fan-assisted Heater, 24 VAC	Axis	$255.00
Axis Power Supply 4 amps. 120/240 VAC input, 24/26/28 VAC output.	Axis	$149.00
CR3000 Micrologger	Campbell Scientific	$2,850.00
Extended Temperature Range (-XT) (for the Micrologger)	Campbell Scientific	$285.00
NL115 Ethernet Interface and CompactFlash Module	Campbell Scientific	$350.00
Extended Temperature Range Support	Campbell Scientific	$35.00
Net232 Serial to Ethernet Converter (used for Lufft Sensors)	GridConnect	$198.00
Nport 5150-T (used for Zydax sensors)	Moxa	$610.00
PS100 12V Power Supply	Campbell Scientific	$245.00
Total ESS Instrumentation Cost		$16,027.85

Table 14. Cost associated with ESS site preparation

ESS Tower Installation Activity	Cost
Concrete Work	$10,248
Electrical Work	$7,137
40' Tower w/ climbing pegs	$2,673
Tower Installation	$1,127
Total Tower Installation Cost	$21,185

Cost Analysis Scenarios

One aspect of particular interest for the NDDOT is the use of only pavement temperature measurements within their ESS and eliminating the use of pavement condition sensors within new ESS configurations. This interest is driven by two considerations. First, the lack of acceptance by maintenance personnel of pavement condition data has grown over the years due to concerns regarding reliability of the sensor data. The other consideration is the high cost of pavement condition sensors, ranging from $6,000 to in excess of $10,000 per installed sensor. To address this NDDOT interest, UND generated two cost scenarios. The first scenario evaluated the projected costs to adapt the existing ESS configurations to integrate an alternative pavement temperature system. A second cost scenario incorporated alternative pavement temperature sensors as part of a transition to an open architecture ESS framework.

Scenario One – Addition of Alternative Pavement Temperature Sensors to Existing ESS

The principal challenge with adding new sensors to an existing proprietary ESS configuration is the cost of integration of the alternate pavement temperature sensor within the proprietary hardware and software system. Most proprietary ESS system vendors already have pavement temperature only sensors. A significant cost will be levied to integrate a new sensor into their proprietary system. Thus, if a pavement temperature sensor is the sole desire, then it is most cost effective to work with the existing ESS vendor to add this to their proprietary system. The cost for this activity was not developed in this project as this would require solicitation of quotes for systems beyond the control of UND.

The development of an alternative pavement temperature sensor that exists as an open architecture ESS sensor, but exists alongside the proprietary ESS, was also considered. The costs associated with this configuration include not only the alternate pavement temperature sensor, but also the addition of a data logging device to interface to the sensor. Considerable cost savings would be realized by using an IP-addressable sensor. This latter situation would remove the data logger requirement, but would still require an appropriate data communications link as well as a power source be established. The hardware cost to complete each of the above considerations is presented in Table 15.

Table 15. Hardware costs to provide only non-proprietary pavement temperature sensors to ESS

Scenario One Options	Data Communications Interface	Estimated Cost Per Sensor Installed
Addition by Existing proprietary vendor provided	Requires Vendor Quote	Requires Vendor Quote
Addition of alternate pavement temperature sensor interfaced to data logger	$4,375	$282
Addition of alternate pavement temperature sensor using IP addressable interface	$850	$282

The dominant cost above is associated with the communications interface to acquire the data from the alternate pavement temperature sensor separate from the proprietary ESS vendor's hardware. An economy of scale would be realized should multiple alternate pavement sensors be installed at a given ESS location as the cost to provide a communications interface to sensors would be imposed only once for an ESS site.

Routine data acquisition costs would be approximately the same for any of the above options. However, there would be an additional setup costs in software development for the data acquisition cost of the non-proprietary sensor data. These costs would largely be a one-time cost for the entire RWIS network as additional ESS could benefit from the same data acquisition software for polling and data management.

The final cost in this case would be that incurred to develop software to permit the merging of the proprietary and non-proprietary ESS data. As the UND STWRC has routinely acquired the ESS data from the NDDOT RWIS data server managed by ND-ITD, it has experience in the process of merging these two datasets. Although the resulting software has addressed specific UND STWRC needs, it has provided a means to assess the amount of time that will be required to develop a common database between the existing proprietary ESS data and open architecture ESS data. This time requirement would be approximately 180 man-hours of development time. Using a database developer loaded rate of $95 per hour, this translates to a development cost of a merged ESS database of $17,100. While there would be ongoing additional development costs with the growth and further customization of the database system, it is believed that additional personnel costs to refine the software would be negligible.

