FINAL REPORT

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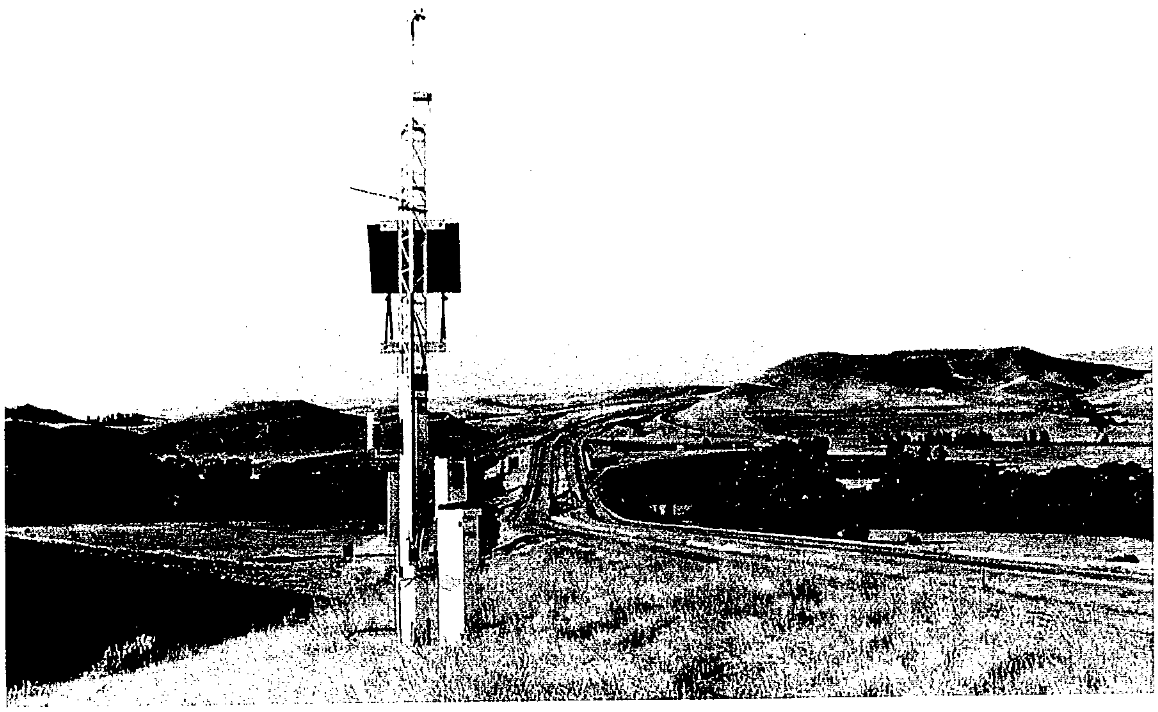

Improving the Wyoming Road Weather Information System

By:

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Supplementary Notes

WYDOT Technical Contact: Ken Shultz, P.E., Maintenance Staff Engineer

Abstract

A two-year study of the Wyoming Road Weather Information System (RWIS) indicated that the system will facilitate and improve maintenance operations and enhance the safety and convenience of highway travel if certain critical improvements are made. Without these improvements, benefits will be marginal and continued operation may not be cost effective. Areas identified for improvement include:

1) upgrading the radio communications system;
2) integrating the two systems presently in use (SSI and Vaisala);
3) upgrading software to improve data displays and simplify use;
4) adding supplementary weather information such as Nexrad radar, satellite images, and weather maps;
5) making RWIS data and weather information directly available in every maintenance shop, preferably via satellite communications such as that available from DTN;
6) installing additional roadside weather stations;
7) improving site selection procedures;
8) and provide additional training.

Other recommendations included improving forecasting services, conducting research to determine visibility sensors suitable for blowing snow conditions, archiving data, and assigning personnel dedicated to managing and maintaining the RWIS system.

Key Words Road Weather Information Service, RWIS, SSI, Vaisala, DTN, weather station, Satellite communication, climatological data, WYDOT, Wyoming		Distribution Statement Unlimited	
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SI* (Modern Metric) Conversion Factors

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	Millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
Area				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
Volume				
ml	Milliliters	0.034	fluid ounces	fl oz
l	Liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
Mass				
g	Grams	0.035	ounces	oz
kg	Kilograms	2.202	pounds	lb
Mg	Megagrams	1.103	short tons (2000 lbs)	T
Temperature (exact)				
°C	Centigrade Temperature	1.8 C + 32	Fahrenheit temperature	°F
Illumination				
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	pound-force per square inch	psi

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
In	Inches	25.4	millimeters	mm
Ft	Feet	0.305	meters	m
Yd	Yards	0.914	meters	m
Mi	Miles	1.61	kilometers	km
Area				
In^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
Yd^2	square yards	0.836	square meters	m^2
Ac	Acres	0.405	hectares	ha
Mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	ml
Gal	Gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
Yd^3	cubic yards	0.765	cubic meters	m^3
Mass				
Oz	Ounces	28.35	grams	g
Lb	Pounds	0.454	kilograms	kg
T	short tons (2000 lbs)	0.907	megagrams	Mg
Temperature (exact)				
°F	Fahrenheit Temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
Illumination				
Fc	foot-candles	10.76	lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
Lbf	pound-force	4.45	newtons	N
Psi	pound-force per square inch	6.89	kilopascals	kPa

FIGURES

TABLES

ABBREVIATIONS AND SYMBOLS

A	Coefficient of proportionality between motorist visual range and 10-meter wind speed
AC	Alternating current
ASOS	Automated Surface Observation System for weather stations
AWOS	Automated Weather Observation System
CPU	Central Processing Unit
DOS	Disk Operating System
DOT	Department of Transportation, as in Iowa DOT
DTN	Data Transmission Network, Inc.(Omaha, Nebraska)
e	Base of natural logarithms (2.71828...)
ESS	Environmental Sensor Station protocol
ETI	ETI Instrument Systems, Inc. (Fort Collins, Colorado)
I	Precipitation intensity (cm/h)
ITS	Intelligent Transportation Systems
K	Variable coefficient relating low frequency scintillation intensity to precipitation intensity
L	Low frequency scintillation intensity
Lat	Latitude (degrees north)
LEDWI	Light Emitting Diode Weather Identifier (Manufactured by ScTI)
Lon	Longitude (degrees west)
MDT	Montana Department of Transportation
MHz	Megahertz
NCAR	National Center for Atmospheric Research
NTCIP	National Transportation Communications for Intelligent Transportation Systems Protocol
NWS	National Weather Service
OPD	Optical Precipitation Detector
OWI	Optical Weather Identifier (manufactured by ScTI)
RFP	Request for Proposal(s)
RPU	Remote (or roadside) Processing Unit
RWIS	Road Weather Information System
SCAN	Trade name for RWIS system marketed by SSI Inc. (St. Louis, Missouri)
ScTI	Scientific Technology Inc. (Gaithersburg, Maryland)
SSI	Surface Systems Incorporated (St. Louis, Missouri)
U_z	Wind speed at height z above ground
U_{10}	Wind speed at 10 meters above ground
V	Observer's visual range (meters)
WIVIS	Weather Identifier and Visibility Sensor (manufactured by ScTI)
WYDOT	Wyoming Department of Transportation
x	Time since first measurement (s)
Y2K	Year 2000 (reference to potential computer problem in Year 2000)

FOREWARD

This report addresses findings from a study on various aspects of the Wyoming Department of Transportation's Roadway Weather Information System (RWIS). The issues that were investigated included site selection, training, system integration and ease of use.

RWIS users within WYDOT were polled by questionnaire and then interviewed for further clarification. The information received during this process then focused the research toward issues of the greatest impact.

All of WYDOT's RWIS Remote Processing Unit (RPU) sites were analyzed extensively for suitability according to accepted criteria for the various instruments used for data measurements. RWIS users were asked to rate the usefulness of the many pieces of information provided by each site they use regularly and to give an overall rating to the management value and the accuracy information provided by that site. They were also asked to provide an idea of what additional information, if any, might help them to make operational decisions that might improve the efficiency of their crews' operations.

Previous training efforts were reviewed and compared with those efforts where RWIS has gained more acceptance. The format the data is presented in was also evaluated, as was the difficulty of obtaining the data that the separate systems provide. Advances in technology will help to address the deficiencies identified in these subject areas.

This report should be of interest to transportation personnel concerned with RWIS deployment and operation, especially those faced with the same difficulties Wyoming faces as an extremely rural state.

Kenneth L. Shultz, P.E.
Maintenance Staff Engineer
Wyoming Department of Transportation

EXECUTIVE SUMMARY

Studies in other states and countries have shown that Road Weather Information Systems (RWIS) can improve the efficiency of snow and ice control operations and reduce accidents. Potential uses include:

- Indicate when snow and ice control operations are required, such as plowing, sanding, and anti-icing applications
- Supplement other sources of information for tracking storms or other weather conditions affecting year-round maintenance and traffic operations
- Indicate need for traffic advisories, warnings, or restrictions
- Allow automatic sign operation
- Provide site-specific weather and surface temperature forecasts incorporating present on-site weather information to facilitate crew scheduling and assignments
- Allow automatic operation of permanently installed anti-icing chemical spray systems on bridges and at other critical locations
- Provide climatological data base for designing mitigation measures for blowing snow
- Provide current road and travel information to the public

Wyoming's use of RWIS differs from most other states in the snow-belt because of the frequent winds and blowing snow, relatively low traffic volumes, and the long sections of highways in sparsely populated areas. Other states rely on road surface information from RWIS stations for applying anti-icing chemicals. Although blowing snow will limit this technology in Wyoming, RWIS data and forecasts for pavement temperatures, wind and other weather conditions, will be essential if this practice is to be used successfully in Wyoming.

The RWIS network in Wyoming is presently comprised of 27 roadside weather stations (referred to as remote processing units or RPUs), and a stand-alone site on Teton Pass originally intended for avalanche forecasting. RWIS systems in adjacent states presently consist of 59 weather stations in Montana, 36 in South Dakota, 13 in Nebraska, 64 in Colorado, 8 in Utah, and 15 in Idaho. Coordination and integration of data with these other states is potentially synergistic and could enhance the value of the Wyoming system.

The large capital investment in this system (approximately $50,000 per site), the sizable operational cost ($215,900 budgeted for FY 1998), and the potential benefits to WYDOT maintenance and the public, are compelling reasons to insure that the system is functioning efficiently and utilized to its full advantage, and it was for this purpose that this study was commissioned. The objectives of this study were to review the Wyoming RWIS system, recommend changes and improvements, develop an outline for a training program, and develop guidelines for future weather station site selection. A major preliminary objective was to identify areas for improvement by conducting a statewide survey of Wyoming Department of Transportation (WYDOT) personnel using RWIS. For this purpose, a written questionnaire was sent out to all maintenance supervisors, dispatchers, and selected managers and administrators, followed up with personal and group interviews to clarify and supplement the written responses. Telecommunications technicians were also interviewed to identify their concerns and needs regarding maintenance and operation of the system.

A separate step was to inspect all existing RPUs to evaluate instrumentation and siting, as well as some of the locations requested as candidates for future RWIS sites. This field inspection identified what stations should be relocated, instrumentation deficiencies, and provided background for site selection criteria for future sites. Alternative sensors for road surface condition, visibility, and precipitation were reviewed to determine if there were advantages or disadvantages to various instruments based on their principles of operation, signal processing, and specifications. Detailed discussions were held with instrument vendors to supplement technical literature, as well as with scientists evaluating instrumentation at the National Center for Atmospheric Research (NCAR), National Weather Service (NWS), and other organizations. Results from published studies were also reviewed. Software presently in use was evaluated, and next-generation software was examined to determine apparent advantages and disadvantages. Key personnel involved with RWIS systems in Colorado, Iowa, Minnesota, Montana, Nebraska, Nevada, and South Dakota were interviewed to determine their experience and plans. Copies of recent Requests for Proposals (RFPs) for RWIS upgrades were obtained from Minnesota and Nevada. Finally, experience with third-party weather information providers was obtained by subscribing to a satellite-delivery weather service offered by DTN (Data Transmission Network Corporation), including a subscription to Iowa's DTN pages displaying current RWIS data.

The questionnaire used as a starting point for this study (Appendix A) was mailed to 88 individuals in January, 1997. Sixty nine, or 78%, were completed and returned. The answers to the following two questions indicate that although RWIS in its present condition is considered marginally useful, the utility of the system would be greatly enhanced if problems and deficiencies were corrected. This response justifies the study undertaken here, and provides a compelling reason to implement changes:

How useful is RWIS in doing your job?

21%	Very
78%	Somewhat
1%	Not at all

How useful *could* RWIS be to you if problems or deficiencies were corrected?

62%	Very
36%	Somewhat
1%	Not at all

Perhaps the most important conclusion from this study is that the system will facilitate and improve maintenance operations and enhance the safety and convenience of highway travel *if certain critical improvements are made*. Without these improvements, benefits will be marginal and continued operation cannot be expected to be cost effective. The need for upgrading the system was also identified by an earlier study (French and Wilson 1993).

Highest priority should be given to two recommendations:

1. Upgrade communications system for better reliability and faster data transfer rates.

2. Integrate the SSI and Vaisala systems, which are currently incompatible. This will require upgrading hardware and software, which should be Year 2000-compliant, and replacing the current DOS-based software with a Windows-based version allowing improved graphic displays to make RPU data and forecasts easier to read and interpret. Graphs showing how selected weather and pavement conditions have changed with time over the last 8 hours or so, and statewide (or regional) maps displaying current weather conditions, would facilitate cognition of trends important for crew and equipment scheduling and dispatching.

The first recommendation is basic, because the communications system should be specified in the Request for Proposals (RFP) for upgrading RWIS. Upgrading the WYDOT communications system would require converting the statewide microwave system, and the 450 MHz radio links to the RWIS sites, from analog to digital—an improvement having benefits reaching far beyond the RWIS system. The second item can be addressed as part of an RFP for upgrading the system, specifying forward and backward compatibility with NTCIP-ESS protocol. Other recommendations, in *approximate* order of decreasing priority, include:

3. WYDOT should actively participate in the annual "Multistate RWIS Users Workshop," attended by Kenneth Shultz, Maintenance Staff Engineer, in 1998. This is an excellent forum for exchanging information, sharing experience, and keeping abreast of the rapidly changing RWIS technology.

4. Make available supplementary weather information (Nexrad radar, satellite images, weather maps, etc.) as part of the RWIS system (include in RFP).

5. Make RWIS and other weather information *directly available* in every maintenance shop. Making this information available through dispatchers is not an acceptable substitute. It is recommended that DTN be evaluated as a medium for RWIS information by installing units in at least 10 shops for a trial evaluation over two years, and arranging for transmission of RPU data updated at 30-minute intervals—a provision that should be included in the RWIS RFP. Advantages include full-time data display, availability of detailed weather information, simple operation, ready acceptance by personnel unfamiliar with computers, independence from telephone and network communications, minimal maintenance requirements, and relatively modest capital investment.

6. Coordinate and integrate RWIS data from adjacent states (include in RFP).

7. Allow for third-party weather forecasting services in RFP.

8. Improve preventive maintenance provided by vendors and WYDOT telecommunications personnel. Several pavement sensors require repairs to encapsulation or surrounding cracks.

9. Take action to prevent damage to surface sensors during pavement maintenance operations—paint locations and make contractor or supervisor pay for damaged units.

10. Move existing WIVIS weather identifier/visibility instrument back to Vedauwoo where it can be used to better advantage.

11. Discontinue use of the Wyoming/South Dakota shared site. It is surrounded by trees, wind instrumentation is too close to the ground, and overall conditions are unrepresentative of conditions on the Wyoming side. It should be replaced with an RPU near Four Corners.

12. Relocate selected RPUs, in following order of priority: Dead Horse, Cemetery Separation, Belle Fourche, Vedauwoo, Arlington, Sage (nearby), Pumpkin Vine, Gun Barrel (nearby), (Sibley Peak?) after due deliberation and concurrence of maintenance foremen.

13. Install precipitation gauges at RPU sites to quantify snowfall rate until optical methods are improved and validated. Considering the importance of quantitative information on snowfall rate and accumulation, it is ironic that this information is unavailable at over 90% of the RWIS sites in Wyoming, and estimates from the two sites that do have instruments (Skyline and Pumpkin Vine) are unreliable because of the limitations of the instrumentation.

14. Conduct formal study of visibility sensors to determine instruments best suited to measuring visibility in blowing snow, and changes required in signal processing. Studies should involve instrument manufacturers and the National Center for Atmospheric Research.

15. Install visibility sensors at the following RPUs after determining suitable instrumentation: Vedauwoo, Continental Divide (remote from RPU), Bitter Creek (remote from RPU), Cemetery Separation (only if relocated), Sage (if relocated), Shute Creek, Rim, Beaver Rim, I-25 Divide, Dead Horse, Inyan Kara, Belle Fourche (if relocated), Hiland (remote from RPU if RPU not moved), Pathfinder, Deer Creek, Bordeaux, Arlington, Gun Barrel (remote from RPU if not moved).

16. Improve RWIS training using a "train-the-trainer" approach.

17. Train personnel in using and improving forecast services.

18. Install additional RPUs using the guidelines in this report. The sixteen most useful candidate locations identified in this study include:

    - Mule Creek Junction (US 85 near Mile 196)
    - Pine Tree Junction (WY 387 Mile 127.86)
    - Four Corners (near Mile 247 on US 85)
    - Togwotee Pass (near Mile 26, US 287)
    - South Pass (WY 28, Mile 36.4 or 37.6)
    - Church Buttes (I-80 near Mile 54)
    - Elk Mountain area (I-80 Mile 255)
    - Montana State Line (I-90 Mile 109.9)
    - North of Lusk (US 85 Mile 160)
    - North of Gillette (WY 59 Mile 150 or 170)
    - North of Cody (WY 120 Mile 109.9)

- US 14/16 between east of Sheridan (Between Mile 52 and 76)
- Shirley Basin (WY 487 between Mile 18 and 29)
- South of Jay Em (US 85 Mile 124 vicinity)
- North of Baggs (WY 789 Mile 10 vicinity)
- North of Fort Washakie (US 287 Mile 30 vicinity)

19. Use more care in selecting locations for atmospheric and pavement sensors to assure data are representative of problem areas, paying particular attention to the possible effects of local terrain, structures, *snow fences*, and vegetation conditions. The following guidelines should be followed in establishing future RPUs:

    - Exposed location where wind and blowing snow are not affected by trees, hills, buildings, or snow fences
    - Tower base at elevation approximately equal to or greater than that of road
    - Tower 15 m or more from edge of pavement
    - Upwind side of road preferable, essential at deep cut sections
    - 600-m or more open fetch upwind, and preferably in all directions
    - AC power preferable

20. Assign dedicated personnel to the RWIS system, to include one person with over-all responsibility for the system, and one or more telecommunications technicians with specialized training in RWIS instrumentation including principles of operation, installation specifications, and maintenance requirements. All RWIS personnel should be trained in the rudiments of blowing snow and boundary layer meteorology, and site selection.

21. Purchase vehicle-mounted infrared temperature sensors to check pavement sensor performance, aid in the selection of future RPU and pavement sensor sites, supplement *in situ* data from RPUs during storms as needed, and provide in-house road thermal mapping capability.

22. Discontinue using optical precipitation detectors near the ground that were originally intended to detect blowing snow.

23. Solicit data archival services in the RFP or use in-house archiving system. Historical weather data are valuable for designing mitigation measures for blowing snow, documenting RPU performance for maintenance and communications, providing experience-based maintenance training, evaluating forecasting services, and developing weather prediction models.

24. Consider basing payment for forecasting services on performance.

25. Upgrade "E" type SSI pavement sensors with newer FP2000 model, whenever replacement is required (if SSI equipment continues to be used).

26. Maintain better permanent records (logs) for each RPU, documenting commissioning date(s); atmospheric and pavement sensor models, serial numbers, heights, and locations; dates preventive maintenance and other service was performed; and dates instruments and electronic components were installed, replaced, and calibrated.

27. Improve marking of pavement sensor locations with posts and reflectors to facilitate finding them for inspection and service, and to allow plow operators and other personnel to compare actual surface conditions at the sensors with status reported by sensor.

28. Sign buried cable locations better to reduce the possibility of damage.

29. Place pavement sensors no further from the RPU than necessary to reach the section of road for which an indication is desired. Most of the existing sensors are much farther away than necessary, increasing installation cost and the susceptibility to cable damage.

30. Install sensors to monitor vehicle count and speed at selected sites as another method of evaluating visibility and surface conditions.

31. Test the utility of slow-scan or freeze-frame video cameras by installing one at the Vedauwoo RPU (after relocation). Although video will be a valuable addition to RPUs in the future, it will not replace the need for quantitative data from other sensors. The primary advantage is believed to be for supplementing Road and Travel information on the Internet.

32. Support study proposals comparing reliability of alternative surface sensors, and the development of new sensors sampling conditions over an area larger than the 20- to 125 cm^2 represented by conventional passive sensors. The University of Wyoming is testing a microwave instrument that has a potential for sensing surface conditions over an area on the order of 1 m^2, and WYDOT may wish to consider participating in this research effort.

33. Evaluate benefits of continuing forecasts and full system operation through summer months.

34. Make evaluation of Wyoming's RWIS a continuing process and include this subject as a routine agenda item for annual state maintenance meetings.

1. INTRODUCTION

1.1. DEFINITION AND USES OF ROAD WEATHER INFORMATION SYSTEMS

Road Weather Information Systems (RWIS) typically consist of: 1) roadside weather stations equipped with sensors for determining road surface and atmospheric conditions, and a remote processing unit (RPU) for sampling, processing, storing, and formatting weather sensor output for transmission via radio or land-line; 2) a communications system over which the data are transmitted; 3) one or more Central Processing Units (CPU) which retrieve, process, disseminate and store data from multiple RPUs; 4) an on-line computer with specialized software for providing continuous access to the CPU, historical data, and forecast information; 5) forecast services utilizing the roadside weather data and National Weather Service information to make site-specific forecasts for the RPU locations; and 6) a communications system for relaying road and weather information to the traveling public.

The potential uses and benefits of RWIS have been documented in numerous publications (Boselly, Doore, an Ernst 1993; Boselly, Doore, Thornes and Ulberg 1993; Castle Rock Consultants 1995; Doore 1989; Matsuzawa, Kajiya, Ishimoto and Takeuchi 1997). Applications relevant to maintenance and traffic operations in Wyoming include:

- Indicate when specific maintenance operations are required, such as plowing, sanding, and anti-icing applications
- Supplement other sources of information for tracking storms or other weather conditions affecting year-round maintenance and traffic operations
- Indicate need for traffic advisories, warnings, or restrictions
- Allow automatic sign operation
- Provide site-specific weather and surface temperature forecasts incorporating present on-site weather information
- Allow automatic operation of permanently installed anti-icing chemical spray systems on bridges, etc.
- Provide current road and travel information to the public
- Provide climatological data base for designing mitigation measures for blowing snow

Theoretically, the real-time information on road and weather conditions, coupled with improved forecasts, should result in more efficient scheduling and dispatching of maintenance crews, thereby reducing expenditures for fuel, personnel, and chemicals. Whether or not these benefits can actually be realized depends primarily on how well the system is used, and how well it functions. The benefits to public safety and convenience are even more difficult to quantify, but if the RWIS data were used to make only one or two decisions each year that prevented a serious crash, the annual cost for maintaining the system could be justified. A study in Finland showed that the savings in maintenance costs and accidents attributable to RWIS resulted in a cost/benefit ratio of about 1:5 (Pilli-Sihvola, Toivonen, and Kantonen 1993).

1.2. THE WYOMING ROAD WEATHER INFORMATION SYSTEM

The Wyoming Department of Transportation (WYDOT) pioneered road weather monitoring with the installation of roadside weather stations near Arlington in 1974, and Elk Mountain in 1975 (Tabler 1979; Tabler 1984). Analog wind and visual range data from both of these stations were transmitted by a radio/microwave/land-line system to the WYDOT dispatcher's office in Laramie, where data were recorded on strip charts. An on-line computer was added for the 1977-78 winter to allow real-time analysis of the data, with printed summaries, advisories, and recommendations for traffic operations based on standardized criteria. Overhead variable-message signs, installed at Laramie and Walcott in 1976, were controlled by that computer starting with the 1978-79 winter.

Road Weather Information Systems have been gaining in popularity since experimentation began as part of the Strategic Highway Research Program initiated under the Surface Transportation and Uniform Relocation Act of 1987. Implementation of these research results has led to RWIS systems being installed in over forty states. The installation of the present RWIS system in Wyoming started in 1988 utilizing "SCAN" equipment and software marketed by Surface Systems Incorporated (SSI), and by 1992 the system consisted of 19 sites. Two additional SSI sites were installed in 1994 with funding from Highway Safety Funds. Six more sites were added in 1995-96, equipped with Vaisala Inc., "IceCast" systems. The Vaisala and SSI systems use different processing units, communications protocol, and software, and are operated separately because vendor-imposed restrictions in the past would not allow interfacing. In addition to the 27 sites making up the Wyoming RWIS network, there is one stand-alone station on Teton Pass originally intended for avalanche monitoring and control. Locations are shown in Figure 1.1 and Table 1.1.

There are 6 CPUs serving the SSI system, including a master in Cheyenne, and one CPU serving the Vaisala system at the Rock Springs district office. All RPUs are linked to the statewide microwave communications system via 450 MHz analog radios. The National Weather Service in Cheyenne has access to data from both systems, with a full-time connection to the SSI CPU in Cheyenne, and dial-up access to the Vaisala data. The University of Wyoming also has full-time access to the SSI through the CPU in Laramie.

Weather station instrumentation consists of sensors to measure wind speed and direction at a height of 6- to 10 meters, air temperature and relative humidity at approximately 2.5-m height, pavement surface temperature and condition (e.g., dry, wet, ice), and subsurface temperature.

Table 1.1. Locations of RWIS RPUs in Wyoming.

RPU #	Site Name	RPU abbrev.	Sensor number	District (X)=near	Route	Milepost	Distance from nearest town	Year commi-sioned	Latitude	Longitude	Elevation
									-deg N-	-deg W-	-m-
SSI SCAN STATIONS											
1	ARLINGTON	ALN	1 - 4	1	I-80	271.88	W. of Arlington exit	1991	41.598	106.213	2388
2	CONTINENTAL DIVIDE	CDV	5 - 7	3 (1)	I-80	184.19	30 miles west of Rawlins	1991	41.715	107.784	2144
3	BITTERCREEK	BRC	8 - 10	3	I-80	141.83	12 miles east of Point of Rocks	1991	41.646	108.583	2157
4	BEAVER RIM	BVR	11 - 13	5 (2)	US 287	48.28	25 miles west of Jeffrey City	1991	42.587	108.287	2029
5	MEETEETSE RIM	MET	14 - 16	5	WY 120	61.53	10 miles north of Meeteetse	1991	44.271	108.873	1773
6	HILAND	HIL	17 - 19	5 (2)	US 20/26	57.42	45 miles west of Casper	1991	43.092	107.321	1854
7	PATHFINDER HILL	PAT	20 - 22	2	WY 220	79.93	7 miles west of Alcova	1991	42.560	106.853	1916
8	TWENTY MILE HILL	20M	23 - 25	2	I-25	207.18	20 miles north of Casper	1991	43.123	103.337	1720
9	I-25 DIVIDE	I25	26 - 28	2 (4)	I-25	267.32	13 miles north of Kaycee	1991	43.941	106.646	1521
10	PINEY CREEK	PCR	29 - 32	4	I-90	43.66	14 miles north of Buffalo	1991	44.534	106.817	1401
11	DEAD HORSE	DHS	33 - 35	4	I-90	91.53	33 miles west of Gillette	1991	44.219	106.104	1223
12	INYAN KARA	INY	36 - 38	4	I-90	170.51	17 miles west of Sundance	1991	44.293	104.630	1313
13	BELLE FOURCHE	BFO	39 - 41	4	WY 59	86.99	26 miles south of Gillette	1991	43.933	105.446	1361
14	PUMPKIN VINE	PKV	42 - 44	1	US 287	420.36	20 miles south of Laramie	1991	41.053	103.469	2438
15	VEDAUWOO	VDW	45 - 47	1	I-80	329.37	32 miles west of Cheyenne	1991	41.157	105.403	2543
16	WHITAKER	WHT	48 - 51	1 (2)	I-25	28.12	18 miles north of Cheyenne	1991	41.419	104.874	1888
17	SIBLEY PEAK	SIB	52 - 54	2	I-25	107.62	4 miles south of Glendo	1991	42.449	105.036	1490
18	FIRST DIVIDE	EVN	55 - 57	3	I-80	13.88	9 miles east of Evanston	1988	41.296	110.773	2235
19	CEMETERY SEPARATION	GRV	58 - 61	3	I-80	90.65	At Green River	1988	41.533	109.462	1948
20	DEER CREEK	DCK	62 - 64	2	I-25	164.25	Near Glenrock exit	1994	42.836	105.844	1551
21	BORDEAUX	BCX	65 - 67	2	I-25	70.86	8 miles south of Wheatland	1994	41.930	104.945	1585
7 (SD)	S. DAK. SHARED SITE	WY/SD			US 85	2.40	2.4 miles from Wyoming line	?	44.199	104.037	1984
VAISALA STATIONS											
1	SAGE JUNCTION	SAG		3	US 30	34.21	20 miles west of Kemmerer	1995	41.840	110.940	2371
2	RIM	RIM		3	US 191	127.00	16 miles south of Bondurant	1995	43.105	110.322	2310
3	SKYLINE	SKL		1	WY 230	113.46	13.5 miles south of Encampment	1995	41.132	106.567	2469
4	GUN BARREL	GBR		1	US 85	46.80	36 miles northeast of Cheyenne	1995	41.439	104.349	1707
5	CHIEF JOSEPH	CHJ		5	WY 296	32.66	31 miles northwest of Cody	1995	44.755	109.374	2530
6	SHUTE CREEK	SCR		3	WY 372	34.00	6 miles southeast of Fontenelle	1995	41.931	109.969	1999

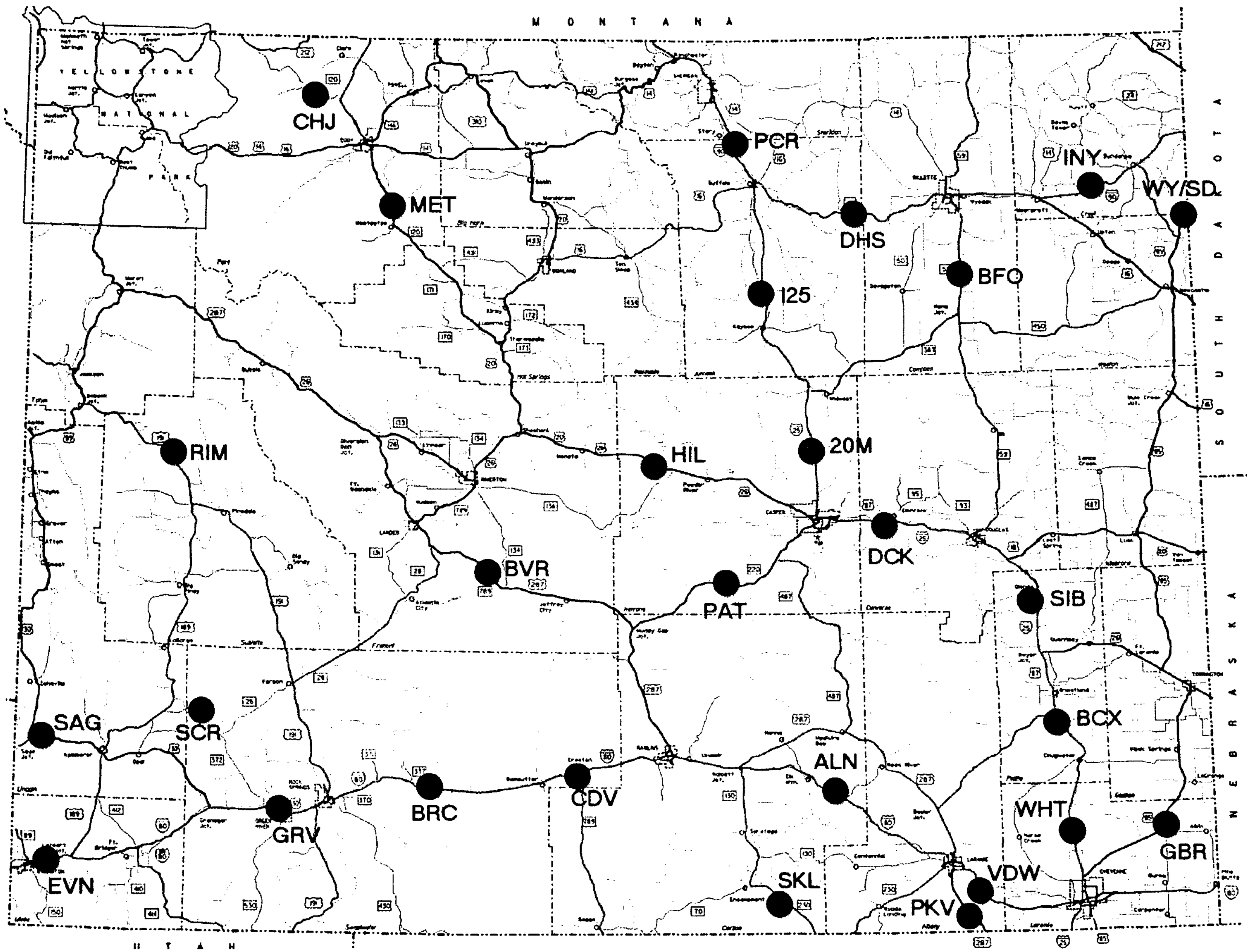

Figure 1.1. Locations of RWIS RPUs in Wyoming as of 1998

Most SSI systems are also equipped with one or more "optical precipitation detectors" (OPD) to detect the presence of precipitation, and some stations have a second OPD installed at 0.75 to 1.0 m above the ground to detect blowing snow. Vaisala systems are equipped with a capacitance-based precipitation detector (DRD11A). One SSI station (Pumpkin Vine) and one Vaisala station (Skyline) are equipped with visibility sensors. Approximately 15 to 20 minutes are required to poll all RPUs.

Forecast services, which include predicted pavement temperatures calculated from proprietary algorithms, are available with both systems—Northwest WeatherNet Inc. provides forecasts for the Vaisala system in Wyoming, and SSI provides their own forecast service (SCAN*Cast). These forecast services have been utilized by all districts in the past, but were provided for only four districts over the 1997-98 winter.

The RWIS systems in adjacent states presently consist of 59 weather stations in Montana, 36 in S. Dakota (including 5 sites operated by cities and counties), 13 in Nebraska, 64 in Colorado, 8 in Utah, and 15 in Idaho. Coordination and integration with RWIS systems in adjacent states provides a potential synergistic effect further enhancing the value of the Wyoming system.

1.3. THE PROBLEM

There is presently some disagreement among highway personnel as to the reliability and utility of the data and forecasts provided by the system. Possible explanations for dissatisfaction with the current system include difficulty in accessing data and using vendor-provided software, hard-to-read display formats for data and forecast information, inadequate vendor support, malfunctioning instrumentation, poor siting of stations, problems arising from the incompatibility of the SSI and Vaisala systems, deficiencies in forecast services, and insufficient training in how the data and forecasts should be accessed, interpreted and utilized. A study of the Wyoming RWIS system through 1991 (French and Wilson 1993) concluded that the system needed to be upgraded to improve reliability, with a need for additional weather sites, vehicle speed monitoring, and visibility sensors.

The large capital investment in this system ($50,000 per site), the sizable operational cost ($215,000 in FY 1997 and $215,900 budgeted for FY 1998), and the potential benefits to WYDOT maintenance and the public, are compelling reasons to insure that the system is functioning properly and utilized to its full advantage. It can be argued that RWIS is a basic and essential component of an "Intelligent Transportation System" (ITS) in Wyoming and other northern states where winter maintenance is critical to the functioning of the highway system during six months or more of the year. If the present study had indicated that RWIS had little acceptance by users, however, it might have been prudent to "mothball" the system until some future time when better hardware and software became available.

Wyoming's use of RWIS is somewhat different than in other northern states because of the dominance of strong persistent winds and blowing snow, relatively low traffic volumes, and the long sections of highways in sparsely populated areas. Although other states are beginning to rely on road surface information from RWIS stations for applying anti-icing chemicals, there is less utilization of this technology in Wyoming because of the low traffic volumes and the limitations imposed by blowing snow. Anti-icing is being tested at several locations in Wyoming, however, and RWIS data on current and forecast pavement temperatures and weather conditions will be essential if the practice is to be used successfully under the weather conditions typical of the state.

Studies and surveys of RWIS systems have been done in many countries and states. Although the results from these are useful, Wyoming's weather, maintenance needs, and RWIS system are sufficiently different to warrant an independent and objective study to help identify how the Wyoming RWIS can best be improved.

1.4. Objectives and Scope

The study objectives were to determine the strengths and deficiencies of the present RWIS system, recommend changes and improvements, develop an outline for a training program, and develop guidelines for future weather station site selection. Although the scope of this study included all components of the RWIS system, the extent and complexity of the RWIS system made it necessary to focus on areas having the greatest need for improvement. A major preliminary objective was therefore to identify these specific areas from a statewide survey of all WYDOT personnel using the RWIS.

Dissemination of RWIS information to the public was not included as part of this study.

1.5. Procedures

The first step in the study was to survey all WYDOT users of RWIS information to determine if the system was worth maintaining, and if so, what areas most needed improvement. A written questionnaire was sent out to all maintenance supervisors, dispatchers, and selected managers and administrators, followed up with personal and group interviews to clarify and supplement the written responses. Telecommunications technicians were also interviewed to identify their concerns and needs regarding maintenance and operation of the system.

All existing RWIS roadside weather stations were inspected to evaluate instrumentation and siting, and where possible proposed alternate sites were also reviewed. This field inspection identified what stations should be relocated, instrumentation deficiencies, and provided background for site selection criteria for future sites.

Alternative sensors for road surface condition, visibility, and precipitation were reviewed to determine if there were advantages or disadvantages to various instruments based on their principals of operation, signal processing, and specifications. Detailed discussions were held with instrument vendors to supplement their technical literature, as well as with scientists evaluating instrumentation at the National Center for Atmospheric Research (NCAR) and the National Weather Service (NWS). Results from published studies such as Lewis and Bradley (1998); Bradley, Lewis and Haas (1993); Castle Rock Consultants (1995); Lewis (1993); Rasmusssen et al. (1998); Shannon, Kyte, and Lien Liang (1997); and others listed in the References (Section 5), were also reviewed.

Output format of current and next-generation software was examined to determine relative advantages and disadvantages.

Key personnel involved with RWIS systems in Colorado, Nebraska, Nevada, Minnesota, Montana, South Dakota, and Iowa were interviewed to determine what their experience and plans were. Copies of requests for proposals were obtained from Minnesota and Nevada. The principal investigator also attended the multi-state RWIS meeting in Omaha in 1997.

Finally, experience with third-party weather information providers was obtained by subscribing to DTN's weather center for 18 months, including a subscription to Iowa's DTN pages displaying current RWIS data. Five DTN units were leased by WYDOT for trials in district offices during a portion of the 1997-98 winter, although this test was not formally a part of this study.

2. SURVEY RESULTS AND INTERPRETATION

The questionnaire used as a starting point for this study was mailed to 88 individuals in January, 1997. Sixty nine, or 78%, were completed and returned, and responses are tabulated in Appendix A. The following discussion also includes reference to a survey conducted in Iowa in May, 1997, referred to as "the Iowa study" (Takle *et al.* 1997).

2.1. PERCEIVED VALUE OF RWIS

The answers to the following two questions indicate that although RWIS in its present condition is considered marginally useful, the utility of the system would be greatly enhanced if problems and deficiencies were corrected. This response would seem to justify the study undertaken here, and provides a compelling reason to implement changes.

How useful is RWIS in doing your job?

21%	Very
78%	Somewhat
1%	Not at all

How useful *could* RWIS be to you if problems or deficiencies were corrected?

62%	Very
36%	Somewhat
1%	Not at all

The need for upgrading the Wyoming system is reinforced by the previous study by French and Wilson (1993).

2.2. AREAS FOR IMPROVEMENT

Areas for improvement, in approximate order of decreasing importance, are listed below. Detailed discussion follows in subsequent sections.

- Make additional weather information available such as radar, satellite, maps (affirmed by 85%)
- Improve forecasts (affirmed by 67%)
- Install additional weather stations (affirmed by 63%; 29% were not sure)
- Move certain stations (affirmed by 14% with 55% uncertain, but in this case percentages are not meaningful because perceived need is a local issue)

- Improve graphic displays of output (affirmed by 58%)
- Add visibility sensor at some sites (44% very useful; 25% somewhat useful)
- Provide more training (affirmed by 53%; 17% uncertain)
- Add instrumentation to quantify snowfall (precipitation) (this was the most frequent of "other suggestions")
- Improve reliability of visibility instrumentation (only two sites are equipped with visibility sensors, however, so no significant statistics are available)
- Improve reliability of pavement sensors (42% report indicated conditions are "usually representative"

2.3. ADDITIONAL WEATHER INFORMATION

There was a consensus that the utility of RWIS would be enhanced with the addition of supplementary weather information. Specific items requested were current radar and satellite images, detailed synoptic weather maps showing isobars and location of fronts, and maps showing regional temperatures, winds, and precipitation. Long-range (5-day) forecasts and forecasts continued through the summer were other suggestions. Although this information is generally available on the Internet and the weather channel, these sources are not available to all personnel, and the access is often inconvenient. Maintenance personnel often cannot afford the time it takes to access and review Internet sources, and obtaining regional information on the Weather Channel can also be a time-consuming process. The demand for supplementary weather information was confirmed in the Iowa study, which indicated that information on weather radar, weather satellite, and forecasts on TV and radio was considered to be more useful information than current RWIS data or SSI forecasts.

At least one of the RWIS equipment vendors (SSI) now offers supplementary weather information for a monthly fee, and satellite delivery of weather information is available from several sources.

2.4. IMPROVE FORECASTS

Forecast services historically have been limited to those offered by equipment vendors because of the specialized and proprietary algorithms used to forecast surface temperatures. Forecasts for the Vaisala system in Wyoming have been provided by Northwest WeatherNet, Inc. in Seattle, Washington. Forecasts for the SSI system are provided by SSI from their offices in St. Louis, Missouri. Northwest WeatherNet provides forecasts derived independently from National Weather Service zone forecasts, but SSI customizes National Weather Service forecasts for RPU/CPU locations in Wyoming. Both forecast services emphasize the importance of feedback from clients to help fine-tune and improve site-specific forecasts; however, some maintenance personnel have become discouraged in their attempts to communicate with forecasters when they fail to see any improvement in vendor forecasts resulting from user input. Comments received from both weather service providers indicate that WYDOT personnel are "very quiet" compared to other clients, implying that forecasters are not receiving adequate feedback.

The most common complaints included 1) failure to update forecasts in a timely manner, 2) under-estimating wind speeds, 3) inaccurate precipitation forecasts, 4) apparent repetition of National Weather Service zone forecasts.

Because of the relatively few Vaisala systems in Wyoming compared to SSI systems, a quantitative objective comparison of forecast services is not possible. However, it is worth noting that the service provided by Northwest WeatherNet Inc., is highly regarded by the WYDOT personnel interviewed in this study. This acclaim is shared by the Nevada DOT, which uses this service exclusively as a third-party forecast service. In addition to developing independent forecasts, Northwest WeatherNet seeks to maintain close contact with maintenance users, video-tapes roads to familiarize forecasters with local conditions, updates forecasts as changing conditions warrant (rather than at only pre-determined times), faxes copies of updates as well as providing on-line changes, and provides more detailed and customized text forecasts. A majority of WYDOT personnel reported favorably on the responsiveness and courteous treatment received from SSI forecast personnel.

The relative accuracy of pavement temperature forecasts could not be evaluated directly in this study, but some evidence does allow comparison of the two forecast models. Temperature forecasts using the IceBreak forecast model developed by Shao (1990), and used operationally for forecasts by Vaisala, have been convincingly verified in the article by Shao, Thornes, and Lister (1993): "The IceBreak model has a near-zero bias and about 1°C standard deviation in overall and minimum temperature predictions."

Although published verification of the SCAN*Cast forecast model is unknown to the author, results from an unpublished study at three sites in Iowa found that, for the period December 1, 1996 through March 31, 1997, the error in 3-hour surface temperatures averaged 1.4 °C and 1.6 °C for pavement and bridge deck temperatures, respectively. The percent of time the predicted pavement surface temperature was within 1°C of actual averaged 50.5%, and 44.4% for bridge deck forecasts, implying a somewhat lower accuracy than reported for the IceBreak model..

Accuracy of forecast surface temperatures also depends on the accuracy of forecasts for weather parameters used to calculate heat and moisture fluxes: air temperature, dew point temperature, cloud cover, cloud type, and wind speed. Although the accuracy of forecasts also depends on assumptions regarding the pavement and subgrade properties affecting heat transfer, Thornes and Shao (1991) report that the IceBreak forecast model is "not very sensitive to road thermal properties."

One factor affecting forecast surface temperature is the accuracy of the surface temperature sensor embedded in the road. Random tests by the author during the 1998 spring indicated that the temperature indicated by surface sensors (both SSI and Vaisala) were 1- to 2 °C higher than the temperature measured by a vehicle-mounted infrared sensor under partly cloudy to clear conditions during the daytime. Although more tests need to be done to determine if the temperature differences are statistically significant, a disparity of this nature could affect forecast surface temperatures.

According to the Iowa study, maintenance personnel feel that the most important elements of weather forecasts are, in decreasing order of importance:

1. Precipitation type
2. Storm start time
3. Wind speed
4. Air temperature
5. Storm end time
6. Pavement temperature

Because of the factor's relative importance, the Iowa study also evaluated the performance of the SCAN*Cast forecasts for onset of precipitation. For the period December 1 through March 31, 1997, averaged over three locations in the state, precipitation events started within one hour before forecast time 52.6% of the time, and an average of six precipitation events occurred that were not forecast. Although these statistics are not comprehensive, they do suggest room for improvement in forecasts.