Scenario Two – Use of Alternative Pavement Temperatures Sensors within a Transition to an Open Architecture ESS Framework

The use of an alternate pavement temperature sensors within a transition to an open architecture ESS deployment suggests that each new ESS would exists as an open architecture ESS while existing proprietary ESS systems continue to be utilized. It is expected that any subsequent replacement of the existing proprietary ESS systems would be made using the open architecture design. Over a period of time spanning from several years to more than a decade, the system would eventually transition to a fully open ESS

architecture framework. Having a hybrid system during this transition would permit the NDDOT to gain optimum benefit from the previous ESS investment and allow for an orderly transition from a proprietary to an open architecture.

The cost to develop a merged database of closed (proprietary) and open architecture ESS data was described above to be $17,100. This same cost estimate is valid estimate for this scenario. Therefore, the additional costs to establish open architecture ESS sites would be associated entirely with the selection of the desired sensor configuration and providing for the appropriate data interface and communications. Using the prototype open architecture ESS developed by UND at the STWRC RWFRF, the estimated cost to establish a new ESS site would be approximately $16,000 for sensors and communications interface and an additional $20,000 for tower and tower installation. Therefore, the cost to develop a new open architecture ESS site would be approximately $40,000, where an allowance of $4,000 has been made to account for unforeseen incidentals. This cost does not include the personnel costs to install the sensors and conduct calibration and testing to certify the ESS as acceptable for operations. Estimating this sensor installation and certification process to take approximately 120 man-hours, the ESS setup and certification cost would be approximately $8,000 for each new ESS site. This brings the total new ESS site cost to approximately $48,000. The most recent NDDOT proprietary ESS site installation cost was approximately $90,000. Comparing these two costs, the installation of the open architecture ESS represents a nearly 2-to-1 cost savings. Applied across the recommended eighteen new ESS sites this comes to almost $1 million in savings over expanding a proprietary RWIS network. Table 16 summarizes the approximate costs for an open architecture ESS expansion to the NDDOT RWIS.

Table 16. Summary of costs to transition to 18 open architecture ESS

Cost Item	Estimated Unit Cost	Recommended No. of Units	Total Item Cost
ESS sensors and data interface	$16,000	18	$288,000
ESS Tower and Tower Installation	$20,000	18	$360,000
ESS installation cost	$8,000	18	$144,000
One-time software development to merge existing and open architecture ESS data	$17,100	1	$17,100
		Total Cost	$809,100

Open Architecture ESS Data Management Cost Analysis

Additional costs to those cited above will exist in the transition to an open architecture ESS in much the same way as on-going sensor maintenance and data collection. The costs can be categorized as being routine sensor maintenance and replacement, data collection, and data management activities. Table 17 summarizes the estimated costs associated with each of these actions under an open architecture ESS framework. For the deployment of eighteen new open architecture ESSs these cost will constitute a significant budget requirement. Estimation of costs required for routine ESS sensor maintenance assumes that the personnel involved are adequately familiar with each sensor's maintenance, testing, and calibration procedures to provide an efficient maintenance effort. With the completion of new open

architecture ESS site commissioning, it is expected that only periodic maintenance will be required. It is recommended this maintenance be performed once each quarter of the year. Experience with ESS and other environmental sensors at UND suggest that the annual cost of sensor repair and/or replacement is a fraction each year of the total sensor package original cost. A convenient budgeting process utilized at UND for several decades has been to budget for the cost of replacement of the one single most expensive sensor each year. This has been incorporated in this cost analysis by estimating that the average annual ESS replacement/repair cost will be equivalent to the cost of the most expensive sensor, which is the Lufft R2S precipitation sensor.