2.5. REQUESTED LOCATIONS FOR FUTURE RPUs

The following locations (Figure 2.1) were suggested for future RWIS weather stations (milepost locations are only general vicinity):

<u>District 1</u>
Meriden area (US 85 Mile 56: on District 1 / 2 boundary)
S. of Cheyenne (I-25 Mile 3.2)
Cooper Cove (I-80 Mile 272)
Dana Ridge (I-80 Mile 247-250): *later changed to Elk Mountain*
Elk Mountain (I-80 Mile 255)
Shirley Basin (WY 487 Mile 18.5)
Shirley Basin (WY 487 Mile 24 or 29: near District 1 / 2 boundary)
Baggs area (WY 789 Mile 10)

<u>District 2</u>
Mule Creek Junction (US 85 Mile 196: in District 4 but near boundary)
Pine Tree Junction (WY 387 Mile 132: on District 2/4 boundary)
Meriden area (US 85 Mile 56: near District 1 / 2 boundary)
LaGrange (US 85 Mile 64)
Jay Em area (US 85 Mile 124)
North of Manville (WY 270 Mile 105)
South of Manville (WY 270 Mile 523)
Lusk (US 85 Mile 149)
Hat Creek area (US 85 Mile 160)
Shirley Basin (WY 487 Mile 24 or 29: near boundary between Districts 1 and 2)
Jeffrey City (US 287 Mile 23)
I-25 Mile 100
Outer Drive (Wyoming Boulevard) in Casper (WY 258—no milepost given)

District 3	Bear River bridge at Evanston (I-80 Mile 5)
	Kemmerer (US 30 Mile 53)
	Church Buttes (I-80 Mile 54)
	Rock Springs area (I-80 Mile 100)
	Dry Lakes area (I-80 Mile 113)
	Superior Interchange (I-80 Mile 122)
	Point of Rocks (I-80 Mile 130)
	Tipton (I-80 Mile 158)
	Snake River Canyon or Hoback Canyon (no milepost)
District 4	Mule Creek Junction (US 85 Mile 196)
	Pine Tree Junction (WY 387 Mile 124-132: on District 2/4 boundary)
	Four Corners (US 85 Mile 247.5)
	Leiter area (US 14/16 Mile 51-52)
	Spotted Horse area (US 14/16 Mile 60)
	Wildcat area (US 14/16 Mile 76)
	South Dakota / Wyoming line (I-90 Mile 207)
	I-90 Mile 96
	I-90 Mile 109
	Montana/Wyoming line (I-90 Mile 0)
	North of Weston (WY 59 Mile 150)
	Montana / Wyoming line (WY 59 Mile 170)
District 5	Wind River Canyon (US 20 Mile 126 and 116.17)
	South Pass (WY 28 Mile 41 and Mile 59)
	South of Meeteetse at WY 120/431 Junction (WY 120 Mile 32.3)
	Elk Basin, north of Powell (WY 295 Mile 20-25)
	North of Cody (WY 120 Mile 110)
	Togwotee Pass (US 287 Mile 26)
	Winkleman Dome north of Fort Washakie (US 287 Mile 30?)
	Blue Hill south of Lovell on Meeteetse Rim (US 310 Mile 224-226)

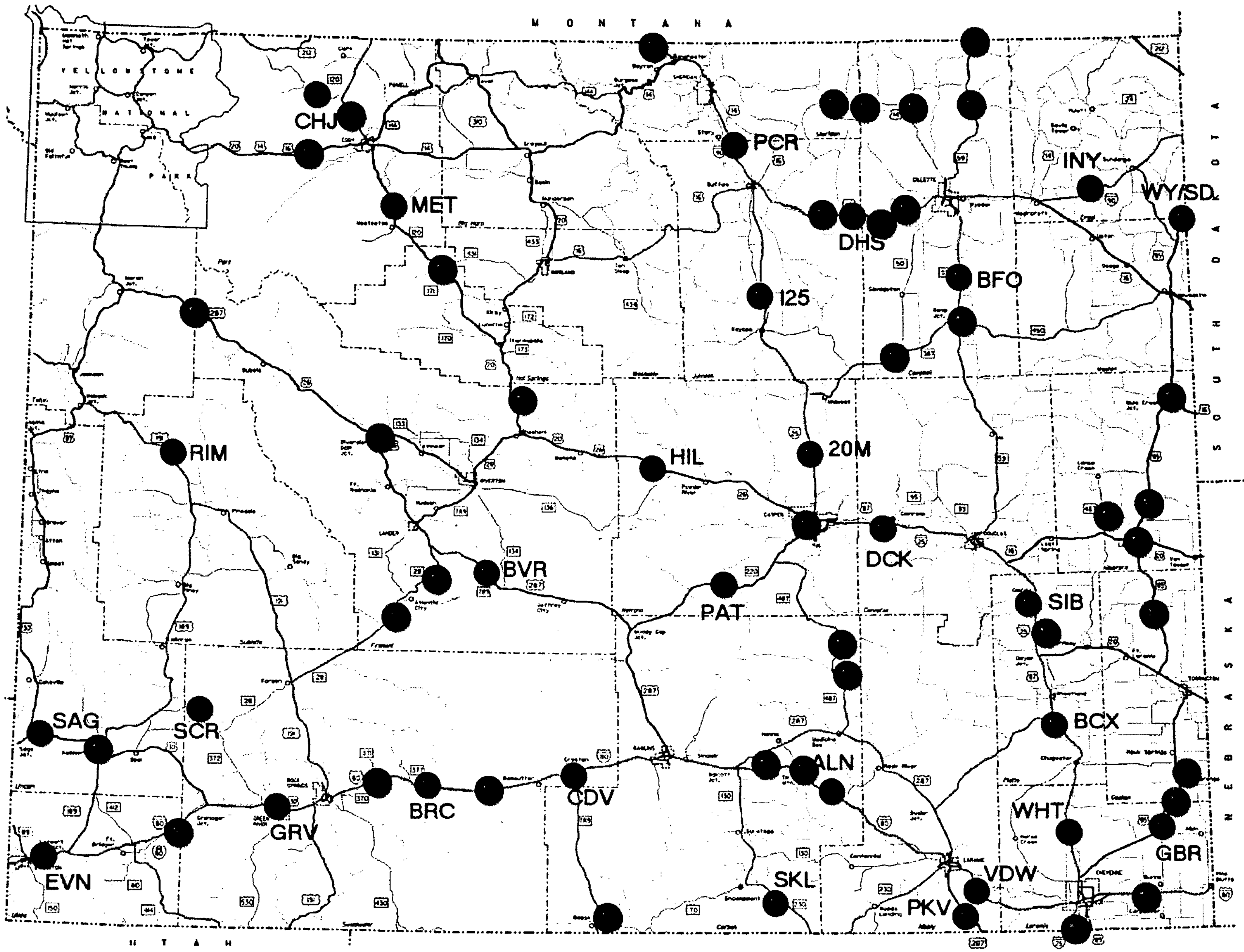

Figure 2.1. Locations suggested for future RPUs.

2.6. SUGGESTIONS FOR RELOCATING RPU SITES

Suggestions were received for relocating the following sites:

Dead Horse (RPU #11 = DHS) (I-90 Mile 91.53): Location not representative with respect to snowfall, wind or road surface conditions. Suggested moving to Mile 78-79 or between 76 and 80.

Arlington (RPU #1 = ARL)(I-80 Mile 272.13): Not representative with respect to wind. Move to Cooper Cove?

Chief Joseph (RPU #5 = CHJ)(WY 296 Mile 33): Not useful for contract snow removal in effect at time questionnaire was filled out. Suggest moving to WY 120 Mile 110.

Cemetery Separation (RPU #19 = GRV)(I-80 Mile 90.65): Not representative of wind, precipitation, or surface condition. Suggest moving it back to Peru Hill (I-80 Mile 83.5) where it was originally.

Pumpkin Vine (RPU #14 = PKV)(US 287 Mile 420.36). Not representative of conditions. Move to Mile 423.5, 425, or 419.

Belle Fourche (RPU #13 = BLF)(WY 59 Mile 86.99): Not representative of troublesome locations. Move to Mile 75.5 (Reno Junction vicinity)

Vedauwoo (RPU #15 = VDW)(I-80 Mile 329.37): Not representative of worst conditions. Downwind of snow fences. Move to Mile 327 or 330.

South Dakota / Wyoming shared site (US 85 Mile 2.4): Not representative, data unavailable/inaccessible. Need site near Four Corners.

2.7. IMPROVING GRAPHICS AND OUTPUT FORMAT

Specific suggestions for improving the method of displaying data and forecasts included the following:

- Add up-to-date weather maps, radar, and satellite imagery to the output
- Improve displays of air/surface temperature graphs showing actual and forecast values, including use of color. Data are currently "lumped together and hard to read."
- Use Windows-type point-and-click maps with pop-up data
- Include video views of road at weather station sites
- Use graphical displays for historical data
- Provide instructions on how to read graphics
- More and better forecasts

2.8. ADDITION OF VISIBILITY SENSORS

Although there are currently only two sites equipped with visibility sensors, and the instrumentation and placement of these instruments are not optimal, maintenance personnel intuitively feel that visibility information is important. This conclusion was also borne out by the study by French and Wilson (1993). In addition to blowing snow being a common feature of the Wyoming winter weather, this perceived need relates to the association of blowing snow to rapid snowdrift development, slush and ice formation, and errant vehicle incidents. Visibility is useful for traffic operations decisions such as advisories and road closures, but it can be even more useful as a quantitative indication of the rate of snowdrift development and encroachment at locations where drifts tend to form, as well as providing an indication of adverse road surface conditions. Visibility information can be used to determine when the snow cover is beginning to "blow out", and as a very sensitive indication of when snowfall begins and ends—information that wind data alone cannot provide (Tabler 1979). Accurate visibility information, when combined with wind data, can be used for computer-assisted maintenance decisions as well as for traffic operations (Tabler 1984). As will be discussed later in this report, additional research is needed before specifying instrumentation suitable for blowing snow conditions.

2.9. NEED FOR ADDITIONAL TRAINING

Although 73% of respondents had received some training in obtaining, interpreting, and using visibility information, only 16% thought that they had received "considerable" training, and 53% believe more training would be beneficial. It is likely that many of the perceived problems related to reliability and representativeness of instrumentation and forecasts derive from insufficient training.

2.10. RELIABILITY OF SNOWFALL / PRECIPITATION DETECTION AND QUANTIFICATION

Precipitation detection for SSI (SCAN) systems presently utilizes the Optical Precipitation Detector (OPD) manufactured by ETI Instrument Systems Inc. of Fort Collins, Colorado (970-484-9393). These instruments are based on the detection of particles passing through an infrared beam, with the latest model having an optical path 25 mm in diameter and 150 mm long. The only current-model ETI instrument in Wyoming's RWIS system is at Deer Creek (Figure 2.2), but three stations have the original version of the ETI precipitation detector consisting of curved stainless steel cylindrical horns (Figure 2.3). Precipitation detection threshold is adjustable from 1 to 15 particles per minute, with a default setting of three. The analog output from this device can be used for discriminating between rain and snow with the aid of a temperature algorithm, and offers the opportunity for distinguishing light, medium, or heavy precipitation intensities. However, the standard SSI RPU configuration only uses the signal to determine the presence (Y) or absence (N) of precipitation. Moderate or heavy fog will be identified by OPD's as precipitation, and there is no way to avoid this error in the absence of a visibility sensor or an optical "weather identifier."

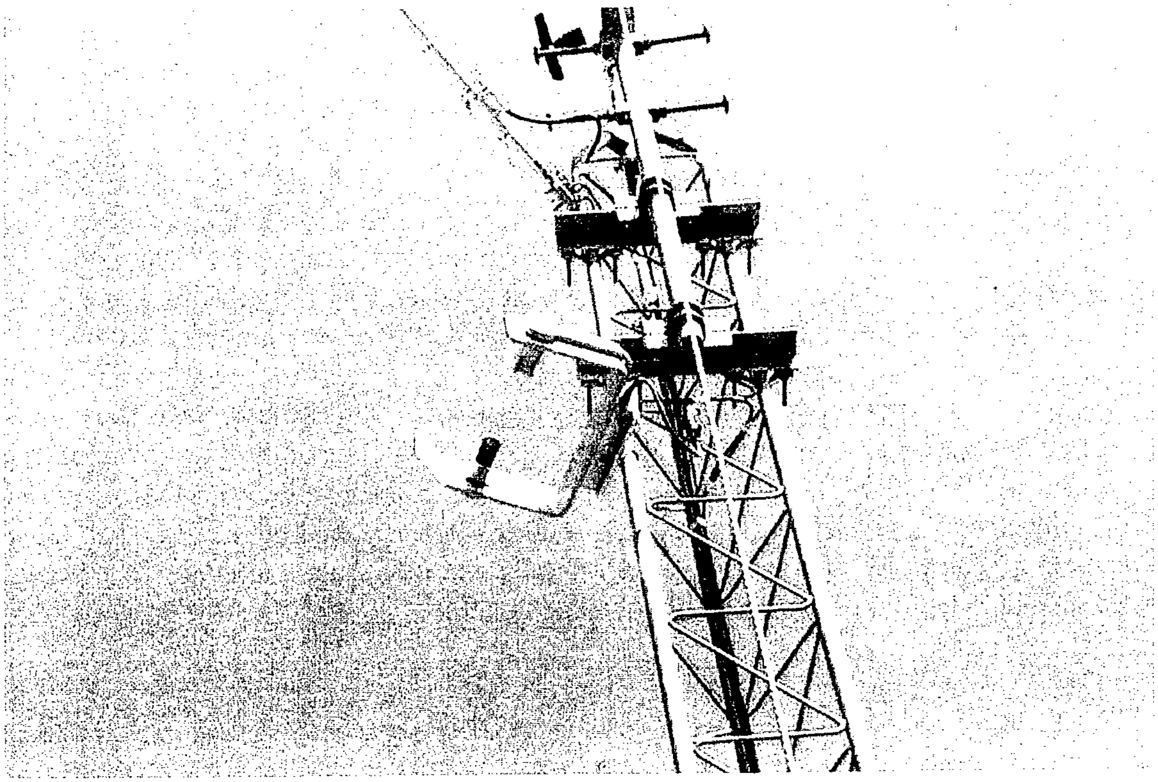

Figure 2.2. Latest model of the ETI Opitical Precipitation Detector (Deer Creek, 8/15/98).

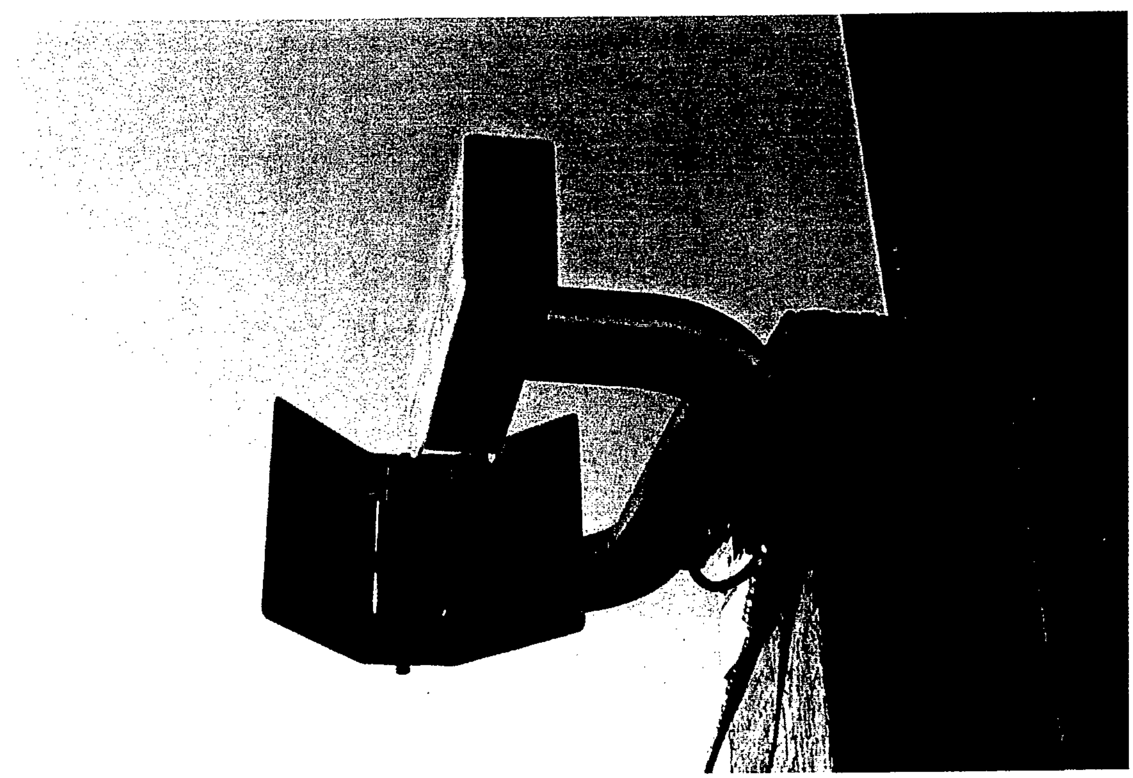

Figure 2.3. Original Model of ETI Optical Precipitation Detector (First Divide, 8/11/98).

Precipitation detectors at 16 of the SSI sites are the rectangular frame-shaped IRSS88 instrument (Figure 2.4) manufactured by R. Rudolph of Germany which was used prior to the availability of the ETI sensor. The Rudolph sensor operates on the same principal as the more recent instruments, utilizing a dual infrared light beam having a sensing area of 25 x 120 mm mounted within a stainless steel frame195 x 165 x 85 mm. Sensitivity is selective, ranging from 1 to 15 interruptions per 95-s time interval (4 is the factory default). The fact that the sensing volume is completely surrounded by the frame precludes the use of this device to detect blowing snow, and also degrades performance during snowfall events accompanied by wind because of the tendency for particles to be deflected by the frame. Many of the weather stations in Wyoming are equipped with a Rudolph sensor near the top of the mast, and a second one within a meter or so above the ground for the purpose of detecting blowing snow. All of these lower sensors suffer from being obstructed by the instrument tower and ancillary equipment through an arc of at least 90° (Figure 2.5). One of the recommendations from this study is that these lower instruments be removed, and perhaps used for future installations or replacement units. The value of precipitation detection is marginal by itself, but could be substantially greater if used in conjunction with quantitative precipitation instrumentation.

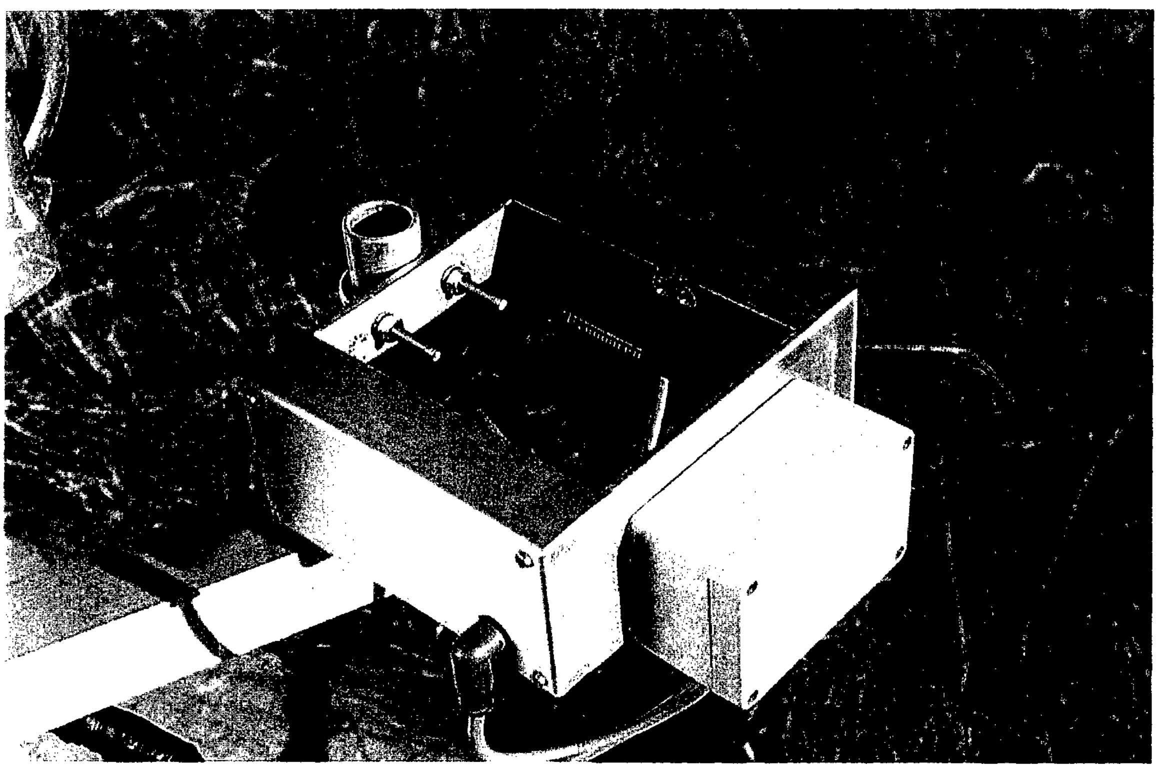

Figure 2.4. Rudolph Model IRSS88 precipitation detector (Piney Creek, 8/14/98).

Figure 2.5. Precipitation detector at 93-cm height obstructed by tower and enclosure (Meeteetse Rim, 8/12/98).

The survey conducted for this study indicated a general dissatisfaction with yes/no information, with respondents favoring information on precipitation rate or accumulation. Quantitative information on current snowfall or precipitation rate is important for maintenance operations decisions related to crew scheduling and dispatching. Typical questions that are asked in the decision-making process for snow and ice control include:

- Should plows be dispatched to a location?
- What locations within the maintenance area are receiving the most snowfall?
- How much snow is expected in the area based on current precipitation rates at weather stations that the storm has already reached?
- Is the storm intensity increasing or decreasing?
- How much snowfall has there been since the last time plows were dispatched to a location?
- Is it time to reapply anti-icing chemical?
- Is the current snowfall rate likely to cause visibility problems?
- How much snowfall has been received since this storm started?

Considering the importance of the information, it is ironic that snowfall intensity is the one piece of information that is currently unavailable at over 90% of the RWIS sites in Wyoming, and precipitation information at the other two sites is suspect because of the limitations of the instrumentation. The only instrumentation for quantifying precipitation presently offered by vendors is described in the following paragraphs.

Vaisala uses a rain detector (DRD11A) to estimate three intensities of precipitation--light (<2 mm/h), moderate (2 - 8 mm/h), and heavy (>8 mm/h)--based on the capacitance of a heated plate inclined at a 30° angle, and enclosed on four sides by a small rectangular wind screen (Figure 2.6). This device was not originally intended for snow, and data supporting its accuracy are apparently unavailable. Perhaps the greatest potential error of the device derives from the inevitable deflection of snow around the sensor when snowfall is associated with wind—a problem common to standard precipitation gauges (Tabler et al. 1990). Some users have installed a larger windscreen around the device to help reduce this problem, but again no quantitative data are available to indicate what improvement, if any, this modification makes. When the device is used in conjunction with the Vaisala visibility meter (FD12), the combination of instruments is called the FD12P weather sensor (Figure 2.6) or "Present Weather Detector," Model PWD11. According to the manufacturer, analyses of the optical scattering signal makes it possible to identify precipitation type, and provide an analog estimate of precipitation intensity. The accuracy specified for accumulation in light and moderate *rainfall* is ± 30% for the PWD 11. No specification is given for intensity, although detection sensitivity is specified at 0.1 mm/h for liquid precipitation. No specifications are given for snowfall.

Figure 2.6. Vaisala Present Weather Detector FD12P. Box-like object on horizontal arm is the Model DRD11A Precipitation Detector (Skyline, 8/11/98).

SSI, or SCAN, systems offers three optical devices for highway use that measure precipitation. The least expensive of these is the optical precipitation detector, or OPD, that detects hydrometeors passing through a beam of infrared light, as described previously. OPDs are used by SSI only to indicate the presence or absence of precipitation, although the analog output contains much more information on the size and numbers of particles. At a cost of approximately $1,600, they are relatively inexpensive.

The *WIVIS* is a dual purpose optical device manufactured by Scientific Instruments Incorporated (ScTI) for measuring both visibility and precipitation (Figure 2.7). The instrument is theoretically able to discriminate among drizzle, rain, and snow ("WI" in WIVIS refers to "weather identifier"); determine precipitation intensity and accumulation; and measure visibility ("VIS" in WIVIS). This instrument is similar to Vaisala's present weather detector, although distinctly different in that it utilizes a split beam of infrared which allows measurement of forward scattering as well as spectral analysis of a direct beam. The principle upon which precipitation identification and measurement is based is described by Bradley, Lewis, and Haas (1993), as follows. The device measures scintillation in two bandwidths—the high frequency range (1000 to 4000 Hz) is associated with rain, and the low frequency range (75 to 250 Hz) is related to snow crystals. Low frequency scintillation intensity, L, is related to snowfall accumulation rate, I (cm/h), according to

$$I = K[\text{antilog}\ (L/100)] \qquad (1)$$

K is a correction factor which depends on factors such as the density, shape, structure, and size distribution of the snow particles. The variability of K implies that the accuracy of precipitation rate measurements will vary from storm to storm, as well as during a storm event. A more recent form of this equation, and parametric values for the correction factor, are given by Lewis and Bradley (1998).

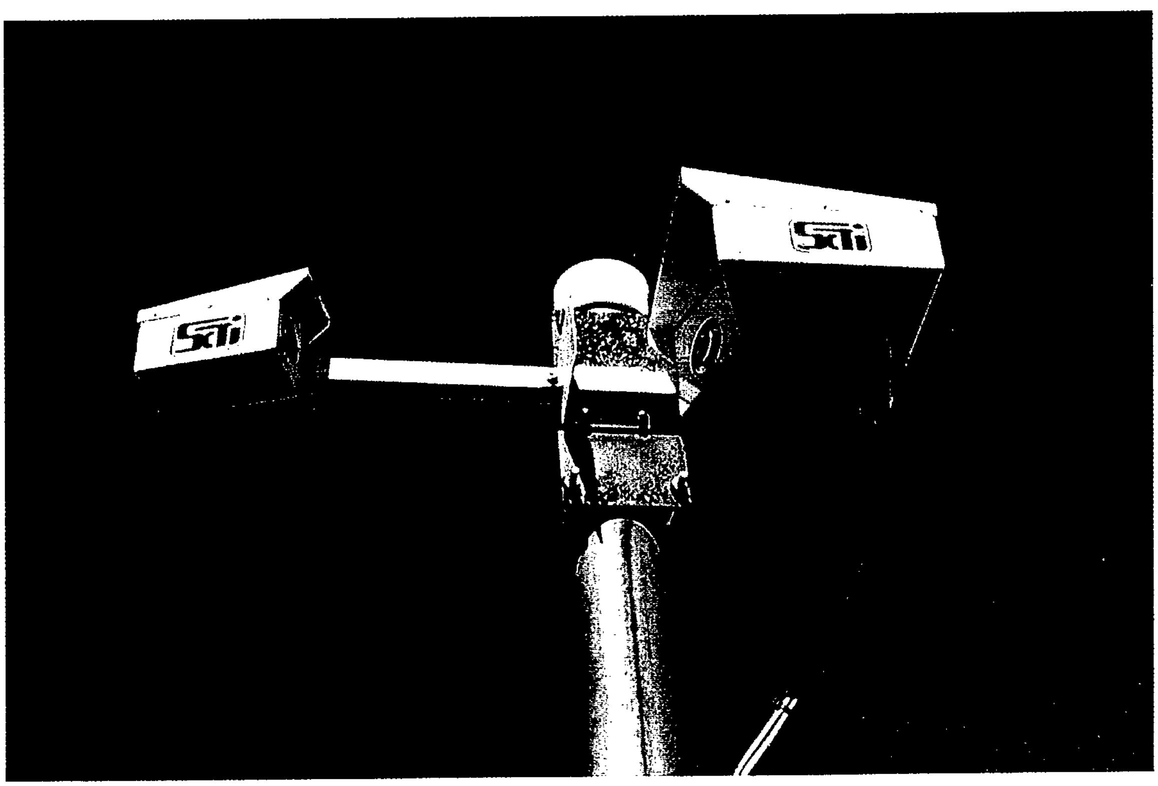

Figure 2.7. WIVIS combination "weather identifier" and visibility sensor (Pumpkin Vine, 8/6/98).

Output from WIVIS sensors is interpreted in terms of precipitation type, intensity, and water-equivalent accumulation, as well as visual range. Reports from WIVIS-equipped RPU's include an output of precipitation rate, in inches (water-equivalent) per hour, and identify precipitation intensity as being light, medium or heavy (e.g., S-, S, S+ , R-, R, R+), or when precipitation type is indistinguishable, Y-, Y, and Y+. Rain and snow accumulation "accuracy" is stated to be 5%- and 10%, respectively, although it is difficult to believe that this level of accuracy can be realized considering the principle of operation. Resolution for snow is 0.001 mm water-equivalent. One of the primary problems associated with using this type of device for snowfall measurements is the blockage of the optics that occurs when the instrument is oriented so that the wind is parallel to the beam (Lewis and Bradley 1998). This problem has not been resolved.

At a price of approximately $9,000, WIVIS is an expensive addition to an RWIS site. A less expensive ($7,500) instrument for measuring precipitation type and relative intensity is the *OWI*, or Optical Weather Identifier, also manufactured by ScTI. The OWI is essentially the WIVIS without the forward scattering measurement for determining visibility. The OWI is the less expensive version of the *LEDWI* (Light Emitting Diode Weather Indicator), another ScTI instrument, which is equipped with hood heaters and wider operating temperature specifications, and which is used for the Automated Surface Observation System (ASOS) of the National Weather Service (Bradley and Nadolski 1983). ASOS systems do not yet record accumulated precipitation from snowfall during the winter, but research is underway to resolve the problems associated with blockage.

Research reported by Bradley, Lewis, and Haas (1993) and Lewis (1993), indicated that the LEDWI (or WIVIS, by implication) do not provide accurate measurements of snow accumulation unless some other instrument, such as an ultrasonic snow depth detector, is used to adjust the *K* value in Equation (1), and disparities are greatest in the presence of wind. A recent paper (Lewis and Bradley 1998), however, concludes that where snow is generally "wet" and blowing snow rare, a LEDWI-derived snow accumulation is comparable to manual measurements. According to personal communication with one of the above authors (Richard Lewis), there is no evidence that the addition of forward scattering information from the WIVIS improves the accuracy of snowfall rate estimates, although *downward-looking* visibility sensors can be used to estimate snowfall rate when the LEDWI (or WIVIS) is blocked by blowing snow. Unfortunately, the WIVIS visibility sensor is not downward-looking, so it suffers the same blockage problems as does the direct beam.

The National Center of Atmospheric Research (NCAR) at Boulder, Colorado, is also comparing optical precipitation estimates such as those offered by the instruments described above, with the catch of shielded precipitation gauges. Results from two winters indicate large and variable discrepancies between visibility-based measurements and collector gauge estimates. Discrepancies depend on the type, density, wetness, and degree of aggregation of snow crystals as well as time of day (Rasmussen et al. 1998), but it is intuitive that wind would also affect accuracy. Measured versus true snowfall rates were reported to vary by a factor of 3 to 10. NCAR research on this instrument is continuing, and the author of this report is being kept apprised of results. In the interim, it is safe to assume that the optical devices in their present configuration do not provide accurate estimates of precipitation under many conditions encountered in Wyoming. One of the recommendations from this study is that shielded precipitation gauges be installed as part of the standard instrumentation for RWIS sites in Wyoming until such time as improved optical measurement systems become available.

2.11. Reliability of Visibility Data

Visibility sensors are presently installed at only two locations in Wyoming—Pumpkin Vine and Skyline. The Pumpkin Vine WIVIS sensor was originally located at Vedauwoo, and was moved in 1996. Both the Pumpkin Vine and Skyline sites are near the Colorado-Wyoming border, so only a limited number of maintenance personnel have had experience with the instrumentation. That being said, only 33% of the survey respondents felt that the visibility estimates provided by the instruments were "usually representative" of motorist visibility. The Skyline RPU site is favorably situated for visibility monitoring, but the Pumpkin Vine site has snow fences, scattered trees, and natural snow deposition areas located upwind which significantly reduce the blowing snow arriving at the sensors. Although the sample size for Wyoming's RWIS experience with visibility sensors is limited, it is obvious from a consideration of the physics of visibility attenuation by blowing snow (Tabler 1979, 1984, 1994) that the polling and averaging times, and signal processing, used in the commercial instruments being sold for RWIS systems are not appropriate for meaningful visibility measurements in blowing snow. In addition, the elevation of the sensors relative to the snow surface is critical because of the vertical distribution of blowing snow (Tabler 1991, 1994). Commercial sensors cannot practically be positioned at a height that would be representative of conditions affecting motorists, requiring a signal processing correction. Some of these conclusions are supported by the observation reported by Castle Rock Consultants (1995):

> "For visibility reduction due to fog, the Belfort, HSS, and Vaisala sensors provided overall accuracy rates which were within the 20-percent accuracy detailed in the functional requirements. During blowing snow the sensors indicated reduced visibility but did not match the very low visibilities being experienced by the manual observers. This may have been due to surface effects causing a greater reduction in visibility near the surface of laying snow. However, the Belfort sensor, which was the highest mounted sensor, provided readings that were closest to those manually observed."

Although there is no reason to believe that the instruments are not capable of providing meaningful measurements, they cannot be expected to provide meaningful output until the signal processing is changed to produce a useable output under blowing snow conditions. Even with adequate sampling and signal processing, however, research remains to be done to determine what statistic of the sample is meaningful with respect to vehicle operation and driver behavior. Results from studies in fog and smoke have only limited relevance because, in these cases, the degree of visual attenuation varies relatively slowly, if at all, whereas visibility in blowing snow changes by several orders of magnitude over a period of a few minutes. This is due to the fact that wind speed changes by a factor of 2 over this time scale, and visual range in blowing snow is inversely proportional to the 5^{th} power of wind speed. The relationship is well approximated by

$$V = AU_{10}^{-5} \qquad (2)$$

where *V* is motorist visual range (meters), U_{10} is wind speed at 10 meters height (meters/second), and A is a coefficient that varies with the extent of snow cover. For a uniform, unlimited snow cover, $A = 1.1 \cdot 10^8$. With a wind averaging 20 m/s, for example, wind speeds over a 5-minute period can be expected to range from about 12 to 28 m/s. With unlimited snow on the ground and no concurrent snowfall, visibility at a fixed point will range from 440 to 6 m (Figure 2.8). Even greater variability is added in the case of a vehicle moving through an environment where conditions vary spatially as well.

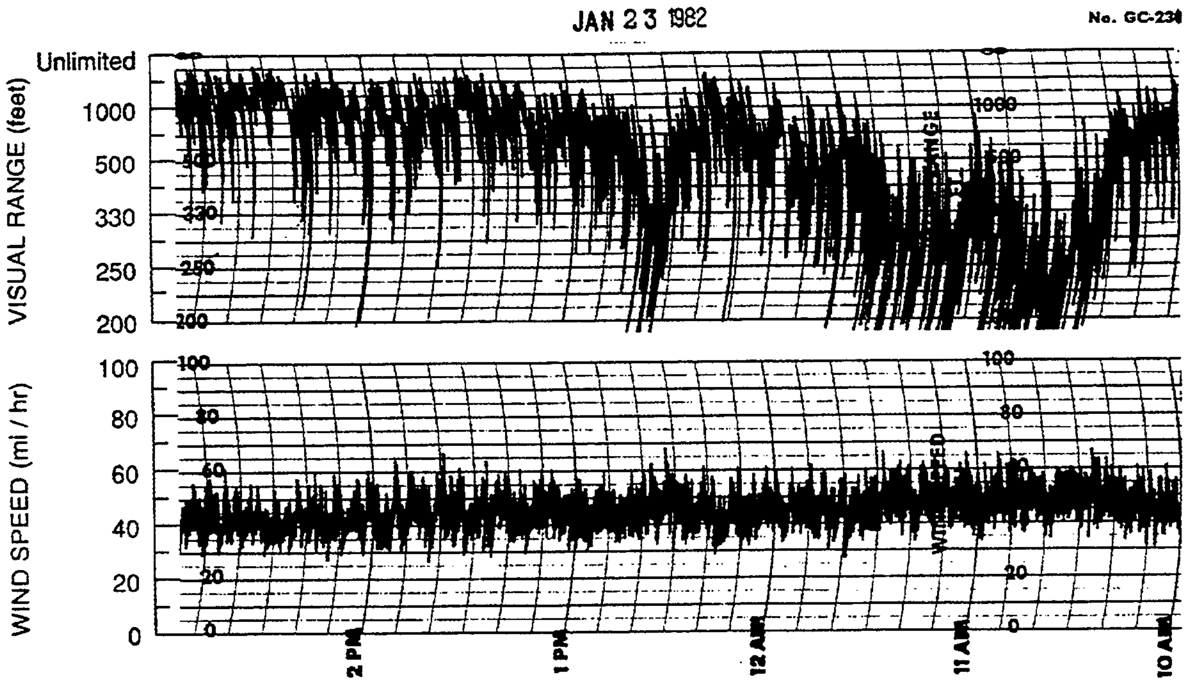

Figure 2.8. Example from the Arlington visual range monitoring station chart shows the variation in motorist visual range in relation to wind speed at 10-m height (From Tabler, 1984).

The deficiencies in sampling and signal processing are illustrated with the case of the WIVIS sensor. According to the author's understanding of the descriptions provided by ScTI, visibility output is a three-minute logarithmic average of readings obtained once every 5 seconds, updated every minute. The current software for this instrument (version 10), allows the user to specify the averaging time to be used. The most recent measurement is given the most weight, whereby each sample is weighted by some exponential function of time since the first measurement used in the average. Although the exact algorithm is unknown to the author, the weighting factor is proportional to e^x, where x is time since first measurement. This may be reasonable for visual range attenuation by fog, rain, or even snowfall under calm conditions, but it does not address the problem of the rapid fluctuation in visibility associated with blowing snow, as previously illustrated, nor the more complex question of what visibility statistic is best correlated with driver behavior.

One of the intrinsic disadvantages of the WIVIS instrument is its combination of visibility and precipitation functions. For sampling visibility in blowing snow, the device should be sufficiently close to the ground surface that blowing snow particles (i.e., particles relocated from the ground) pass through the sampling volume. But if this requirement is met, blowing snow particles may be interpreted as precipitation, and the blowing snow increases the likelihood of blockage because of the horizontal alignment of the forward scattering beam, compared to downward looking visibility sensors such as the Vaisala model used at Skyline. In general, the WIVIS should not be installed closer to the ground than 2 meters or so. Because of the vertical distribution of blowing snow, however, it is therefore necessary to adjust the WIVIS output in order to approximate driver visibility (see Recommendation 14), and this is not presently considered in the signal processing.

Recommendations for addressing this problem include conducting field studies of alternative sensors under blowing snow conditions typical of Wyoming, in cooperation with instrument manufacturers, RWIS vendors, and the National Center for Atmospheric Research.

2.12. Reliability of Pavement Sensors

Forty two percent of respondents reported that surface conditions indicated by sensors were usually representative of actual conditions, and only 3% reported the opposite. The majority (63%) reported that sensors were sometimes representative, and sometimes misleading. Because surface status information was considered to be very important by 72% of respondents, it seems worthwhile to investigate ways to improve performance.

There are many possible reasons why surface conditions as indicated by sensors may not be representative of actual conditions:

- Surface sensors provide only a small sample of the roadway,
- Surface sensors do not always have the same surface characteristics (porosity, color, snow/ice adhesion properties, and thermal conductivity) as the surrounding pavement
- Surface sensors may be contaminated with crack sealant, encapsulating compound, etc.
- Sensors may not be placed in a representative location, such as an area protected by road cut or snow fence,
- Cup on FP2000 sensors may be fouled,
- Sensors may be worn or damaged,
- Inherent limitations of the sensors.

Specific locations identified in the questionnaire were examined in the field to determine possible sources of problems, and these are identified in Section 3.

The only sensors being used in Wyoming are two SSI models--the "E" series (Figure 2.9) and the most recent FP2000 (Figure 2.10), and one model of Vaisala (DRS 12, Figure 2.11). The most recent model of surface sensor offered by SSI is the FP2000 (FP standing for Freeze Point), which is considered to be more accurate than the preceding "E" series. The reason for this relates to the principles upon which these instruments are based. Surface temperature is measured with a thermistor embedded in the sensor, the presence (or absence) of moisture is determined from the capacitance of the surface plate, and the salt content of the solution on the surface is determined from conductivity. Various algorithms are used to filter spurious indications, and compensate for inaccurate measurements in capacitance and conductivity. The accuracy of the conductivity measurement is dependent on the depth of water over the electrodes—as solution depth decreases, conductivity tends to be underestimated. The depression in the surface of the FP2000 sensor is therefore intended to improve the accuracy of conductivity measurements, and hence the accuracy of salt concentration and freezing point determination, and the importance of this improvement is greater in areas where there is limited water on the road surface. The wind, dry atmosphere, and limited snowfall amounts typical of Wyoming's winter weather suggest that the FP2000 sensor would provide more accurate information on surface condition. Initial experience with the FP2000 in Wyoming was unfavorable when first introduced, but subsequent improvements in the signal processing software have remedied these problems, and the foreman who was at first critical of the FP2000 now believes it to be more accurate than the older "E" series. At the present time, FP2000's are installed at four sites (Table 3.1). Two of these (First Divide = RPU# 18; Cemetery Separation = RPU# 19) were identified by survey respondents as providing unrepresentative results, but the causes of complaints are believed to be related to siting or communications problems rather than sensor accuracy.

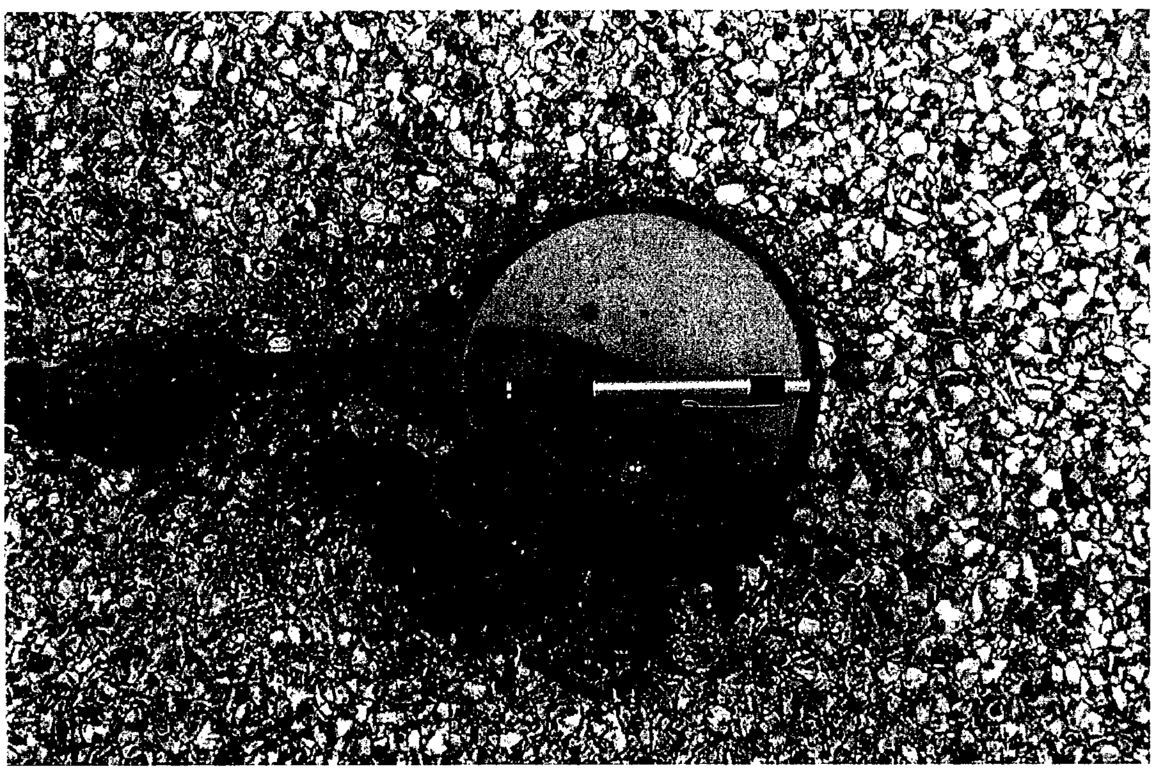

Figure 2.9. SSI "E" Series pavement sensor (Beaver Rim 5/28/97).

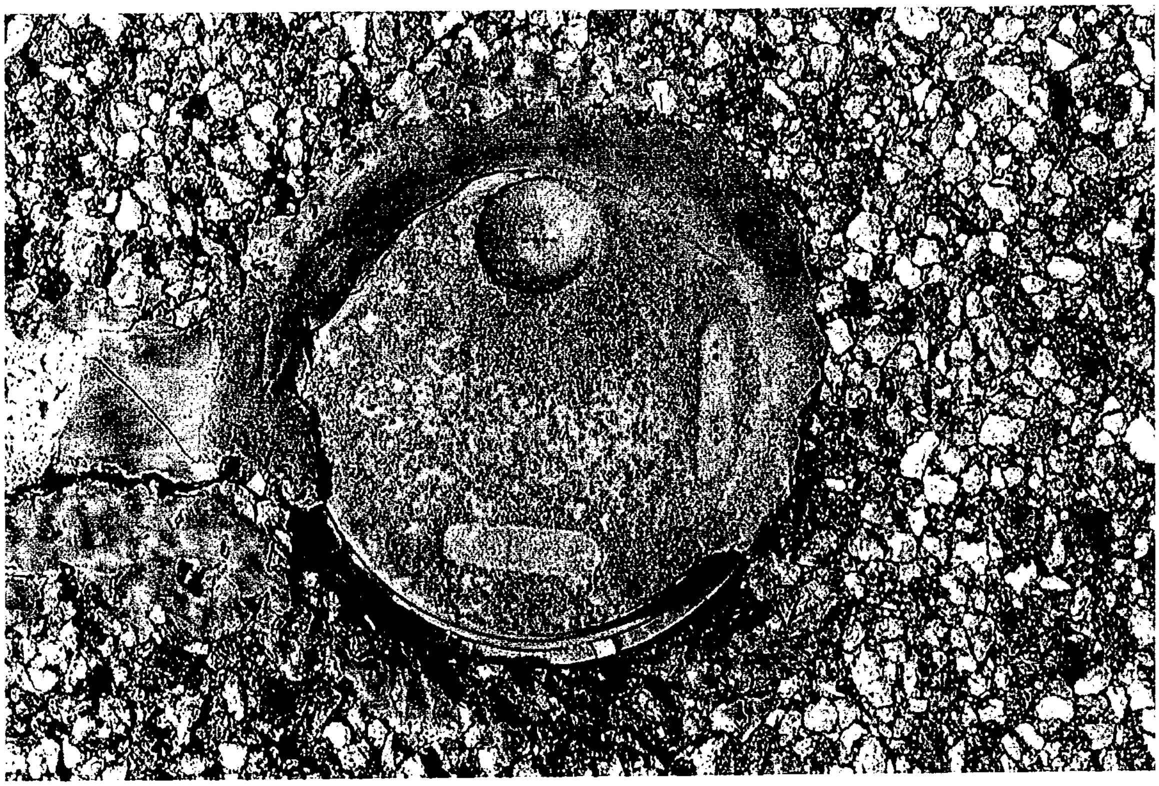

Figure 2.10. SSI Model FP2000 pavement sensor (Bordeaux 8/15/98).

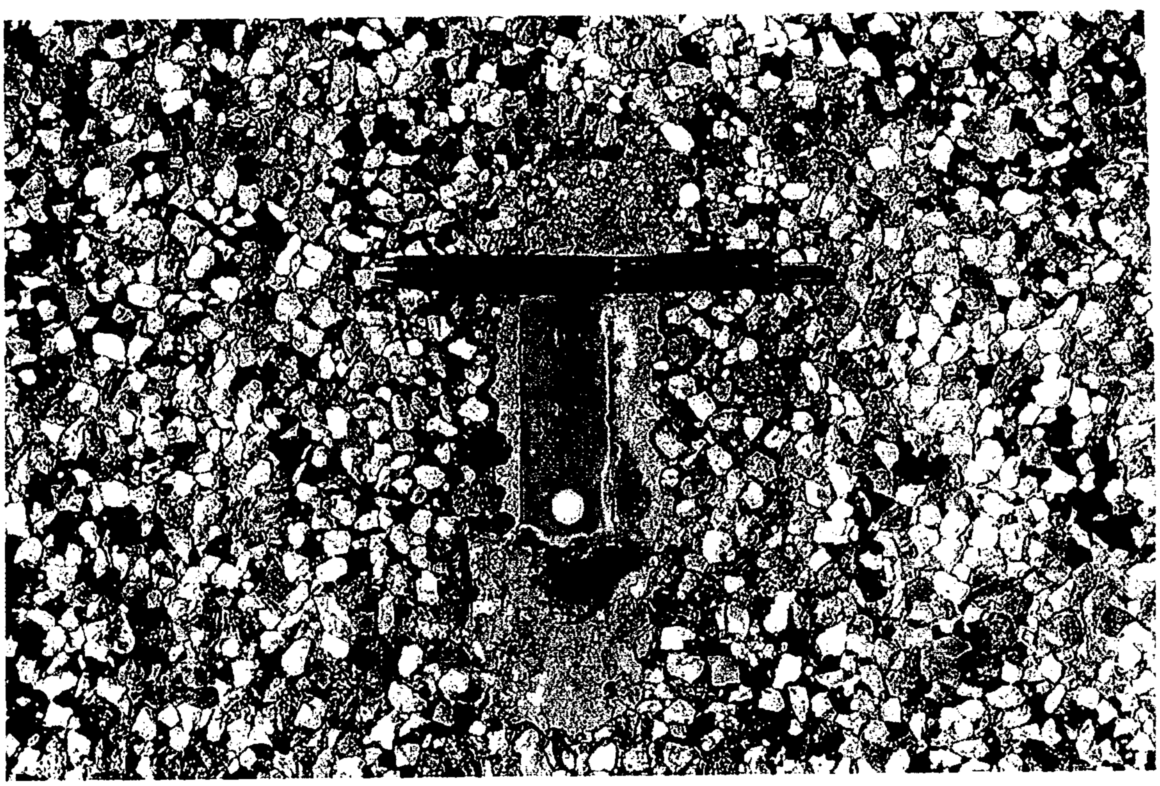

Figure 2.11. Vaisala Model DRS12 surface sensor (Skyline 8/11/98).