Table 17. Estimate annual costs to provide ESS data management

Cost Item	Estimated Unit Cost	Recommended No. of Units	Total Item Cost
Routine ESS maintenance	4 days @ $50 per hour loaded rate	18	$28,800
Sensor Replacement or Repair	$3,365	18	$60,570
Data Management			
Data Collection	$180 per year	18	$3,240
Database Management, Archive and Display	$300 per month	18	$5,400
In-House Data Quality Checking	3 months @ $65 per hour loaded rate	1	$33,800
Clarus Enabled Data Quality Checking	1 months @ $65 per hour loaded rate	1	$11,266
Development	2 months @ $95 per hours loaded rate	1	$32,900
Total Cost (with in-house quality checking)			$164,710
Total Cost (with *Clarus* System quality checking)			$142,176

The cost of a portion of the data management (i.e., data collection and database management, archive, and display) was estimated from information provided by NDDOT regarding current ESS data collection and data management. In a communication provided by the NDDOT-ITD in 2005, the ND-ITD had assumed the data collection and database management of the NDDOT RWIS. In assuming this role the ND-ITD was charging a flat fee of $300 per month to host the database and to conduct all data collection from the existing ESS. At the time, NDDOT had approximately 20 ESS in the RWIS network. Carrying forward these costs with an assumption that ND-ITD will continue this function with any new open architecture ESS, the data collection cost is estimated to be $3,240 annually and the database management, archival and display to be $5,400 annually.

The cost estimate above considers that the data display and archival software are in place. This is not a valid assumption and is not considered to be true. It is expected that new display and archival software will be required for the new open architecture ESS data and for

the merged data of the closed and open architectures. To account for an additional need for periodic software development, a cost estimate was included for supporting annual software development activities. This estimate assumes that these activities are intermittent and not routine such that the total manpower requirement does not exceed two months per year. This results in an annual estimated cost of $32,900.

The final cost category involving data management relates to the cost of maintaining awareness of the ESS data quality. As described in the findings of Task 3 the integrity of data is important to gain trust from the data user. Currently the NDDOT does not have a systematic method of data quality checking and this has likely led in part to the comments of concern over data quality by NDDOT maintenance personnel. Therefore, it is recommended that the NDDOT commit to a consistent and routine process of data quality checking to ensure the integrity of its ESS data. [Note: This finding is transparent to the presence of either a proprietary or open ESS architecture.]

Accomplishing this recommendation can take one of two paths. The first involves the development of an in-house quality checking process requiring the development of appropriate quality checking computer processes and routinely monitoring the results to assist in rectifying resulting quality issues. It is expected that this activity would initially require three man-months to establish the computer processes at an annual expense of approximately $33,800. However, this cost would be expected to diminish to one man-month of effort after the first few years as the process of quality checking becomes more automated and requires less personnel intervention.

The other path would be to take advantage of the quality-checking flags generated by the Federal Highway Administration's *Clarus* System. This would still require an initial software development effort, but would be a minor effort. This effort, too, would eventually give way to routine monitoring efforts to communicate quality issues to appropriate NDDOT personnel responsible for use and maintenance of the data. As such this effort would be less costly at an annual estimated cost of $11,266.

The resulting summary of annual costs for ESS repairs, maintenance, and data management for the transition to an open architecture ESS indicates a sizeable cost requirement. If quality-checking flags from the Federal Highway Administrations *Clarus* System are used, the annual data management costs would be near $142,176. A higher cost of $164,710 would exist if an in-house quality-checking program were utilized. Combining these annual costs with the open architecture ESS deployment costs for a RWIS network expansion of eighteen sites, one still produces a system capability that would be significantly less expensive than that encountered with an expansion following a proprietary architecture. As a result, it is the finding of this cost analysis that transitioning to an open architecture ESS would effect a long-term cost savings to the NDDOT and would enhance the value of the data to the entire road weather community.

VIII. Summary and Conclusions

Lessons learned from the development of the prototype open architecture ESS provided considerable insight into the opportunities and challenges (or barriers to success) associated with a statewide implementation by NDDOT. These lessons can be summarized as follows:

Opportunities

- Vendor neutral incorporation of atmospheric and pavement sensors that can be selected *a la carte* (to a reasonable extent);
- Realization of a lower cost solution to ESS deployment (described further in Section VII) through in-house installation and configuration of ESS and a statewide RWIS;
- Minimal proprietary issues associated with sensor selection and implementation [Note: a truly open architecture would consist of an open source data acquisition software capability. Such open source software is possible in the near future, but not currently.];
- Scalability of the ESS network for future growth while incorporating new sensor technology as it becomes available;
- Development of in-house agency expertise to craft ESS configurations that best match the needs of the NDDOT;
- Cost reduction of ESS sensor packages through the replacement of pavement condition sensors with non-invasive camera imagery and improved precipitation detection sensors;
- The continued use of legacy ESS that are part of a present proprietary architecture while transitioning to an open architecture over time;
- Tailoring of ESS sensors, data management, and associated program data integration to better aide NDDOT-defined objectives of supporting maintenance personnel (both winter and summer), incorporation in Maintenance Decision Support Systems, improved traffic/incident management, improved road weather forecasting, and support for agency-related research efforts; and,
- Provide better information to travelers for weather-related decisions, through integration into 511 traveler information resources.