Sensors provided by other vendors (Vaisala and Coastal Environmental) operate on the same general electrical principles, but with different physical dimensions, placement of electrodes and thermistors, and signal processing algorithms. The Vaisala sensor configuration is such that it remains effective even after it has been worn down by abrasion (4 cm in the case of the DRS 12), whereas the SSI sensor must be replaced when critical wear has occurred. There is no evidence from this study of differences in accuracy among the various sensors, and the author was unable to locate any references to differences in the literature, including the relatively comprehensive review by Castle Rock Consultants (1995). The different design of the Vaisala sensor would be expected to have an effect on its accuracy compared to sensors offered by other vendors. Considering the cost of pavement sensors (about $2,000 for a SCAN or Vaisala sensor replacement), and the importance of the information, a side-by-side comparison of performance would seem to be a worthwhile research project.

The accuracy or representativeness of pavement sensors is also somewhat subjective, in that perception of accuracy may be different from reality. A valid evaluation of sensor performance requires that the observer examine each sensor to determine the condition of the sensor surface compared to the surrounding pavement. In addition, the observer should understand the operational principles that affect readings. The author's experience (Tabler 1973) suggests that determining the accuracy of sensors is not a trivial task.

2.13. Improve Software

This subject area refers to how the software for accessing and displaying the RWIS data and forecasts needs to be improved to make it more "user friendly," including installation. The results of the survey (Appendix A), and the independent experience of the author, indicate that the DOS-version software currently in use for both the Vaisala and SSI systems is problematic to install, and primitive in operational features.

2.14. Other Suggestions for Improvements

Other suggested improvements included (numbers in parentheses indicates number of respondents)

- Improve maintenance of equipment (3)
- Upgrade computers (2)
- Addition of video cameras (2)
- Improved maintenance of computers (1)
- Integrate Road and Travel into RWIS (1)
- Supplement RWIS weather data with National Weather Service data (show AWOS/ASOS weather data on same maps as RWIS)(1)

3. ROADSIDE WEATHER STATION REVIEW

3.1. GENERAL

All of the RPUs were visited at least once, and most on several occasions, during the study. A final field review of all sites was made August 11-16, 1998, that required 65 hours of time and 4,200 km of travel. An all-inclusive review such as this is worth performing every year. Table 3.1 summarizes the instrumentation at each of the existing sites, including locations, heights, and wind vane alignment. It should be noted that many of the statistics in this Table (and Table 1.1 as well) are at variance with the tabulated information provided by WYDOT—the values in Table 3.1 should be considered correct pending independent checks by the Department.

In general, it appears that much more care should be taken in selecting sites to insure that the location will be representative of pavement and atmospheric conditions for the area they are intended to serve. The considerable expense of installing and maintaining an RPU, and the importance of the data for making decisions, suggest that sites should be selected only after careful consideration of how representative the data will be. Examining prospective sites on 7.5-minute topographic maps is essential, as is determination of the prevailing wind direction. This latter information is available in Appendix B in the publication by Tabler (1997).

The most common mistakes in siting the RPU towers have been:

- Placement downwind of snow fences (Continental Divide, Bitter Creek, Beaver Rim, Piney Creek, Twenty-Mile Hill, Hiland, Gun Barrel, Arlington, Vedauwoo, Pumpkin Vine)
- Placement on the downwind side of deep road cuts (Piney Creek, Meeteetse Rim)
- Placement in close proximity to hills affecting wind speed and direction (Sage Junction, Arlington, Cemetery Separation, and to a lesser extent, Dead Horse)

It is important to remember that snow fences do indeed influence road and weather conditions downwind, even though they may be located 100-200 meters away. Snow fences reduce blowing snow arriving at a location by as much as 90%, resulting in greatly improved visibility (Figure 3.1). In addition, reducing blowing snow arriving at the road can result in warmer pavement temperatures, and completely different road surface conditions, compared to adjacent unfenced areas (Figure 3.2). For this reason, RPU sites should not be located downwind of snow fences unless the entire road section is fenced, as is essentially the case at Arlington, or unless there is a need to monitor pavement conditions at a location where there is no other alternative (Beaver Rim).

Table 3.1. Instrumentation at RPUs as of August, 1998. Abbreviations: WB, EB, NB, SB = west-, east-, north-, and south-bound lanes, respectively; D = driving lane; P = passing lane; B = bridge deck; T = tunnel. Numbers in ( ) in pavement sensor column indicate distance, in meters, from RPU tower to sensor, where W, E, N, and S = west, east, north, and south of RPU, respectively. nl = not located, nm = not measured.

RPU #	Site Name	Sensor number	Route	Milepost	Power	Pavement sensor type	Pavement sensor locations	Precip. detector type & (no.)	Precip. detector height(s)	Precip. / vis. type & (ht)	Anem. height	Vane orientation
							-distances in m-		-m-	-ht in m-	-m-	-deg TN az-
SSI SCAN STATIONS												
1	ARLINGTON	1 - 4	I-80	271.88	AC	Type E	WB: B(303 E), P&D (240 W)	Rudolph (2)	1.04; 7.01	No	7.77	357
2	CONTINENTAL DIVIDE	5 - 7	I-80	184.19	AC	Type E	EB: B(160 E), D(357 W)	Rudolph (1)	3.32	No	7.28	359
3	BITTERCREEK	8 - 10	I-80	141.83	AC	Type E	EB: B (543 E), D (0)	Rudolph (1)	3.38	No	7.41	351
4	BEAVER RIM	11 - 13	US 287	48.28	AC	Type E	SB: D(528 N), D(472 S)	Rudolph (1)	6.28	No	7.19	347
5	MEETEETSE RIM	14 - 16	WY 120	61.53	Solar	Type E	NB: D(652 S), D(125 N)	Rudolph (2)	0.93; 6.37	No	6.80	11
6	HILAND	17 - 19	US 20/26	57.42	AC	Type E	WB: D(584 W), D(564 E)	ETI (old)(1)	9.69	No	10.06	2
7	PATHFINDER HILL	20 - 22	WY 220	79.93	AC	Type E	WB: D(553 W), D(397 E)	Rudolph (1)	6.52	No	7.31	1
8	TWENTY MILE HILL	23 - 25	I-25	207.18	AC	Type E	SB: D(233 N), D(540 S)	Rudolph (1)	6.67	No	7.59	2
9	I-25 DIVIDE	26 - 28	I-25	267.32	Solar	Type E	SB: D(711 N), D(156 S)	Rudolph (2)	0.79; 6.43	No	7.44	350
10	PINEY CREEK	29 - 32	I-90	43.66	Solar	Type E	NB: D&P(718 N); B(718 S)	Rudolph (2)	0.94; 7.47	No	8.53	1
11	DEAD HORSE	33 - 35	I-90	91.53	AC	Type E	WB: D(27 W); B(63 W)	Rudolph (2)	0.85; 6.52	No	6.37	7
12	INYAN KARA	36 - 38	I-90	170.51	AC	Type E	EB: D(0), B(216 E)	Rudolph (2)	0.91; 6.58	No	7.47	356
13	BELLE FOURCHE	39 - 41	WY 59	86.99	AC	Type E	NB: D(not located), B(59 N)	Rudolph (2)	0.82; 9.36	No	10.00	358
14	PUMPKIN VINE	42 - 44	US 287	420.36	AC	Type E	SB: D(368 N); D(368 N)	WIVIS (1)	3.05	WIVIS (3.05)	7.47	11
15	VEDAUWOO	45 - 47	I-80	329.37	AC	Type E	EB: D(483 E); D(83 W)	Rudolph (1)	6.74	No	7.35	13
16	WHITAKER	48 - 51	I-25	28.12	AC	Type E	SB: D&P(69N); nl	Rudolph (2)	0.88; 9.75	No	10.00	358
17	SIBLEY PEAK	52 - 54	I-25	107.62	Solar	Type E	SB: D(632 N); D(332 S)	Rudolph (2)	0.84; 6.49	No	7.13	4
18	FIRST DIVIDE	55 - 57	I-80	13.88	Solar	2000FP	EB: D(30 E); B(5 E)	ETI (old) (1)	1.77	No	7.50	334
19	CEMETERY SEPARATION	58 - 61	I-80	90.65	AC	2000FP	WB: DT(710 W); B(152 W); nm	Rudolph (1)	2.53	No	7.68	353
20	DEER CREEK	62 - 64	I-25	164.25	AC	2000FP	SB; D(370 N); D(444 S)	ETI (new)(1)	6.64	No	8.59	359
21	BORDEAUX	65 - 67	I-25	70.86	AC	2000FP	SB: D (405 N); D(not located)	ETI (old) (1)	7.25	No	9.14	3
7 (SD)	S. DAK. SHARED SITE		US 85	2.40	AC	2000FP	SB: D (0); others unknown	WIVIS (1)	2.5	WIVIS (2.5)	3.00	1
VAISALA STATIONS												
1	SAGE JUNCTION		US 30	34.21	AC	DRS12	WB: D(0); D(126 E)	DRD11A	3.72	No	5.97	10
2	RIM		US 191	127.00	Solar	DRS12	SB: D(0); D(122 N)	DRD11A	3.75	No	5.97	4
3	SKYLINE		WY 230	113.46	Solar	DRS12	WB: D (0); P(337E)	DRD11A	3.32	Vaisala	5.97	359
4	GUN BARREL		US 85	46.80	Solar	DRS12	SB: D(3 N); D(109 S)	DRD11A	3.2	No	6.06	355
5	CHIEF JOSEPH		WY 296	32.66	AC	DRS12	WB: 2xD(305 E); 2xD(101 W)	DRD11A	3.35	No	6.10	359
6	SHUTE CREEK		WY 372	34.00	Solar	DRS12	WB: D(0); EB: D(0)	DRD11A	3.38	No	5.97	332

Figure 3.1. Aerial view showing effectiveness of snow fences in reducing blowing snow arriving at road section (I-80 Mile 263.0). Photo by Robert L. Jairell (Tabler 1994).

Figure 3.2. Transition from frozen slush to wet pavement corresponding to the beginning of a 3.8-m-tall snow fence extending left from the center of the picture (looking upwind). Fence is 150 m upwind. I-80 Mile 247.6.

Another general observation from the field review was that RPUs are often not installed or maintained to the specifications mandated for this equipment. This reinforces the independent experience of the author in other states, and suggests that trained WYDOT personnel should oversee commissioning and maintenance, and perform independent inspections. There is also an apparent need to review and revise departmental specifications for installation and maintenance.

Before proceeding with a commentary on each of the RPU sites, there are other general comments that apply to most if not all sites:

- Most SSI surface sensors are of the old ("E") type, and should be upgraded to the newer and more accurate FP2000 whenever replacement is required, if SSI instrumentation continues to be used.

- Crack sealing and chip sealing operations have not always been adequately supervised to insure that the surface sensors are adequately protected (Figure 3.3). Even partial coverage of the sensor can impair the accuracy of capacitance and conductivity measurements, as well as altering the thermal characteristics affecting temperature measurements. The $2,000 cost for a replacement sensor should be sufficient incentive to avoid this mistake, and recommendations to prevent this occurrence are presented Section 4.

Figure 3.3. Pavement sensor at Whitaker RPU contaminated with crack sealant (February 24, 1998). This sensor has since been replaced.

- Field inspection of RWIS sites during a previous study (Tabler 1997) showed misalignment of wind vanes with respect to True North at most Wyoming RWIS stations—in some instances errors as great as 35° were observed. Although there was an attempt to correct this alignment problem in December, 1996 and January, 1997, re-measurement in August, 1998, showed errors as great as 28° (Table 3.1). Wind vane orientation on RWIS stations in adjacent states should also be suspect until verified. As of August 13, 1998, the alignment of Montana's Aberdeen RPU just north of the state line on I-90 was 30° off , and as of August 16, Colorado's Natural Fort RPU on I-25 near the Wyoming line is 35° in error. This is direct evidence that maintenance as well as installation is substandard, because this is one of the items that should be checked at commissioning and during annual maintenance checks.

  Discussions with WYDOT telecommunications personnel provide further indications that vendor preventive maintenance and calibration procedures and standards may be inadequate. One of the recommendations in this report is that maintenance procedures be observed in the field and critically reviewed for the purpose of preparing supplementary specifications for future maintenance contracts.

- Many of the RPUs in Wyoming are equipped with a Rudolph sensor near the top of the tower, and a second one within a few feet of the ground for the purpose of detecting blowing snow. All of these lower sensors suffer from being obstructed by the instrument tower and ancillary equipment through an arc of at least 45° (Figure 2.4). One of the recommendations from this study is that these lower instruments be removed, and perhaps used for future installations or replacement units. The value of precipitation detection is marginal by itself, but could be substantially greater if used in conjunction with quantitative precipitation instrumentation and appropriate decision logic.

- Existing RPU towers are of various heights, with the result that the height of wind instrumentation varies from 6- to 10 meters (Table 3.1). As a general approximation, wind speed varies with height according to

$$U_{10}/U_Z = (10/Z)^{1/7} \qquad (3)$$

  where U_{10} is wind speed at a height of 10 meters, and U_Z is wind speed at height Z (meters). This relationship implies that the wind speed measured at 6 meters is about 93% of the 10-meter wind speed. Although this may seem insignificant, processor algorithms using wind speed as an input variable to compute visibility parameters are sensitive to such differences because of the relationship between visibility and wind speed (Equation 2). Tower height should therefore be standardized at 10 meters for future installations.

- Numerous pavement sensors suffer from surrounding cracks or missing encapsulating compound which should be sealed before winter.

- Most pavement sensors are placed farther than necessary from the RPU (Table 3.1). Twenty five are located 300- to 700 m from the RPU with no apparent reason other than poor judgment in selecting locations for either surface sensors, RPUs, or both. Long cables increase cost of installation and maintenance, and also increase susceptibility to cable damage.

- Pavement sensor locations are generally poorly marked. This makes them difficult to locate for routine inspections and maintenance, and makes it difficult for snow plow operators to properly evaluate sensor accuracy. Sensors are properly marked with distinctive amber reflectors at only three locations (Figure 3.4).

Figure 3.4. Example of proper marking of pavement sensor (Hiland, 8/15/98). The RPU is barely visible on the right side of the road 584 m in the distance—placement could have been much closer to the RPU. Note also the unavoidable depression around the sensor that results from chip sealing

- Buried cable markers are deficient or lacking at most locations. This increases susceptibility to damage during emergency excavation.

3.2. Comments on Individual RPUs

Arlington (RPU #1 = ARL)(I-80 Mile 271.88)

Not representative with respect to wind or visibility. Site is partially sheltered by snow fences and trees to west, and Rock Creek Ridge to the north. Wind is obstructed from 255° through north to 40°. Move to another location, but more deliberation is required for selection than was possible during this study. Site should preferably have AC power for future addition of visibility instrument and video camera.

Continental Divide (RPU #2 = CDV)(I-80 Mile 184.19)

Affected by 2.4-m-tall snow fence 50 m upwind, from 97° to 243° true azimuth. Pavement sensor in bridge deck is loose, and encapsulating compound is chipped out from both sensors. Driving lane sensors is also recessed about 5 mm as result of chip sealing, so water and snow probably tend to collect on sensor (Figure 3.5)—also increases tire impact on sensors.

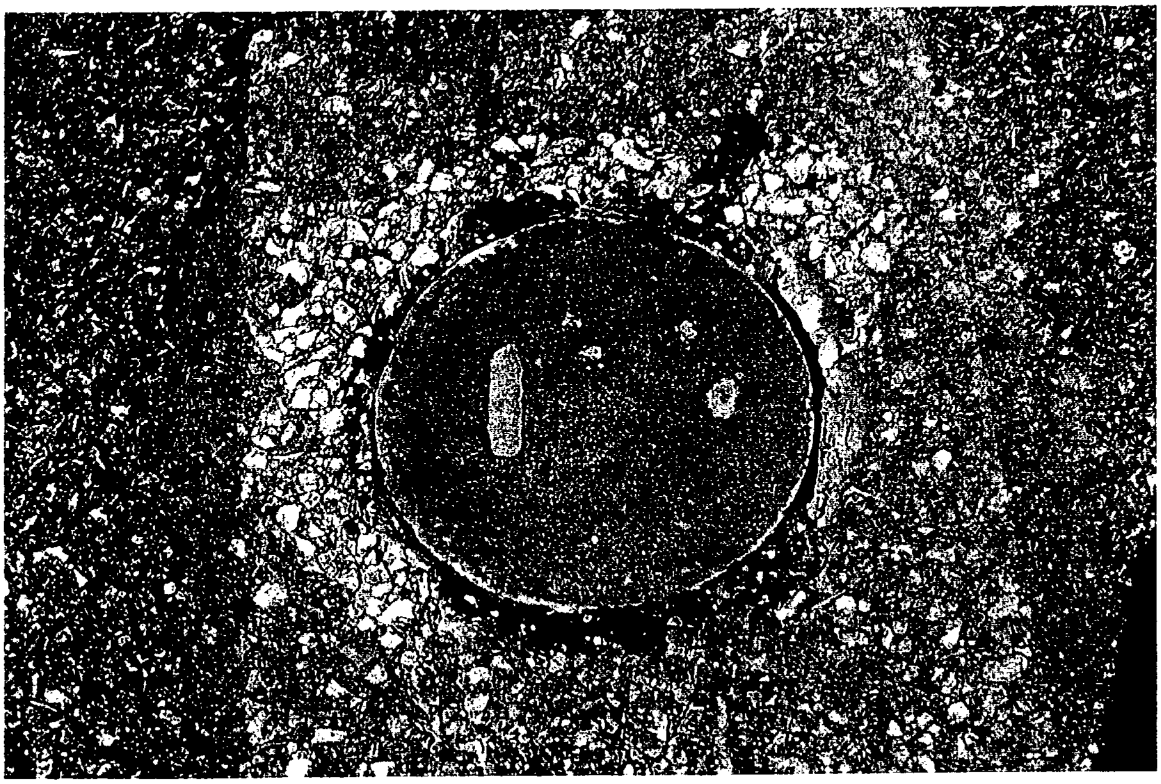

Figure 3.5. Pavement sensor (EB driving lane) at Continental Divide.

Bitter Creek (RPU #3 = BRC)(I-80 Mile 141.83)

Downwind of 3.4-m-tall snow fence through arc of 205° to 263° true-north azimuth. Fence is about 100 m away at closest point. Also snow fences on north side of highway at this location. Site is suitable for wind, but not for visibility. Also, surface sensor in driving lane is sheltered by cut and snow fence, so not representative of exposed areas. Wind vane 9° off (Table 3.1).

Beaver Rim (RPU # 4 = BVR)(US 287 Mile 48.28)

Located downwind of snow fences, but unavoidable to be close enough to grade. Otherwise an excellent site. Fetch from 3.4-m-tall snow fences upwind = 200- to 400 m, so visibility instrumentation would have some utility. Instruments have been shot up in the past, contributing to "com failure" record in the past. RPU was relocated 100 m to north and painted to make it less visible from the road. RPU needs to be fenced to protect tower from damage by livestock—three tires that were intended to provide this protection have been scattered and are not effective. Could use more tires and tie together with wire rope or chain. Encapsulation around western-most sensor needs repair. East sensor smooth—should be checked. Wind vane orientation needs to be corrected—it is 13° off, set at 347°. Precipitation detector and radio antenna may not have sufficient vertical separation (33 cm at present)—any history of spurious precipitation detection?

Meeteetse Rim (RPU #5 = MET)(WY 120 Mile 61.53)

Exposed location on hill, strategically located for pavement condition. However, location on east side of road cut prevents RPU from being representative for blowing snow (Figure 3.6). Would have been better to locate RPU on west side of road—prevailing wind direction at this location is 325° (Tabler 1997). Wind vane orientation is 11° off (Table 3.1). Southern-most pavement sensor is much farther away from RPU than was necessary (652 m), and should be better marked.

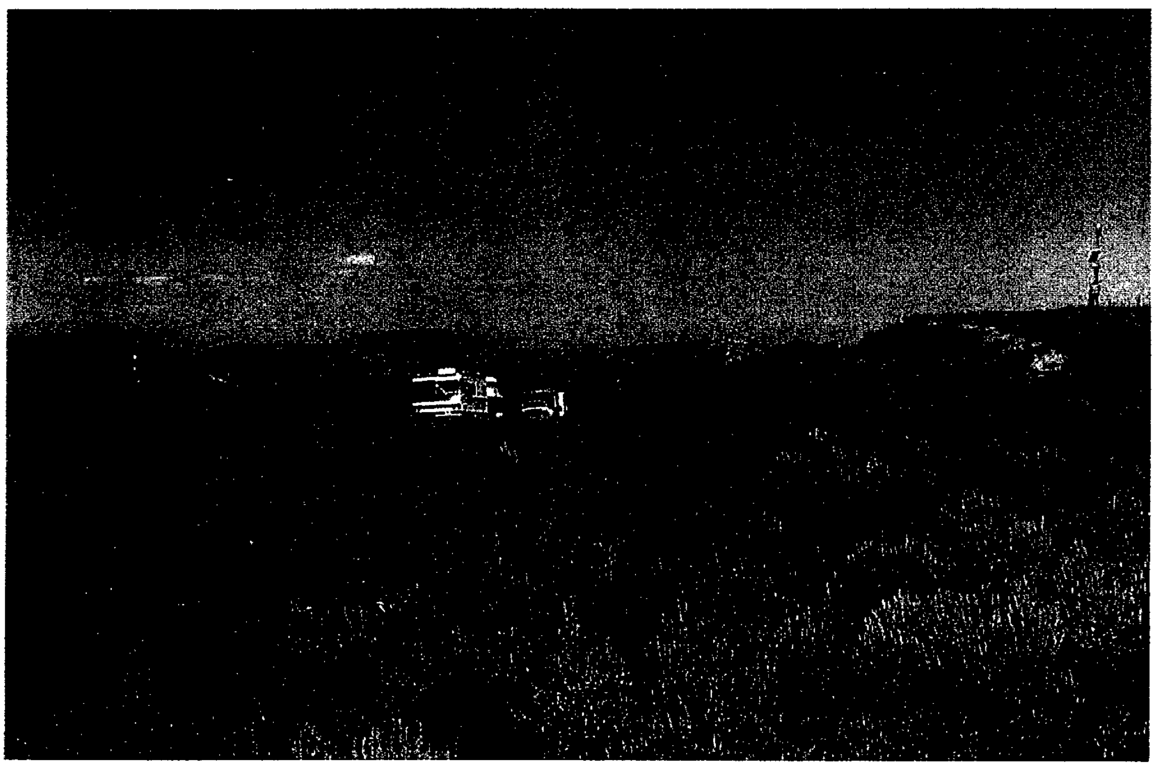

Figure 3.6. Meeteetse Rim site, looking north. Snow deposition in cut would significantly reduce blowing snow at tower when winds were westerly (from left) (8/13/98).

Hiland (RPU #6 = HIL)(US 20/26 Mile 57.42)

Would have been good site except RPU is downwind of 2.4-m-tall snow fence through arc of 270° to 310°. Prevailing wind direction in this location is 235° (Tabler 1997) so limitation not fatal, but still undesirable. Western-most pavement sensor is out of fence effect, but could have been 150 m from RPU instead of the 584 m it is now and still have met that condition. Eastern-most sensor is behind snow fence—undesirable. Could improve exposure by moving tower to east. Sensors are well-marked (Figure 3.4), but additional buried cable signs desirable.

Pathfinder Hill (RPU #7 = PAT)(WY 220 Mile 79.93)

General location good, but on north side of road at 2.5-m fill (Figure 3.7). A perfect site exists about 100 m east, illustrating poor judgment in site selection. Mast is far enough off road that road cross-section probably has only minor effect on wind, but deposition on north side of fill would reduce snow arriving at site and affect vertical distribution of blowing snow, and thus visibility. East pavement sensor is installed about 5 mm above road surface (Figure 3.8). Sensor to west needs encapsulation repair, and is too close to turnout where more braking would be expected to occur. Sensors are adequately marked with posts and reflectors!

Figure 3.7. Pathfinder Hill RPU looking east. Note tower location relative to road elevation (8/15/98).

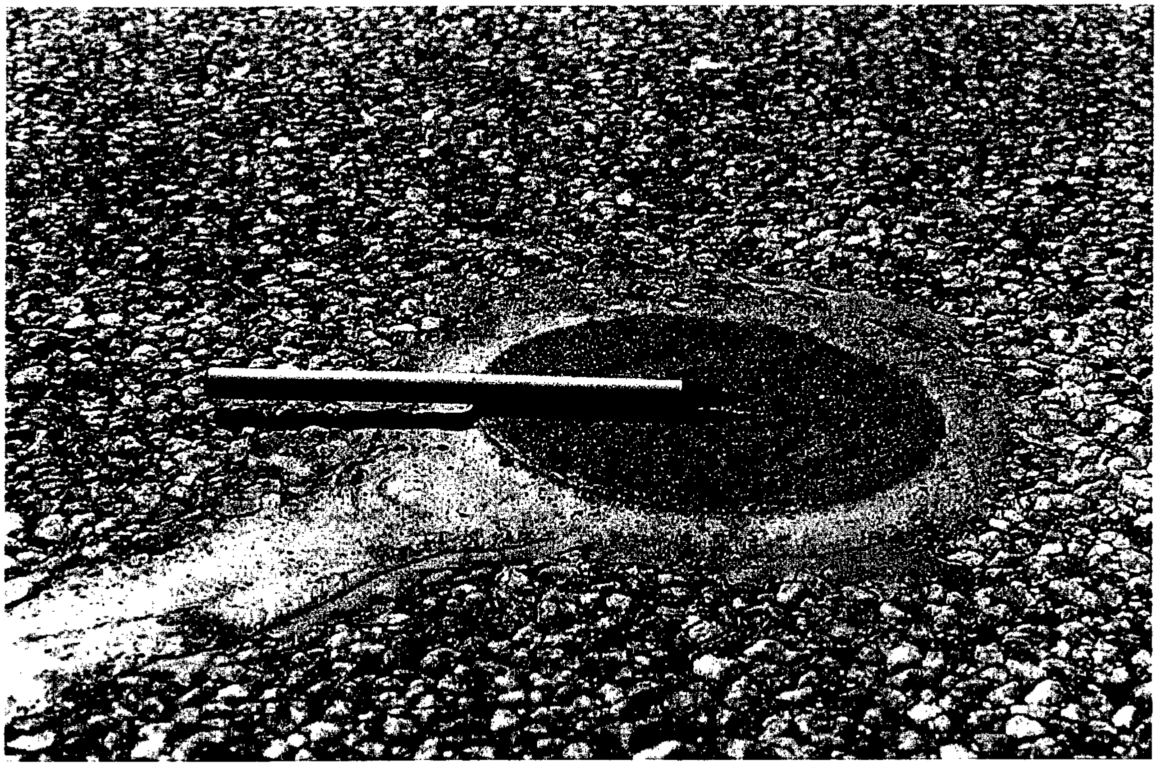

Figure 3.8. East pavement sensor at Pathfinder Hill protrudes above road surface (8/15/98).

Twenty Mile Hill (RPU # 8 = 20M)(I-25 Mile 207.18)

Fairly good site were it not downwind of 3.8-m-tall snow fences. Only open corridor is 300° to 330°, and prevailing wind at this location is 230°(Tabler 1997). Fences will have affect on road surface conditions and visibility, so data from RPU will not always be representative of other nearby locations. Only one sensor location marked. Would not recommend adding a visibility sensor because of snow fences, unless RPU is moved.

I-25 Divide (RPU #9 = I25)(I-25 Mile 267.32)

Well-sited for all parameters, except pavement sensors are much farther from RPU than necessary. No snow fence interference, so good candidate for visibility instrument. Only one pavement sensor located. Other may not yet have been replaced after resurfacing or sealing, because other sensor has been replaced recently. Wind vane error = 10°.

Piney Creek (RPU #10 = PCR)(I-90 Mile 43.66)

RPU on east side of road at cut. This is downwind side for most storms—prevailing wind direction = 330°. Relatively little blowing snow at RPU because of cut and snow fences on west side of road limiting fetch (Figure 3.9). Poor site for visibility monitoring. Pavement sensor locations not marked, and very few buried cable markers.

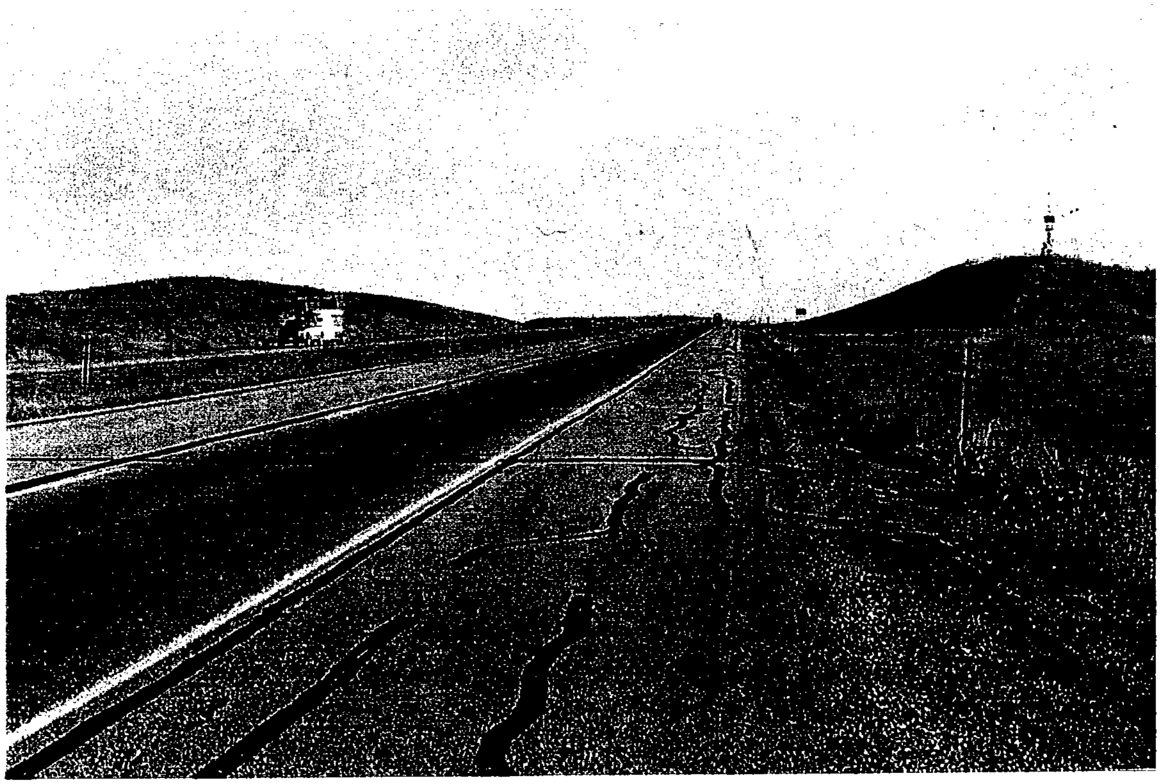

Figure 3.9. Piney Creek site, looking north (8/14/98).

Dead Horse (RPU #11 = DHS) (I-90 Mile 91.53)

Location not representative of problem locations with respect to snowfall or road surface conditions because of topographic position and surrounding vegetation—location is in rolling hills in valley, but problem areas are in upland areas with lower-growing vegetation. Site is fair with respect to exposure, however, and would be candidate for visibility monitoring. Anemometer receives interference from precipitation detector with SSE winds. Best alternate site is near Mile 82.5. Although AC power not available there, it would be location of choice pending further review. Wind vane error = 7°.

Inyan Kara (RPU #12 = INY)(I-90 Mile 170.51)

Main siting deficiency is that topography reduces fetch distance for blowing snow to 500 m north through west. One of the pavement sensors is in a depression, so surface conditions will not always be representative. Encapsulation repairs required.

Belle Fourche (RPU #13 = BLF)(WY 59 Mile 86.99)

According to maintenance personnel, site is not representative of troublesome locations farther north. RPU is not suitable for visibility instrument because it is downwind of concrete "Jersey" barrier (Figure 3.10), and fetch for northerly winds is reduced by stream bank and associated vegetation. Better site for RPU would have been about 300 m south, where AC power is also available. Maintenance personnel suggest relocating to vicinity of Reno Junction. Pine Tree Junction (WY 387/WY 50) also good choice. Could not locate pavement sensor in driving lane—presumed to have been buried under resurfacing. There are no location markers for sensors or cables.

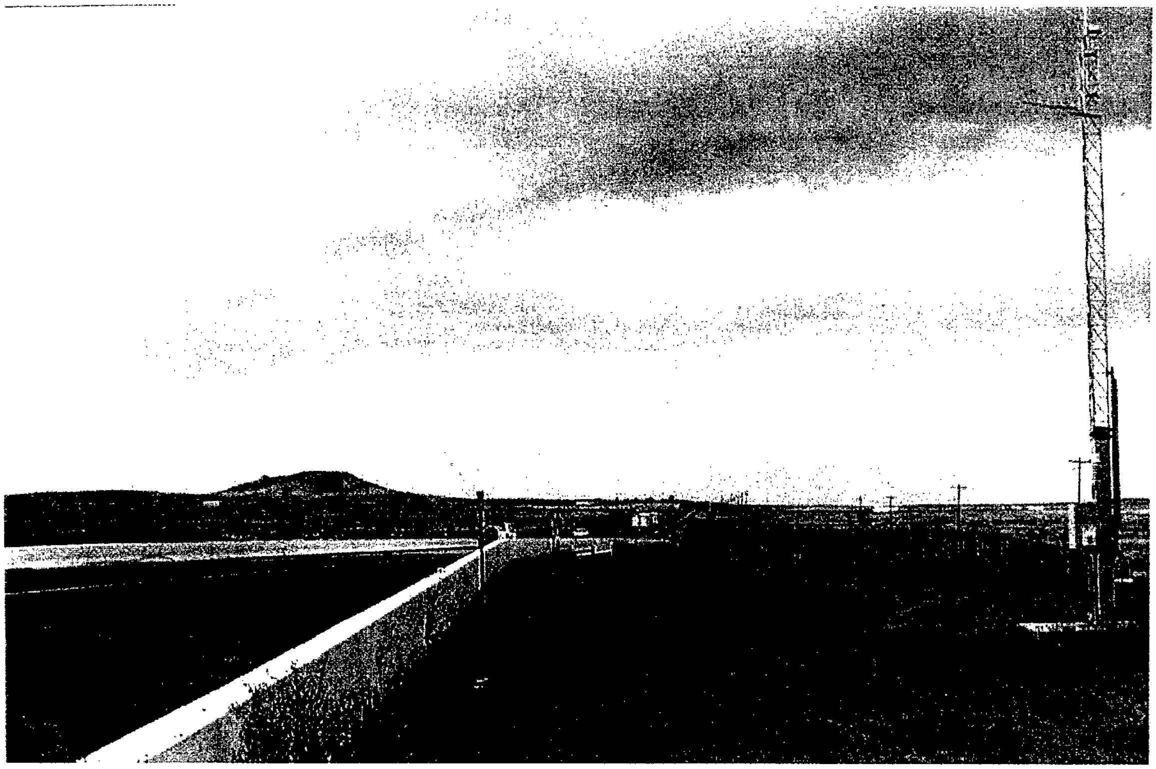

Figure 3.10. Belle Fourche RPU, looking north. Concrete barrier obstructs blowing snow in direction of prevailing wind (8/14/98).

Pumpkin Vine (RPU #14 = PKV)(US287 Mile 420.36)

RPU is downwind of snow fences from 295° through 320° (approximately), and receives some shelter from trees, rock formations, and topography. Prevailing wind direction at this location is 285° (Tabler 1997). Therefore not representative of locations where conditions are most severe, south of Mile 421. Alternate sites do not have AC, but this need not be overriding consideration. Additional study will be required to select optimal site. Suggest moving WIVIS back to Vedauwoo. Wind vane alignment 11° in error (Table 3.1)—should be adjusted to ± 5°.

Vedauwoo (RPU #15 = VDW)(I-80 Mile 329.37)

Not representative of worst conditions because site is downwind of snow fences except for wind directions of 220° to 290°. Prevailing wind direction at this location is 275° (Tabler 1997). Visibility data would be more representative if RPU (or visibility sensor) were moved slightly—good locations in vicinity of Mile 329.7. Other possibilities for relocation include 326.4, 327.7, 330.3, 330.6, and 330.95. AC power is highly advisable because of importance of visibility instrument, and recommendation for testing video here. Serious deliberation should precede selection of alternative location. Even without moving, suggest adding visibility sensor and precipitation gauge because of weather conditions and critical location. WIVIS at Pumpkin Vine should be moved back to this location. Wind vane should be adjusted--presently 13° error (Table 3.1).

Whitaker (RPU #16 = WHT)(I-25 Mile 28.12)

Excellent site for all parameters. Pavement sensor in south-bound lane that had been partially covered with crack sealant in February 1998 (Figure 3.3) had been replaced by August 1998. Could not locate third pavement sensor, presumably in north-bound lane. No marking of sensor or cable locations caused much wasted time in needless searching.

Sibley Peak (RPU#17 = SIB)(I-25 Mile 107.62)

RPU is at top of deep cut, but on upwind side. Scattered trees and irregular terrain reduce blowing snow at this location, but sufficient fetch to warrant visibility sensor. Good location for wind monitoring. Pavement sensors are reasonably placed to be representative of conditions on grade, but not representative of exposed locations farther south. North sensor requires encapsulation repair. Pavement sensor locations unmarked, except for paint on road surface. Inadequate buried cable markers. Note: There is a good RPU site with AC at Mile 98.7.

First Divide (RPU #18)(I-80 Mile 13.88)

Site fair for wind, poor for visibility because prevailing direction of blowing snow is 250° at this location (Tabler 1997), and the road alignment west of the RPU is approximately 237°. Therefore, road cross-section and snow fences on north side of road significantly reduce blowing snow arriving at RPU. Better site would have been on north side of road. Sensor on bridge deck is only a meter or so from abutment—too close to be representative of mid-span. Visibility instrument would not be recommended at this location, but precipitation gauge at this location would be useful.

Cemetery Separation (RPU #19 = GRV)(I-80 Mile 90.65)

According to maintenance personnel, location is not representative of wind, precipitation, or surface condition. Appears to have good exposure for wind directions 80° to 295°, but topographic interference 295° through 360°. Blowing snow limited by development and topography in all directions. Original location on Peru Hill better unless tunnel pavement sensor is essential. Otherwise, candidate site with AC power is Mile 82.7 west of WY 372. Additional study required to evaluate options. Third pavement sensor at bridge approach not observed because only two were shown on tabulation provided by WYDOT. Had sensor locations been marked, this oversight would not have occurred. Pavement sensor located 20 m inside tunnel portal not observed close-up because of heavy traffic.

Deer Creek (RPU #20 = DCK)(I-25 Mile 164.25)

Location acceptable, with blowing snow fetch limited to 1000 m through arc 235° clockwise to about 15°. Site good for wind. Pavement sensor locations and buried cables unmarked, making search extremely time consuming. Sensor west of RPU would require encapsulation repair, but road is under construction so sensors will be replaced. Why is there no sensor on bridge east of RPU? Seems like this was a reason for selecting this location. Precipitation detector (ETI) has been replaced within last year or so, making this is the only late model detector in Wyoming's system.

Bordeaux (RPU #21 = BCX)(I-25 Mile 70.86)

RPU on top of deep cut on upwind side of road. Some effect of surrounding terrain on wind direction and speed (average direction 325°), but relatively trivial. Pavement sensor north of RPU needs encapsulation repair. Could not locate second pavement sensor despite an hour of searching, because again locations unmarked. Also total lack of buried cable markers to help in search. Pavement conditions may not always be representative of exposed locations. Site acceptable, but not optimal, for visibility sensor. Why is there no pavement sensor on bridge? Pavement sensor requires encapsulation repair (Figure 2.10).

South Dakota / Wyoming shared site (SD #7, US 85 Mile 2.4)

Site is surrounded by forest, so it is not representative of conditions on Wyoming side of line (Figure 3.11). Mast is too short and too close to road, so instruments are subject to traffic and plow cast. Anemometer is 3.0 m above bare ground, so recorded wind speed is about 85% of what would be registered at height of typical WYDOT towers. Visibility indication would be of little value (note WIVIS), but precipitation rate and road surface conditions might be useful. WYDOT personnel complain that data are unavailable and or inaccessible. This site should be replaced with one near Four Corners, at location where AC power is available. Numerous options exist, but more study is required for selection.

Sage Junction (Vaisala RPU #1, US 30 Mile 34.21)

A prime example of poor site selection. RPU is behind hill located about 30-50 m away that obstructs wind (and blowing snow) from 315° clockwise to 55° or so (Figure 3.12). Site is also located in area of tall sagebrush and irregular topography that combine to reduce blowing snow at site compared to locations west of here. Base of tower is about 2 m below road surface. Pavement sensor locations not adequately marked. Cracks around pavement sensors should be sealed. Wind vane is 10° off—needs to be adjusted. A much better location, also with AC power, is only 0.16 miles to west, and another is at Mile 33.21. Another example of poor siting.

Figure 3.11. SD/WY shared RPU on US85 north of Four Corners, looking west from road. Surrounding trees and insufficient anemometer height are primary deficiencies (11/4/97).

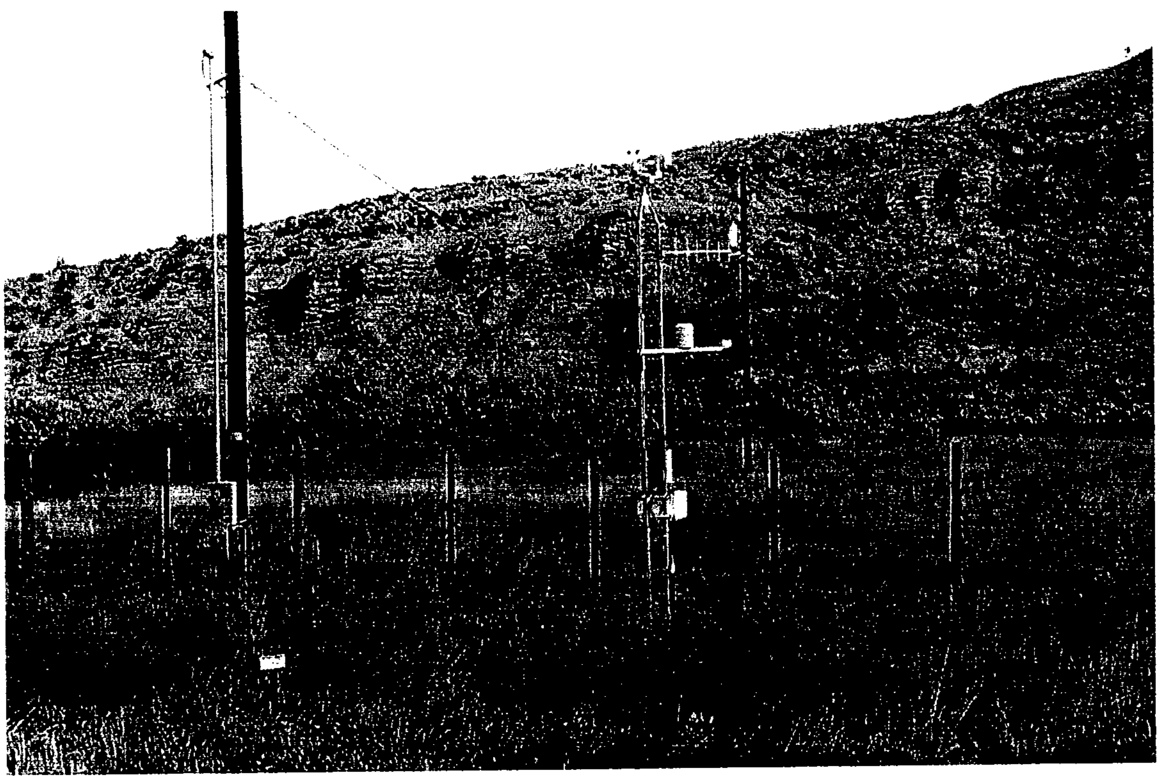

Figure 3.12. Sage Junction RPU, looking north (8/12/98).

Rim (Vaisala RPU #2, US 191 Mile 127.00)

Base of tower is about 1 m below road, but not significant. Generally a good site for all parameters, although fetch is limited by trees to the east. Site is suitable for a visibility sensor. Pavement sensor locations marked. The sensor at RPU is in bad need of encapsulation repairs.

Skyline (Vaisala RPU #3, WY 230 Mile 113.46)

This is a good site for all parameters. Although there are 3.8-m-tall snow fences located 142° to 172° from site, drifting from this direction would occur only rarely. The "Present Weather" detector is on a separate support mast 3.7 m southeast of the tower, with the result that the RPU enclosure would interfere with blowing snow when winds were from 315° or so. Prevailing wind direction at site is approximately 270° (Tabler 1997, Appendix B). Pavement sensors recessed about 5 mm as result of chip sealing, but unavoidable (Figure 3.13).

Figure 3.13. Pavement sensor at Skyline RPU showing depression formed by chip sealing (8/11/98).

Gun Barrel (Vaisala RPU #4, US 85 Mile 46.80)

This would be an excellent site for all parameters, were it not for a 3.8-m-tall snow fence from 345° clockwise to 30° or so (Figure 3.14). Prevailing wind direction here is 295°, so effect of fence is mostly during upslope snowstorms with northerly winds. If a visibility sensor is installed here, it should be offset to the south to reduce the fence effect; Alternatively, the RPU could be moved a hundred meters or more to the south. This site is solar powered, although AC is nearby—why? Pavement sensors unmarked and difficult to locate, as usual, and no buried cable markers. The sensor south of the RPU is chipped and requires encapsulation repairs and operations check. Seems like a sensor on the grade just north of the site would warrant a sensor—why is one not there?

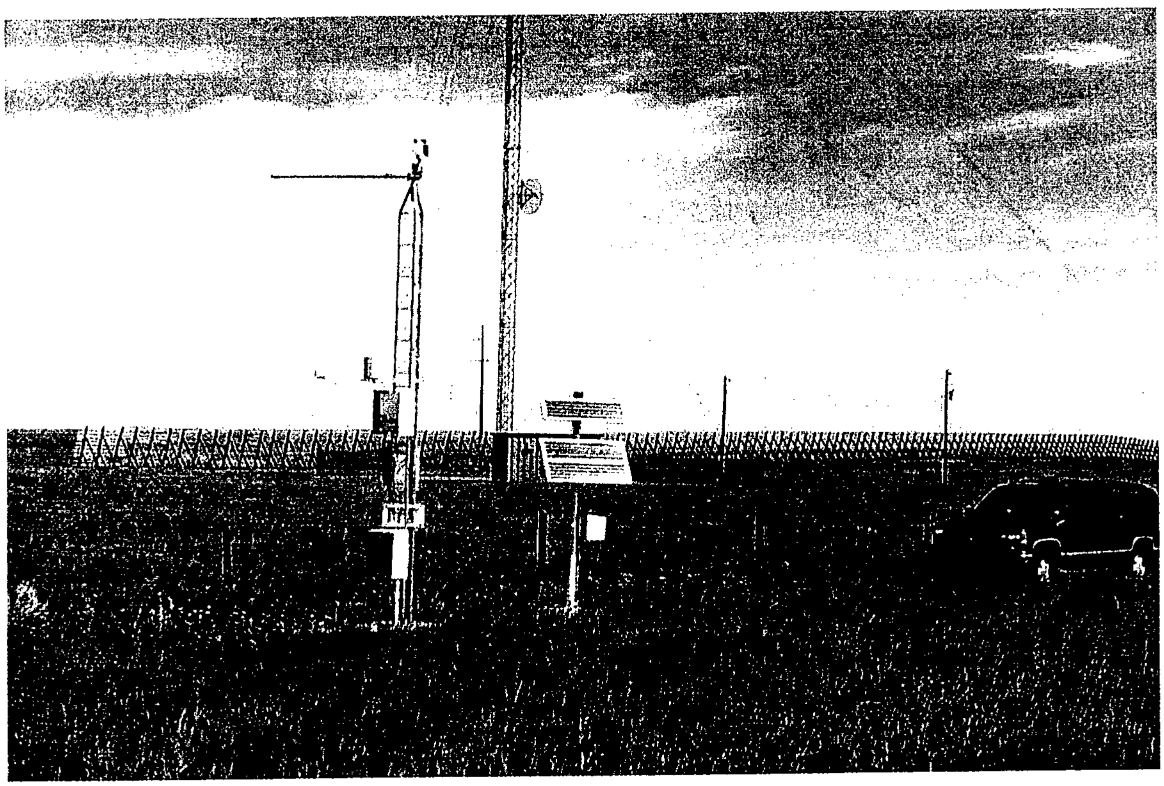

Figure 3.14. Gun Barrel RPU, looking northwest (8/16/98).