Challenges:

- The design and deployment, including sensor installation, data communications, and calibration, of the ESS becomes an agency responsibility requiring higher manpower commitments [Note: this can be mitigated by procurement of these services much as they are currently done with proprietary architectures];
- Development of in-house expertise will take time and an agency investment to understand the intricacies of configuration of sensors within an open architecture, including developing software expertise to work efficiently with ESS sensor data;
- Sustainability of agency budgeting for a long-term RWIS commitment can be difficult during periods of great economic pressure leading to possible loss of critical mass in agency ESS open architecture knowledge and expertise; and,
- Transition of current proprietary RWIS architecture to an open architecture with data integration of legacy ESS will require the development of an interface layer of software to merge the capabilities of the two systems.

It is the opinion of the project's research team that the opportunities afforded by an open architecture ESS clearly outweigh the challenges or barriers to its success. Of the four barriers noted above, two of these involve agency funding, which are of an institutional nature beyond the scope of this study. However, it is believed that a strong and compelling argument can be built from the opportunities cited above to overcome these barriers. The remaining barriers are more technical in nature and reflect the need for an agency commitment to develop the appropriate expertise to provide a sustainable RWIS effort. This includes the addition of agency personnel or the retention of qualified external support services to conduct the routine duties associated with maintaining an open architecture ESS framework. This also includes the development of appropriate software and data management expertise to interface with sensor data and to assimilate these data into a manageable database system. It is believed that such expertise can be quickly established within the NDDOT, and that within a two-year period a sustainable open architecture ESS framework can be implemented. Since the open architecture can co-exist with the present proprietary architecture through development of appropriate system integration software, the transition from a fully proprietary architecture to a fully open architecture can occur over time. As existing proprietary ESS become unusable or obsolete, they would be replaced with an open architecture ESS. A recommended first step toward this transition to an open architecture ESS is the incorporation of the Buxton I-29 open architecture ESS data into a database that also includes the data presently available from existing proprietary ESS architecture.

Appendix A

The following tables summarize the sensor configurations for the twenty-three existing North Dakota Department of Transportation Environmental Sensor Stations

Site: Bismarck @ Grant Marsh Bridge	StationID: 2227	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Wind speed and direction	R. M. Young Company	05103

Site: Sterling	StationID: 2228	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Wind speed and direction	R. M. Young Company	05103

Site: New Salem	StationID: 2229	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Golden Valley	StationID: 2230	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Medina	StationID: 2231	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Fryburg	StationID: 2232	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Crosby	StationID: 2233	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Blaisdell	StationID: 2234	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Rugby	StationID: 2235	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Emerado	StationID: 2236	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Bowesmont	StationID: 2237	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Buxton	StationID: 2238	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Freeze point sensor	Aerotech Telub AB	Frensor Mk II Active Freezing Point Sensor
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Fargo @ Red River Bridge	StationID: 2239	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement sensor	Surface Systems, Inc.	FP2000
Freeze point sensor	Aerotech Telub AB	Frensor Mk II Active Freezing Point Sensor
Active/Passive pavement sensor	Surface Systems, Inc.	Sensit Pavement Sensor
Wx indicator visibility sensor	Optical Scientific, Inc.	Weather Indicator Visibility Sensor (WIVIS)
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Buffale	StationID: 2240	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement sensor	Surface Systems, Inc.	FP2000
Wx indicator visibility sensor	Optical Scientific, Inc.	Weather Indicator Visibility Sensor (WIVIS)
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Grassy Butte	StationID: 2241	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and	R. M. Young Company	05103

direction		

Site: Devils Lake	StationID: 2242	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Wahpeton	StationID: 2243	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Wx indicator visibility sensor	Optical Scientific, Inc.	Weather Indicator Visibility Sensor (WIVIS)
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: New Town	StationID: 2244	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Wx indicator visibility sensor	Optical Scientific, Inc.	Weather Indicator Visibility Sensor (WIVIS)
Wind speed and direction	R. M. Young Company	05103