Chief Joseph (Vaisala RPU #5, WY 296 Mile 32.66)

According to WYDOT personnel, this RPU is not presently useful because of contracted snow/ice control. Desirability of moving, however, depends on future plans for winter maintenance. Present location is poor for monitoring visibility in blowing snow because of limited fetch in all directions except from east. Blowing snow arriving at tower from east, however, is also reduced by a snow deposition area. Although tower barely protrudes above trees, this site is highly vulnerable to lightning strikes, which should have ruled out location in the first place. Location is suboptimal for wind measurement because of obstruction by 5- to 6-m-tall trees in some directions (Figure 3.15). This would be a good site for a precipitation gauge, as discussed in Section 4. Maintenance personnel have suggested moving to vicinity of Mile110 on WY 120. Mile 109.9 appears to be an excellent site with AC power.

Figure 3.15. Looking north toward Chief Joseph RPU (8/13/98).

Shute Creek (Vaisala #6, WY 372 Mile 34.00)

Very good site for all parameters, including visibility. Only problem here is orientation of wind vane—off true north by 28° (Table 3.1). Only pavement sensors located were at RPU.

4. CONCLUSIONS AND RECOMMENDATIONS

The Wyoming Road Weather Information System will facilitate and improve maintenance operations, and enhance safety and convenience of highway travel, if certain critical improvements are made. If the system is maintained without these improvements, benefits will be marginal and continued operation will probably not be cost effective. One important use of RWIS data and associated forecasts is for ice control practices such as chemical anti-icing. If this type of maintenance practice is to be used successfully in Wyoming, RWIS data and forecasts will be essential. Although the improvements suggested here will require substantial capital investment, strategic prioritizing and scheduling should help to make them affordable. Other states that have made this investment such as Colorado, Iowa, Minnesota, and Montana, believe that it has been worthwhile.

Because of the rapidly changing RWIS technology, many of the problems and recommended solutions in this report will be germane for only a few months. Some of the complaints and suggestions obtained from the questionnaire responses in 1997 have been addressed by vendors in their latest software revisions, or by changes in the telecommunications system. The evaluation of the RWIS system should therefore be an on-going task, with annual reviews to make adjustments in planning and implementation.

The conclusions and recommendations resulting from this study are listed below in *approximate* order of decreasing importance. Because two or more items may be equally important, however, numbering is only for reference and does not imply an absolute ranking.

1. One of the first steps is to commit to upgrading the communications system for better reliability and faster data transfer rates. This recommendation is basic to the RWIS system upgrade, because the communications structure must be known before preparing specifications for a Request for Proposals (RFP) to upgrade the RWIS. This would require converting the Department's microwave communications system, and the 450 MHz radio links used to communicate with the RPUs, from analog to digital—an improvement having benefits reaching far beyond the RWIS system. Polling time for the existing RPU sites presently requires 15 to 20 minutes, and the addition of sites and/or instrumentation will increase polling times proportionately. For comparison, the Nevada DOT specifies a capability for polling at 2- to 3-minute intervals. The present 300 baud rate limits the future use of video cameras at RPU sites, and this enhancement seems inevitable in the future. In addition to facilitating video and allowing more frequent polling, a digital network would improve system reliability by reducing analog-to-digital interfacing equipment, and could simplify integrating the SSI and Vaisala systems. According to WYDOT's telecommunications personnel, there is a general need to upgrade to a digital microwave system to provide greater bandwidth, replace aging equipment, respond to FCC decisions, and increase interoperability requirements of users.

2. The incompatibility of the SSI and Vaisala systems is a major deficiency in the Wyoming RWIS, and the resolution of this problem should receive highest priority after the communications system upgrade has been decided. Data from all RPUs in both systems

should be integrated to facilitate access and review, and this can best be accomplished as part of an RFP that includes other critical needs for upgrading the RWIS system. Specifications should include forward and backward compatibility with the National Transportation Communications for Intelligent Transportation Systems Protocol for Environmental Stations (NTCIP-ESS), and Year 2000 (Y2K) compliance. The current DOS-based software for both the Vaisala IceCast and SSI SCAN systems is outdated, mutually incompatible, cumbersome, and is not believed to be Y2K compliant. The RFP for integrating the Vaisala and SSI systems would logically include Windows-based software and associated hardware as required for a general system upgrade, allowing improved graphic displays of current RPU data to make the data easier to read and interpret. Graphs showing how selected weather and pavement conditions have changed with time over the last 8 hours or so, and statewide (or regional) maps displaying current weather conditions, would facilitate cognition of trends important for crew and equipment scheduling and dispatching.

One software interface that is being used by a number of states, including Montana and Colorado, is SCAN Web, an SSI product that runs on a SCAN server running Microsoft Windows NT 4.0 and Microsoft Internet Information Server. SCAN Web allows the RWIS data to be accessed from a World Wide Web address using a browser such as Netscape Navigator or Microsoft Internet Explorer. Detailed information is available at http://surface.com/SCANWeb, and Montana's SCANWeb site can be viewed at http://www.mdt.mt.gov/maintenance. One apparent disadvantage of this approach is that reviewing data from a number of RPUs is time consuming, especially when historical data and graphs are being accessed. Also, utilization of the Internet requires all users to be "computer-friendly", which certainly is not the case at present. More importantly, however, a centralized system's vulnerability to crashes during periods of heavy demand requires redundancy, such as installing a server in each district in addition to the central server in Cheyenne.

Suggestions for RWIS RFPs are given by Boselly, Doore and Ernst (1993), but recent examples are provided by RFPs issued by Minnesota and Nevada, copies of which the author has transmitted to WYDOT Telecommunications separately from this report.

3. WYDOT should actively participate in the annual "Multistate RWIS Users Workshop," attended by the author in 1997, and by Kenneth Shultz (WYDOT) in 1998. This is an excellent forum for exchanging information, sharing experience, and keeping abreast of the rapidly changing RWIS technology.

4. The utility of RWIS will be enhanced with the addition of supplementary weather information such as current radar and satellite images, detailed synoptic weather maps, and maps showing regional temperatures, winds, and precipitation. The demand for supplementary weather information was confirmed in the Iowa study, that indicated that information on weather radar, satellite images, and forecasts on TV and radio were considered to be more useful than current RWIS data or RWIS vendor forecasts. Because it would be most convenient if the weather service were integrated with the RWIS system, the RFP for upgrading the Wyoming RWIS should include this item; however, there are independent weather services available. One example is DTN (Data Transmission Network),

a company specializing in satellite delivery of time-sensitive information. Subscribers pay a flat monthly fee (currently $76), in addition to a one-time "set-up" charge ($367) to receive the basic "Weather Center Service." All equipment (satellite dish, receiver, and 35-cm video monitor) is provided by DTN under lease, the cost of which is included in the monthly fee. The Iowa DOT transmits RPU data and SCAN*Cast information via DTN, including a state-wide map showing surface temperatures and precipitation at each RPU (Figure 4.1). Advantages of the DTN service include full-time immediate access to RWIS data as well as weather information, elimination of communications problems, simple operation, and ready acceptance by maintenance personnel. The Iowa survey (Takle et al. 1997) showed 92% of respondents were "comfortable" or "very comfortable" with using the DTN in their garage, compared to 62% who reported the same comfort levels using a computer. Iowa DOT currently has a DTN unit in every maintenance garage (131), in addition to 38 units in rest areas.

Weather information must be made directly available to maintenance personnel as opposed to having dispatchers relay the information by radio—descriptions of radar, satellite and forecast weather maps cannot replace seeing the images first-hand. It is also essential that personnel be trained in the interpretation and use of radar and satellite imagery if the information is to be used to best advantage.

5. The way in which RPU and weather data are made available to field maintenance personnel must be improved, and this is linked to the hardware and software selected for the system upgrade. Ideally, RPU reports should be displayed continuously in every maintenance shop on a dedicated computer. DTN is one method of accomplishing this, although satellite data transmission is relatively costly. DTN presently charges $720 per month per graphic containing up to three parameters, such as a state map showing the latest air temperature, pavement temperature, and snowfall rate (Figure 4.1), updated hourly. Text files cost $125 per month per page. Additional fees are charged by the RWIS vendor (such as SSI) for polling the CPUs, quality-checking the data, and transmitting the data string to DTN. There are presently three states transmitting RWIS data via DTN: Iowa, Maryland, and Wisconsin, and tests are underway in two others (Illinois and Rhode Island).

   Based on personal observation and the experience in Iowa, it is recommended that DTN be evaluated as a medium for RWIS information by testing units in at least 10 shops for two years, and arranging for RPU data to be transmitted with 30-minute updates.

   Although a computer is not as readily endorsed by maintenance workers as is the DTN terminal, dial-up access to a WYDOT server, or directly to the Internet, could be satisfactory alternatives to satellite delivery if a computer were made available to all personnel at a convenient location in every shop, an adequate training program were implemented, and the server were relatively crash-proof. Supplementary weather information can be provided by the RWIS vendor, or obtained from the Internet. Disadvantages of accessing weather information directly from the Internet include information not always being as current as it needs to be, and "looping" satellite and radar images taking an excessive downloading time. This problem can only be remedied by having weather information continuously updated by a WYDOT network server so that it can be made readily available upon request.

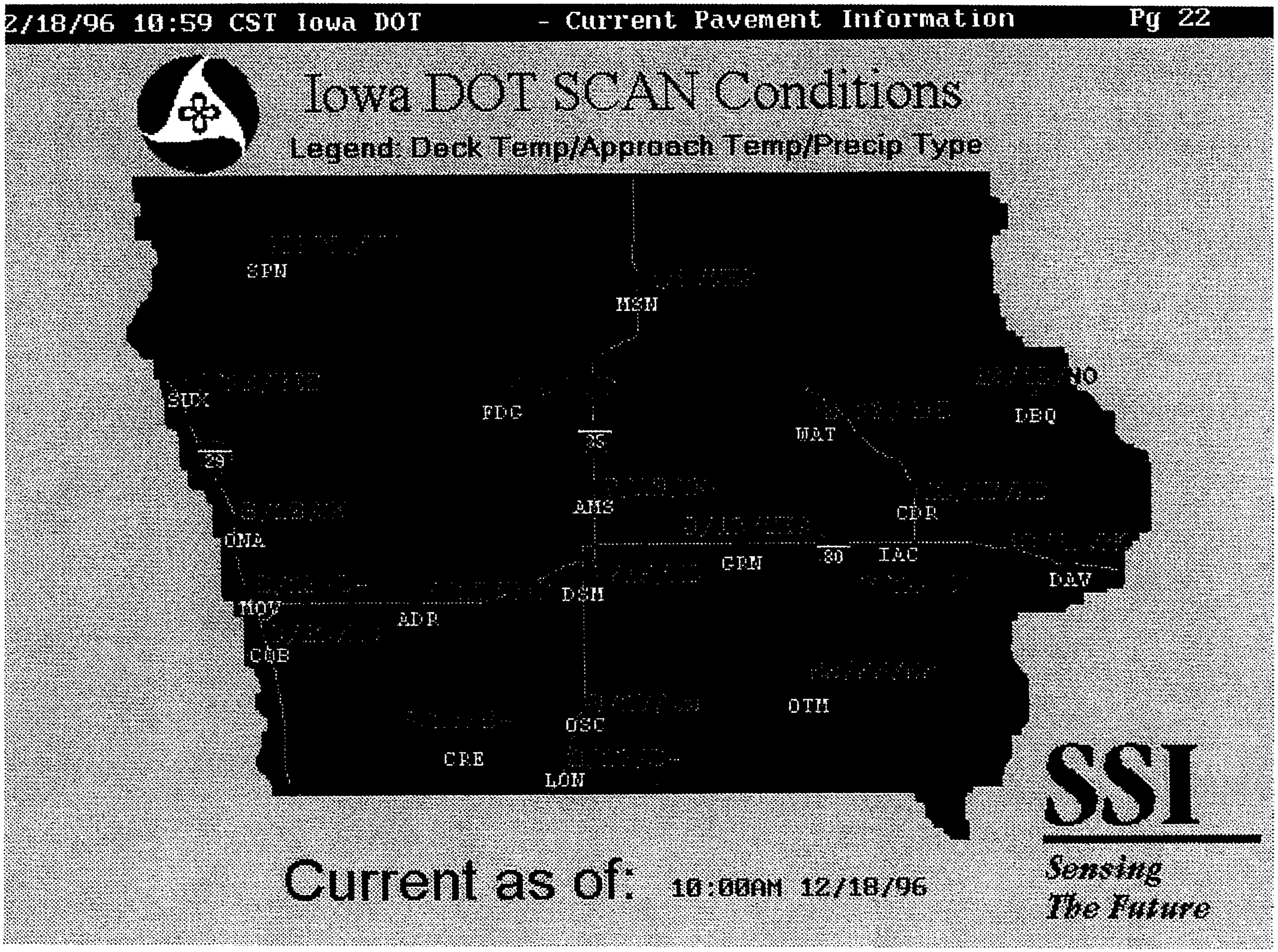

Figure 4.1. Iowa RPU data display on DTN.

6. Current data from selected RPUs in adjacent states (preferably all, but Colorado, Montana, Nebraska, and South Dakota most important) should be made readily available by including these data in the same displays used for the Wyoming data, and this integration should be specified in the RFP. Information from some sites in adjacent states can also serve as indicators for advancing storms. Contacts for adjacent states are:

Colorado:	Wayne Lupton	(970)-385-1651
Idaho:	Bryon Breen	(208)-334-8417
Montana:	James R. Stevenson	(406)-444-7201
Nebraska:	Dalyce Ronnau	(402)-471-4567
South Dakota:	Steve Ulvested	(605)-773-3704
Utah:	Bill Gooch	(801) 399-5921

7. The RFP for upgrading the RWIS system should specify provisions for third-party forecast services so that any weather service selected by WYDOT could have unrestricted access to all RPU data, and could be provided with the SCAN*CAST or Vaisala software and other information required for making pavement temperature forecasts. As specified in the recent RFP by the Nevada DOT:

   "The system shall contain software that has the capability of forecasting pavement surface temperature, pavement frost potential, and pavement ice potential. This forecasting system shall be capable of producing site specific forecasts for each RPU site in the system, and shall be capable of displaying the forecast information in graphical and textual formats...

   "An outside, independent weather forecasting service ... will be producing and in-putting the forecast information into the forecasting module supplied by the [vendor] and will be responsible for the operation of the software prediction model and for the transmission of the final forecast products to the ... users. The forecasting software supplied by the [vendor] shall fully provide for such an arrangement[.]"

8. Annual preventive maintenance of RWIS weather stations by vendors should be reviewed in the field to determine changes and additions that should be made in specifications and RFPs for vendor maintenance. Specifications for annual preventive maintenance / calibration checks should include the following:

   a) Annual substitution of rebuilt anemometer/wind vane (as necessary for annual bearing replacement / cleaning / lubrication / calibration)
   b) Optical precipitation detector sensitivity verification at threshold setting
   c) Wet pavement condition verification (pavement sensor)
   d) Percent chemical saturation in solution, check at 20% ± (pavement sensor)
   e) Surface temperature check: comparison with infrared sensor under shaded condition
   f) Relative humidity calibration at current ambient and 95-100%
   g) Wind vane alignment to True North ± 5°
   h) Visibility instrument calibration check

A WYDOT telecommunications technician should be present to verify service check. Service checks by WYDOT personnel should be performed throughout the year, and standardized procedures need to be developed for this purpose. The wind vane alignment errors (Table 3) and deteriorated condition of pavement sensor encapsulation are indications that maintenance by WYDOT personnel can be improved.

To a close approximation, current magnetic declination in Wyoming is given by (Tabler 1997):

$$\text{Declination} = -49.554 + 0.2136(\text{Latitude}) + 0.4935(\text{Longitude}) \quad (4)$$

where *Declination* is the angle in degrees between true north and magnetic north (magnetic north being east of true north), and *Latitude* and *Longitude* of the site are in degrees north and west, respectively. This equation can be used to check and set the alignment of wind vanes for true north.

9. Measures should be implemented to protect pavement sensors from contamination during pavement maintenance operations. Sensor locations should be conspicuously marked with paint in advance of sealing operations, taking care not to get paint directly on the sensors. Sealing contracts should include a penalty clause to recover costs of replacing damaged instruments, and there should be similar economic incentives for supervisors of WYDOT sealing crews.

10. Move existing WIVIS weather identifier/visibility instrument back to Vedauwoo where it can be used to better advantage.

11. Discontinue use of the South Dakota / Wyoming shared RPU. It is surrounded by trees, wind instrumentation is too close to the ground, ond overall conditions are unrepresentative of the adjacent road section in Wyoming. RPU should be replaced with one near Four Corners. Several suitable sites are possible, some with AC power.

12. Existing RPU sites that should be moved include the following, in approximate order of priority:

    Dead Horse (RPU #11 = DHS) (I-90 Mile 91.53): Location not representative with respect to snowfall, wind or road surface conditions. Suggested moving to vicinity of Mile 82.0, although no AC power available.

    Cemetery Separation (RPU #19 = GRV)(I-80 Mile 90.65): According to maintenance personnel interviewed, location is not representative of wind, precipitation, or surface condition. Suggest moving it back to Peru Hill where it was originally. There appears to be a good site at Mile 82.7.

Belle Fourche (RPU #13 = BLF)(WY 59 Mile 86.99): Not representative of troublesome locations. Not suitable for visibility instrument because RPU is downwind of concrete "Jersey" barrier and blowing snow from northwest to northeast is reduced by river bank. Move to vicinity of Reno Junction vicinity. In addition to locations on WY 59, suitable sites exist on WY 387: Mile 148.0, 145.6, 127.9, 126.9, 125. 6, and 125.3.

Vedauwoo (RPU #15 = VDW)(I-80 Mile 329.37): Not representative of worst conditions because site is downwind of snow fences for some wind directions. This also limits utility of visibility instrument. Several options: Move to vicinity of Mile 329.72, 327.7, 330.29, 330.64, or ?. Suggest more study and deliberation before moving.

Arlington (RPU #1 = ARL)(I-80 Mile 272.13): Not representative with respect to wind or visibility. Site is partially sheltered by snow fences and trees to west, and Rock Creek Ridge to the north. Selection of alternative location merits further study, but best location may be in vicinity of unfenced area near Mile 278. Other options include Foote Creek vicinity, Cooper Hill, or near Mile 276. Selection warrants careful study in consultation with Arlington Maintenance Foreman.

Sage Junction (Vaisala RPU #1 = SAG)(US 30 Mile 34.21): Unrepresentative location, and proximity of hill blocks northerly winds. Move to Mile 34.046 or 33.21 (both have AC power available).

Pumpkin Vine (RPU #14 = PKV)(US287 Mile 420.36): RPU is downwind of snow fences, and receives some shelter from trees, rock formations, and topography. Therefore not representative of locations where conditions are most severe. Most representative sites lack AC power, but this may be unavoidable. Site selection deserves careful study.

Gun Barrel (Vaisala RPU #4 = GBR)(US 85 Mile 46.80): RPU affected by snow fence for northwesterly wind directions. Move RPU south 100 meters or so after careful review.

Sibley Peak (RPU #17)(I-25 Mile 107.62): Reasonable location for pavement sensors, but RPU is not in a location representative of open country to south with more blowing snow problems. If maintenance personnel agree, evaluate alternative sites such as Mile 98.7 (AC power available).

Chief Joseph (RPU #5)(WY 296 Mile 33): Although information from this site is apparently not useful for contract snow removal operations, desirability of moving depends on future plans for maintenance. Although better locations exist east of Dead Indian Summit, where visibility sensor could be used to detect blowing snow, and RPU would be less susceptible to lightning damage, AC power is not available, and radio communications are uncertain. If RPU were relocated to WY 120, a good location with AC power is at Mile 109.9.

13. Snowfall intensity, rate, and accumulation are among the most important weather parameters for winter maintenance and traffic operations decisions. Unfortunately, there is both theoretical and empirical evidence that optical instruments such as the WIVIS, OWI, and LEDWI manufactured by ScTI, Vaisala's PWD11 Present Weather Detector, and similar instruments offered by other manufacturers, do not provide sufficient accuracy to warrant their continued use for this purpose, and the same is true of the capacitance-based DRD11A offered by Vaisala. It is therefore recommended that these devices not be used for precipitation rate measurements until independent research can validate the accuracy of measurements for a comprehensive range of temperature and wind conditions. Because of the potential utility of accurate, quantitative snowfall data, it is therefore recommended that collector-type precipitation gauges be added to Wyoming's RPUs on a trial basis. These gauges should have a minimum capacity of 300 mm (12 inches) water-equivalent, with analog or stepped output at increments of 0.25 mm water-equivalent (0.01 inch) or less, and real-time noise filtering to eliminate the effects of pressure variations caused by wind blowing across the collector orifice. Lag time between precipitation increment and signal output ideally should be 120 seconds or less. The gauges should be equipped with an Altar-type wind shield to reduce under-measurement caused by wind (Tabler et al. 1990), and a provision should be made to incorporate a wind correction algorithm into the RPU.

    One gauge meeting the proposed requirements is manufactured by ETI incorporated (970-484-9393), the same firm providing the optical precipitation detectors (OPD) for SSI systems (Figure 4.2). There may be an opportunity to use the full OPD analog signal by combining it with the output from the precipitation gauge. The unit cost of the ETI precipitation gauge is approximately $2,800. The only disadvantage of the ETI gauge is the lag time between snowfall and gauge response that can result from snow adhering to the inside of the collector tube. This problem is reduced with the Model T-200 gauge ($3,944) manufactured by Geonor (717-296-4884; http://www.geonor.com) because the collector tube is flared to a larger diameter (Figure 4.3). The Geonor gage is based on vibrating wire technology, capable of providing 0.0254 mm resolution, but also requiring a firm foundation. Although NCAR has experienced no significant wind-induced variance at their Marshall Field Site near Boulder, the gauge should be tested for a year in Wyoming to verify suitable performance under strong winds. Another suitable instrument is the Belfort Model 3200 precipitation gauge ($4,835), which also utilizes the flared design, vibrating force transducers, and a built-in microprocessor to filter transducer output. The Belfort gauge has a 0.2 mm resolution, and a 0.5 mm accuracy. The contact for information on this instrument is Steve Mang (410-342-2626) at the Belfort Instrument Company in Baltimore, Maryland. Personal communication with NCAR scientists (Jeff Cole and Charles Wade) indicate that there have been more transducer problems with the Belfort as compared to the Geonor or ETI instruments.

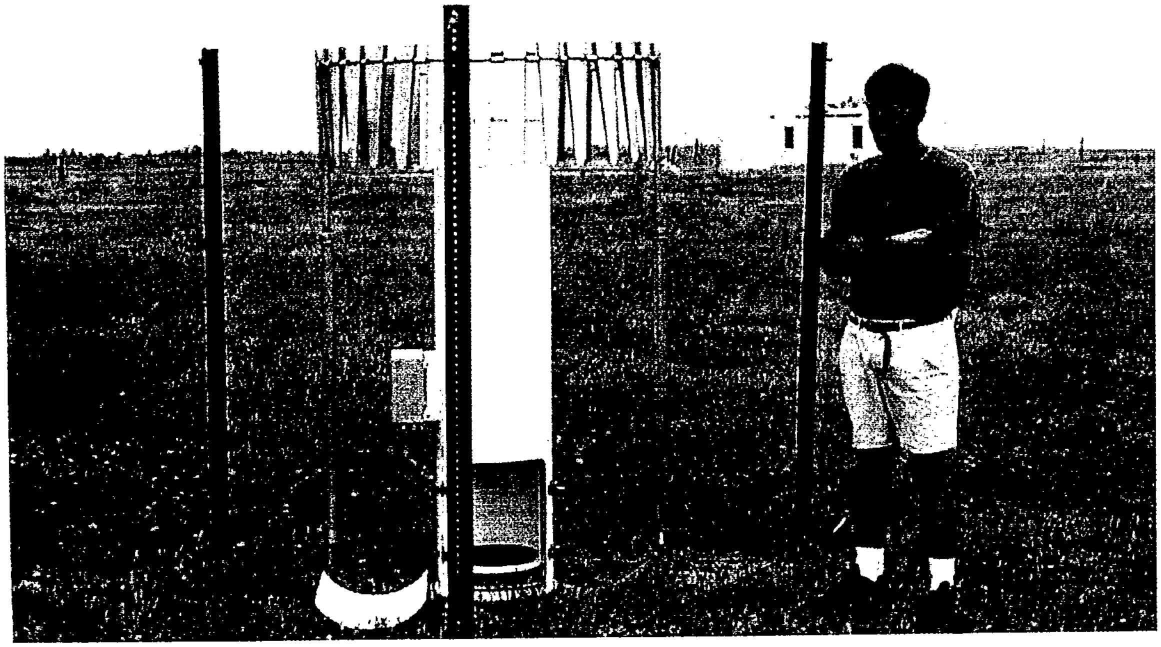

Figure 4.2. Precipitation gauge manufactured by ETI (NCAR Marshall test site near Boulder, Colorado; Jeff Cole in photo).