Site: Grand Forks	StationID: 2245	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	Temperature Depth Probe (TDP) 2.54 cm to 1.8 meters
Wind speed and direction	R. M. Young Company	05103

Site: Bowman	StationID: 2246	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Hawk Eye Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Coleharbor	StationID: 2247	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Price Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Denhoff	StationID: 2248	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Hawk Eye Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Wishek	StationID: 2249	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Hawk Eye Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Site: Ray	StationID: 2250	
Sensor Type	Sensor Manufacturer	Sensor Model
Temp/RH	Thies Clima	SSI 72657501
Pavement Sensor	Surface Systems, Inc.	FP2000
Precipitation Y/N	Surface Systems, Inc.	Hawk Eye Y/N Optical Infrared
Subsurface temperature probe	Surface Systems, Inc.	S16UG-D Sub-Surface Temperature Probe
Wind speed and direction	R. M. Young Company	05103

Appendix B

Performance Features for Procurement Specifications

The following are performance features recommended for use in development of procurement specifications for open architecture ESS sensor components. These systems have been vetted against the results of the UND RWFRF field trials, which identified required the availability of vendor provided interface specifications, performance specifications, and applicability to the recommend NDDOT ESS sensor package.

Recommended required ESS sensors should include: temperature/relative humidity, wind speed/direction, pavement temperature, sub-pavement temperature, precipitation, and a camera. The optional recommended ESS sensors should include: barometric pressure, pavement condition, chemical concentration, and radiation. With each sensor, both recommended required or optional, exists minimum operating specifications that must be met. Outlined below are these minimum operating specifications for each category along with the qualified vendor and corresponding sensor model.

The minimum requirements for a temperature/relative humidity sensor must include:

- Temperature Measurement Range of -30°C to +50°C,
- Relative Humidity Measurement Range of 0 to 100%,
- Temperature accuracy of ±0.3°C at 20°C,
- Relative humidity accuracy of ±2% over 0-90% RH, and ±3% over 90-100% RH,
- Operating Temperature Range of -30°C to +50°C,
- Support an open architecture for communications, and
- Must provide an interface specification document.

Minimum specifications that must be met for a wind sensor are:

- Wind speed range of 0 to 50 m/s,
- Wind direction range of 0 to 360 Degrees,
- Wind speed accuracy of ±0.135m/s or ±3% of reading,
- Wind direction accuracy of ±2°,
- Operating temperature range of -40°C to +50°C,
- Must have a heater associated with the sensor,
- Support and open architecture for communications, and
- Must provide an interface specification document.

Minimum specification requirements for a pavement temperature sensor are:

- Operating temperature range of -30°C to +70°C,
- Accuracy of temperature measurement: ±0.2°C (-10°C to +10°C), otherwise ±0.5°C,
- Support an open architecture for communications, and
- Must provide an interface specification document.

The minimum requirements for a sub-pavement temperature sensor are:

- Operating temperature range of -30°C to +70°C,
- Accuracy of temperature measurement: ±0.2°C (-10°C to +10°C), otherwise ±0.5°C,
- Support an open architecture for communications, and
- Must provide an interface specification document.

The minimum specifications for a precipitation sensor are:

- Operation temperature of -30°C to +70°C,
- Precipitation quantity/type repeatability > 90%,
- Precipitation type distinction: rain, snow, hail, freezing rain, sleet,
- Precipitation amount options: 0.1 mm, 0.01mm, 0.001mm,
- Precipitation intensity,
- Support an open architecture for communications, and
- Must provide an interface specification document.

The minimum specifications for a camera are:

- Operating temperature range of -30°C to +70°C,
- Pan/tilt/zoom capabilities,
- Support an open architecture for communications, and
- Must provide an interface specification document

Recommended Optional ESS Equipment

The following sensors have been determined to be desirable optional equipment to enhance and diversify the data available from ESS. They are not recommended in this project either due to their higher costs or limited benefit to the North Dakota Department of Transportation winter maintenance personnel. The addition of these sensors are encouraged where proper ESS siting deems the beneficial incorporation into a regional road weather forecasting design or to satisfy local winter maintenance needs.

The barometric pressure sensor minimum specification requirements are:

- Pressure measurement range of 500 to 1100 hPa,
- Accuracy of ±0.30 hPa @ 20°C,
- Operating temperature range of -40°C to +55°C,
- Support an open architecture for communications, and
- Must provide an interface specification document.

The minimum specifications for a pavement condition sensor are:

- An operating temperature range of -50°C to +85°C,
- Pavement condition (active and passive cycles): wet, dry, trace, chemical wet,
- Support an open architecture for communications, and
- Must provide an interface specifications document.

The minimum requirements for a sensor to provide chemical concentration are:

- Operating temperature range of -30°C to +70°C,
- Support an open architecture for communications, and

- Must provide an interface specification document.

The minimum requirements for a radiation sensor are:

- Operating temperature range of -40°C to +70°C,
- Provide downward welling shortwave and longwave radiation,
- Expected accuracy for daily totals of ±10%,
- Sensitivity range of 10 to 20 $\mu V\ W^{-1}\ m^{2}$,
- Support and open architecture for communications, and
- Must provide an interface specification document.

Appendix C

List of Qualified ESS Equipment Vendors Supporting an ESS Open Architecture

The following vendors have undergone a vetting process by the research team to identify their capability to satisfy the recommended performance specifications in Appendix B. Where only one qualified vendor is denoted this is due to either a specialized performance capability that only the identified vendor can attain or due to the lack of available performance data from other vendors to permit the vetting process for that vendor. Where the singular qualified vendors are found, a notation is made to specific with of the two situations above are applicable. While there are other vendors who manufacture comparable sensors to those listed below, only the sensors listed met the requirements of supporting an open architecture ESS framework.

Qualified vendors that meet the minimum specifications for temperature/relative humidity sensors are:

- Campbell Scientific HMP45C Temperature/Relative Humidity
- RM Young Model 41382 Relative Humidity/Temperature Probe
- Vaisala HMP155
- Vaisala QMH101/102 (based on HMP45D probes, HMP45A/HMP45D probes only available until June 30th 2010).

Qualified vendors for a wind sensor are:

- RM Young Ultrasonic Anemometer (Heated) Model 85004
- VaisalaWINDCAP Ultrasonic Wind Sensor Model WS425 (heated)
- Vaisala WINDCAP Ultrasonic Wind Sensor Model WS425 F/G
- Met One Instruments (Heated) Model 50.5H.

Qualified vendors for pavement sensors are:

- Zydax Active Passive Surface Sensor
- Zydax Temperature Sensor
- Lufft IRS31 Intelligent Road Sensor Model 8510.U052

Qualified vendors for sub-pavement temperature sensor are:

- Zydax Drop Down Temperature Sensor
- Zydax Temperature Sensor
- Lufft IRS31 Intelligent Road Sensor Model 8510.U052.

The only qualified vendor for a precipitation sensor is the Lufft R2S Radar Precipitation Sensor. A comparison with various winter time precipitation systems including the Yankee TPS-3100 Hotplate Total Precipitation Sensor and the Geonor Vibrating Wire Rain Gauge

was conducted at the UND RWFRF. Only the Lufft R2S achieved a reliable result that warranted a vendor qualification.

The qualifying vendors for a camera that meets the above specifications are:

- Visual Zoom Axis Model 233D

  [NOTE: No other pan-tilt-zoom cameras were able to be successfully evaluated during the project]

Qualified barometric pressure sensor vendors are as follows:

- Campbell Scientific CS100 Setra Model 278
- Campbell Scientific CS106 Vaisala PTB110
- RM Young Barometric Pressure Sensor Model 61202V/61202L (with recommended Pressure Port Model 61002)
- Vaisala BAROCAP PTB110
- Vaisala BAROCAP PTB210
- Vaisala BAROCAP Digital Barometer PTB330
- Met One Instruments Barometric Pressure Sensor Model 092

Qualified pavement condition vendors are as follows:

- Zydax ZAPSS Active Passive Surface Sensor.
- Lufft IRS31 Intelligent Road Sensor

[NOTE: The Lufft IRS31 does not yet provide pavement condition codes, which presents a limitation in its implementation. However, there is sufficient data from the sensor to permit the inference as to pavement condition and thus it is included on this list of qualified vendors]

The qualifying vendors and associated sensors for radiation are:

- Campbell Scientific CNR1 Net Radiometer
- Campbell Scientific CNR2 Long and Short Wave Net Radiometer
- Kipp and Zonen CNR1 Net Radiometer
- Kipp and Zonen CNR2 Long and Short Wave Net Radiometer