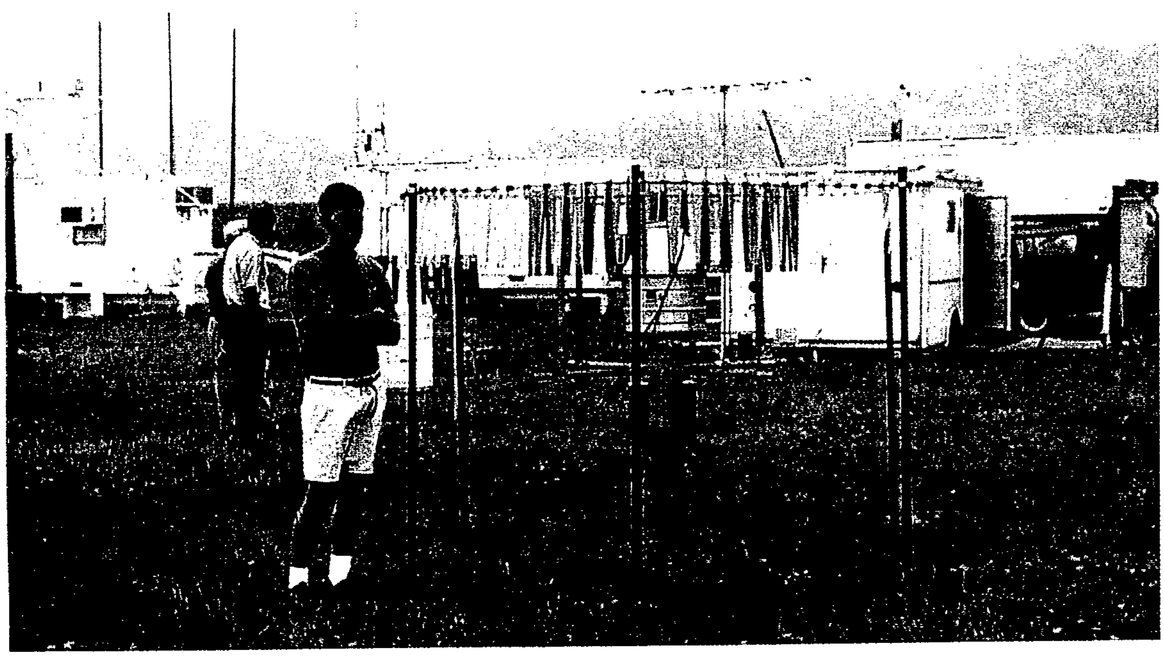

Figure 4.3. Geonor Model T-200 precipitation gauge (NCAR Marshall test site near Boulder, Colorado; Jeff Cole in photo).

14. Although visibility sensors would be a useful addition at many RPU locations, research is first needed to determine which sensor(s) are suitable for blowing snow, and what signal processing is required to make the output correspond to visibility as perceived by motorists. Current studies underway by NCAR (personal communication with Cole and Wade), NWS (personal communication with Lewis), and Idaho Department of Transportation (Shannon, Kite and Liang 1997) will not provide the validation and testing required for WYDOT's needs. Studies should be conducted in Wyoming under a study plan approved by WYDOT. Candidate sensors for testing include the ScTI WIVIS, Vaisala FD12 and PWD11, Belfort Models 6100 and 6210, and Handar Model 470. Although the WIVIS and Handar could be disqualified from consideration because of the horizontal beam alignment, orientation requirements, susceptibility to snow accumulation on lenses, and configuration of the housings, it can be argued that their limitations should be demonstrated by experimentation. Of the instruments listed, the Belfort Models 6100 and 6210, and the Vaisala, are downward-looking instruments that appear to be the best candidates for monitoring visibility in blowing snow conditions. Downward-looking sensors are preferable because this configuration minimizes the influence of the support arms, minimizes the sensitivity to orientation, and reduces the tendency for snow accumulation on optical surfaces.

    The initial objective of a visibility sensor test should be to determine which instrument(s) provides output best correlated with observer's visual range during daytime conditions, and the adjustment algorithm required to correct output for height of sensor above ground surface as a function of wind speed. A secondary objective should be to determine the visibility sampling statistic best correlated with vehicle speed as monitored concurrently near the study site. The visibility sensor study should involve NCAR (contact Charles G. Wade at 303-497-2807) and as many sensor vendors as possible. It is anticipated that many, if not all, of the visibility sensors could be provided by the manufacturers at no charge.

    In the absence of additional tests, and not taking costs into consideration, the instruments of choice would be the Belfort Model 6210 ($13,500) or Model 6100 ($9,500) with software modified to output values for mean (geometric) minimum visibility output at intervals of 5- to 10 seconds. Polling parameters should be the lowest such value observed, in addition to the geometric average of lowest values since the last polling (Tabler 1983).

    All visibility sensors on Wyoming RWIS sites should be installed at a single standard height such that the sampling volume is not blocked by the RPU enclosure, anti-climb panels, or other obstructions. This height will be between 2.0 and 2.6 meters above the surface, which is above 80% of the relocated blowing snow under most wind conditions (Tabler 1991). However, proper sampling and signal processing to adjust measurements to passenger car windshield level based on wind speed, should allow motorist visual range to be calculated for critical weather conditions.

15. Visibility sensors should be installed at the following RPUs after determining suitable instrumentation: Vedauwoo, Cemetery Separation (only if relocated), Sage Junction (if relocated), Shute Creek, Rim, Beaver Rim, I-25 Divide, Dead Horse, Inyan Kara, Belle Fourche (if relocated), Hiland (remote from RPU if not moved), Pathfinder, Deer Creek, Bordeaux, Arlington, Gun Barrel (remote from RPU if not moved). In addition, it might be

possible to install visibility sensors remote from RPUs at Continental Divide and Bitter Creek, at nearby locations not affected by snow fences. Visibility sensors should be installed as a standard part of the atmospherics at all future RPUs.

16. Priority should be given to providing more training in the use of RWIS information within the Department, and a comprehensive program should be implemented after the new integrated software platform is installed. Training should involve Department personnel familiar with the system and its use in Wyoming, as well as equipment and software vendors and forecasters. Material that should be covered in the training includes:

    - What RWIS is
    - Description of Wyoming's RWIS and relevant stations in adjacent states
    - What information is available
    - How information can be obtained
    - How the various sensors work and what their limitations are
    - Interpreting current and historical data
    - Interpreting forecasts
    - How to work with forecasters to improve forecasts
    - How to obtain and interpret supplementary weather information—radar, satellite images, and weather maps
    - Limitations of radar and satellite images under various weather conditions
    - How to use RWIS information for maintenance decisions

    Iowa uses a "Train the Trainer" approach whereby a few individuals within the department are selected to receive detailed training to become local experts, who can then provide one-on-one training and assistance to others within the Department. The trainers are given more detailed information on a wider variety of subjects than would be feasible, or desirable, for maintenance personnel statewide, and are selected because of their advocacy for RWIS, their willingness to learn, their familiarity with snow and ice control operations at the operator level, and their technical aptitude.

    According to Dennis Burkheimer, Winter Operations Administrator (515-239-1355), the Iowa Department of Transportation will be releasing this fall a training video on RWIS as part of their "Winter Operations Training Program." Judging from the four volumes on other subjects that they have released, the video should prove to be a good training resource.

17. Although state-wide RWIS training may be deferred until after the new integrated system is in place, in the interim it is important to again inform all personnel how important it is for them to provide feedback to forecasters if they want to see improved forecasts for their specific areas. Feedback does not have to be negative to be valuable—it is just as important for forecasters to hear what they are doing right, as well as what they need to improve on. This educational effort could be accomplished as an agenda item during District meetings, independently from other RWIS training. It is recommended that maintenance personnel be required to keep a log of their contacts with forecasters over a winter, documenting the date, time, forecaster's name, feedback comment, and result (if any) as a training exercise.

18. There are numerous considerations in determining where RPU sites are needed, and a list of candidate sites should originate from maintenance foremen in consultation with District Maintenance Engineers. Because of the cost associated with installing and maintaining a weather station, however, objective criteria should provide the basis for selection and prioritization. Although it would be nice to know exactly what benefits might be expected from a proposed location, such as reduced expenditures for snow and ice control, improved level of service, and improved public safety, in reality the final decision must be at least partly intuitive. Preference should be given to the following factors:

    - Locations in areas remote from existing RPUs
    - Known problem areas for snow and ice control and/or accidents
    - Locations where data would be useful for two or more maintenance sections
    - Locations distant from shops where weather data may reduce dead-hauling
    - Primary highways
    - Locations having suitable sites for meteorological measurements.

    Examples of the sites requested in the survey (Section 2.5) that meet most, if not all, of these criteria, include:

    - Mule Creek Junction (US 85 near Mile 196) (the South Dakota RPU at Edgemont is not believed to be a satisfactory substitute)
    - Pine Tree Junction (WY 387 Mile 127.86)
    - Four Corners (near Mile 247 on US85)
    - Togwotee Pass (near Mile 26, US 287)
    - South Pass (WY 28, Mile 36.4 or 37.6)
    - Church Buttes (I-80 near Mile 54)
    - Elk Mountain area (I-80 Mile 255)
    - Montana State Line (I-90 Mile 109.9)
    - North of Lusk (US 85 Mile 160)
    - North of Gillette (WY 59 Mile 150 or 170)
    - North of Cody (WY 120 Mile 109.9)
    - US 14/16 between east of Sheridan (Between Mile 52 and 76)
    - Shirley Basin (WY 487 between Mile 18 and 29)
    - South of Jay Em (US 85 Mile 124 vicinity)
    - North of Baggs (WY 789 Mile 10 vicinity)
    - North of Fort Washakie (US 287 Mile 30 vicinity)

19. Criteria for RPU sites depend on the desired instrumentation, but as a general rule, sites should be suitable for a complete weather and pavement instrumentation package, to include pavement sensors, air temperature and relative humidity, snowfall rate and accumulation, wind speed and direction, and visibility in blowing snow. Consideration should also be given to the future addition of a video camera. The basic requirement for RPU sites is that they be in exposed locations, where wind and visibility in blowing snow are not influenced by local features such as trees, buildings, hills and snow fences. When possible, the RPU should also

be located on the upwind side of the road relative to the prevailing wind direction, as identified for Wyoming in the publication by Tabler (1997), to minimize effects of the road cross-section on wind direction and blowing snow, and to reduce the possibility of wind-carried spray and plow cast from reaching the atmospheric sensors. RPUs should be far enough from the road that atmospheric sensors are not affected by traffic, and locations at the top of cuts are often preferable for this reason. In any event, the base of the RPU mast preferably should be at or above the elevation of the road. All of Wyoming's existing RPUs are satisfactorily located with respect to distance from the road. SSI pavement sensors can be located up to 10 miles away from an RPU using their "Outpost" wireless data station, although it is obviously preferable to have the pavement sensors close enough to the RPU that they can be hardwired. It is desirable to situate RPUs where pavement temperatures at bridges or tunnel portals can be monitored in addition to approaches. If visibility is to be measured, sites should have unobstructed "fetch" distances of 600 m or more in the direction of the prevailing winds, and preferably in all directions. This requirement can be readily verified from a 7.5-minute topographic map of the proposed area. Although solar power can be used where there is no alternative, preference should be given to locations where AC power is available for heating visibility sensor shields, and for artificial lighting in the event video capability is added. It is better to select a site without AC power, however, than to install an RPU at a location unsuitable for weather monitoring. The Wyoming/South Dakota shared site is a prime example of a site with AC power where wind speed, direction, and visibility are totally unrepresentative of conditions on the Wyoming side of the state line. Siting requirements for RPUs can be summarized as follows:

- Exposed location where wind and blowing snow are not affected by trees, hills, buildings, or snow fences,
- Tower base at elevation equal to or greater than that of road,
- Tower 15 m or more from edge of pavement,
- Upwind side of road preferable, essential at deep cut sections,
- 600-m or more open fetch upwind, and preferably in all directions,
- AC power preferable

20. Assign dedicated personnel to the RWIS system, to include one person with over-all responsibility for the system, and one or more telecommunications technicians with specialized training in RWIS instrumentation including principles of operation, installation specifications, and maintenance requirements. All RWIS personnel should be trained in the rudiments of blowing snow and boundary layer meteorology, and site selection.

    The present RWIS system is serviced and supported by WYDOT telecommunications personnel, assisted by contracts with vendors to provide software, parts, help desk, training, and annual systems checks. Because the statewide system must experience minimal downtime and maximum accuracy, and because the sensors and RPUs require specialized expertise, consideration should be given to assigning dedicated telecommunications support personnel to the RWIS system. Another important roll of support personnel is to keep abreast of emerging technology to improve overall performance and benefits, and this assignment alone requires a full-time commitment to RWIS.

21. Consideration should be given to purchasing vehicle-mounted infra-red surface temperature detectors to check performance of pavement sensors, aid in the selection of future RPU or pavement sensor sites, supplement *in situ* data from RPUs during storms, and to provide in-house road thermal analysis capability. Road thermal analysis, or thermal mapping, involves driving an instrumented vehicle over a road section or system to measure pavement temperatures during typical winter weather conditions. The resultant temperature profile is useful for determining the representativeness of existing or proposed pavement sensors and/or RPU locations, and also provides excellent information for RWIS training. Weather conditions selected for analysis are typically restricted to nighttime with calm winds and clear skies, and windy and/or cloudy conditions. In Wyoming, measurements should also be obtained in blowing snow conditions to quantify temperature differences arising from spatial variations in the mass flux of snow crossing the road--differences between exposed areas and adjacent areas sheltered by cuts, trees, and snow fences.

    Tests in Wisconsin (personal communication with Michael J. Adams (608-266-5004) of Matrix Management Group in Wisconsin indicate that the instrument available from Control Products (360-571-0988; www.orionsys.com/cpi) is the most accurate, although it is more than twice as expensive ($1,360) as the Sprague instrument. The author has been testing a Control Products unit since February, 1998, and has found it to be reliable and accurate. The "seen" area measured by the instrument is approximately 10 cm in diameter at a mounting height of 60 cm above the pavement, providing an output that can be compared to a pavement sensor reading. Readings are made 10 times per second, but variable sampling frequencies can be selected with the laptop software option. Control Products also offers other software for inexpensive thermal mapping, including a "mini-mapping" system that integrates output with a Nu-Metrics distance measuring instrument for logging location.

22. Low level precipitation detectors should no longer be used because readings are made unreliable by mast interference (especially anti-climb panels and RPU enclosures), and by the design of the instruments themselves—especially those made by Rudolph—which prevents wind-driven particles from passing through the sensing area. The reliability of the latest model of ETI detector is good when wind is from a direction toward the open face (i.e., from the west), but sensitivity is reduced when winds are from other directions. Precipitation detectors are normally located about 60 cm below the top of the mast. Existing low-level precipitation detectors should be removed, and reserved for future installations or replacement units; however, all Rudolph instruments should eventually be replaced with the latest model of ETI sensor.

23. Data archival services should be solicited as an item in the RFP for upgrading RWIS. Historical climatological data are valuable for many research purposes, as well as for designing snow fence systems and to design drift-free highways using the computer-aided subroutines developed under a separate research agreement (Tabler 1997). Archived data also form the basis for experience-based maintenance training, provide documentation of RPU performance as it relates to maintenance and communications, allow evaluation of forecasting services, and provide the basis for in-house or third party weather prediction models. Minimum requirements for archived data include hourly tabulations of air temperature, surface temperature, surface status and salt concentration, precipitation rate and

accumulation, visibility, wind speed (mean and maximum gust), wind direction, and traffic count and speed (see Item 30) for each RPU, in addition to forecast information for performance evaluations. Although data for the last 12 months should be available within 7 days or so of a request, data should be recorded on compact disk at the end of each year in a format suitable for importing to a spreadsheet. Simply knowing that data and forecasts are being archived should provide an additional incentive for vendor or third party forecasters.

24. Consideration should be given to specifying that payment for forecasting services will be based on performance, to include accuracy, timeliness, updates, and support. This stipulation would require post-storm critiques over a prescribed sample of events each year, with equal numbers selected by WYDOT and the forecast provider. This concept is planned for testing by both Montana and Iowa next winter. Archiving data would facilitate this process.

25. Most SSI pavement sensors are of the old ("E") type, and should be upgraded to the newer and more accurate FP2000 whenever replacement is required, if SSI instrumentation continues to be used.

26. Maintain better permanent records (logs) for each RPU, documenting commissioning date(s); atmospheric and pavement sensor models, serial numbers, heights, and locations; dates preventive maintenance and other service was performed; and dates instruments and electronic components were installed, replaced, and calibrated.

27. Improve marking of pavement sensor locations with posts and reflectors to facilitate finding them for inspection and service, and to allow plow operators and other personnel to compare actual surface conditions at the sensors with status reported by sensor.

28. Sign buried cable locations better to reduce the possibility of damage.

29. Place pavement sensors no further from the RPU than necessary to reach the section of road for which an indication is desired. Most of the existing sensors are much farther away than necessary, increasing installation cost and the susceptibility to cable damage.

30. Sensors should be installed to monitor vehicle count and speed at selected RWIS sites, particularly on the routes with high traffic counts. This information can be used for computer-assisted interpretation of driving conditions to alert maintenance personnel of problems, and to advise the traveling public. The study by French and Wilson (1993) in Wyoming showed a high correlation of vehicle speed with visibility and pavement condition, suggesting that vehicle speed could be used as an index to driving conditions.

31. Test the utility of slow-scan or freeze-frame video cameras by installing one at the Vedauwoo RPU. Although video will be a valuable addition to RPUs in the future, primarily for supplementing Road and Travel Information on the Internet, it will not replace the need for quantitative data from other sensors. One of the principal disadvantages of video is the requirement for a human observer to view and interpret the image—a camera view is nice to have available, but it does not replace quantitative data available from other sensors. A wet pavement and "black ice" can appear identical on video, for example, but surface temperature

and condition from pavement sensors are necessary to tell the two conditions apart. Video images are also time-consuming to transmit and store, and downloading images from cameras can significantly reduce polling frequency--cameras would not be feasible in Wyoming unless the communications system were upgraded, as recommended in Item 1. A camera was installed in the fall of 1997 on US 12 at McDonald Pass in Montana (the image from this site can be viewed at http://rwis.mdt.mt.gov/SCANWeb, under the Butte RPUs). The quality from this camera remained so poor as to be unusable throughout the 1997-98 winter, despite efforts by the Montana Department of Transportation to have the problem corrected.

Limitations for using video to monitor visibility in blowing snow include: 1) relatively slow rate at which images are collected compared to temporal variability of visibility (limitation arising from data transfer rate), 2) lack of suitable software for automated image analysis, requiring frequent manual monitoring of images to keep abreast of changing visibility conditions, 3) tendency for snow accumulation on optical surfaces, 4) large amounts of memory required to store or archive images, 5) artificial lighting required for nighttime viewing in absence of traffic, 6) conditions over optical path not representative of driver visibility because of variation of visibility with height. One purpose that video can serve is to better inform the public about driving conditions by having the image available for viewing on the Internet, DTN, or rest area, and a candidate site for a video trial would be on I-80 between Laramie and Cheyenne, at the location proposed for the Vedauwoo relocation. This image could help inform truckers about conditions on the "Summit" when it was closed to traffic, and would be a popular addition to the Road and Travel report.

32. The author's experience (Tabler 1973) suggests that determining the accuracy of sensors is not a trivial task, and a study of pavement sensor accuracy requires that observers be trained in the theory of operation and the various surface conditions that can influence readings. For this reason, it is difficult to judge sensor performance from maintenance operator reports. The relative accuracy of pavement sensors available from different vendors has not been studied sufficiently to know if significant differences exist. Considering that the sensor from Coastal Environmental is about $1,000 less expensive than either the Vaisala or SSI models, a comparative study could have economic benefits.

    There are numerous alternative pavement sensors based on cyclic cooling and heating to determine freeze point and presence of water/snow/ice, and these are described in the report by Castle Rock Consultants (1995). An inexpensive pneumatic ice detection sensor marketed by the Vistron company (916-273-3250) has been used to activate ice warning signs, but has not yet been incorporated into an RPU station. A major disadvantage of all of these sensors is the small area which they sample—on the order of 20- to 125 cm^2. Radar- or microwave-based instruments can potentially provide a measurement over a larger area, on the order of a meter or so. A "Road Condition Radar" system is reportedly under development by an Austrian company (Castle Rock Consultants 1995), and a microwave sensor is being tested by the University of Wyoming (Tapkan, Yoakum-Stover, and Kubichek 1997; Kubichek and Yoakum-Stover 1998). WYDOT may wish to participate in the evaluation of the microwave device and include a side-by-side comparison of alternative passive sensors, particularly those available from SSI, Vaisala, and Coastal Environmental.

33. Evaluate benefits of continuing forecasts and full system operation through summer months.

34. Make evaluation of Wyoming's RWIS a continuing process and include this subject as a routine agenda item for annual state maintenance meetings.

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APPENDIX A

Wyoming RWIS Survey Results

WYDOT ROAD WEATHER INFORMATION SYSTEM

PURPOSE: This study is being conducted by the Wyoming Department of Transportation to gather information on how the Wyoming Road Weather Information System (RWIS) can be made more useful to maintenance personnel and other users. Even if you use RWIS information only occasionally, your input will be useful.

DEFINITION: RWIS refers to the 27 road-side weather stations, the system used to disseminate this information to users, and the forecast services provided by the equipment vendors.

INSTRUCTIONS: Please complete by **February 28, 1997**, and return in the enclosed pre-addressed and stamped envelope. If envelope is missing, please mail to:

Attn: Ron Tabler
Tabler & Associates
P.O. Box 483
Niwot, Colorado 80544

You will be contacted in February or March to arrange for a meeting to discuss your responses.
Thank you for taking the time to participate in this study!

Please provide the following information:

Name **88 copies mailed / 69 completed**
Title ______________________________
Location ______________________________
Phone ______________________________

10 Check here if you want your responses to be kept confidential.

If you do not want to complete this survey, please indicate the reason(s) and return this page only:

1. How useful *is* RWIS in doing your job?

3%	RWIS information is not available for the area in which I work.
0%	I do not want to take the time
4%	Other 1. How useful is the RWIS in doing your job?
21%	Very
78%	Somewhat
1%	Not at all

2. How useful *could* RWIS be to you if problems or deficiencies were corrected?

62%	Very
36%	Somewhat
1%	Not at all

3. How do you usually obtain RWIS information?

29%	Verbally from radio room operator or other source
8%	From computer operated by someone else
61%	From computer operated by you
2%	Usually do not bother to obtain this information

4. How easy is it for you to obtain current RWIS information?

16%	Always easy
78%	Usually easy
6%	Usually difficult
0%	Always difficult

5. How often do you (or your source) encounter problems with getting an open line when you dial in for data?

39%	Seldom
46%	Sometimes
15%	Often
3%	Information not obtained this way
4%	Don't know

6. How often do you (or your source) encounter problems with the computer hardware or software?

31%	Seldom
52%	Sometimes
12%	Often
0%	Information not obtained this way
4%	Don't know

7. How often do you encounter the problem of data from weather station sites not being current?

35%	Very seldom
57%	Sometimes
8%	Frequently

What specific locations, if any, are the most likely to experience delays in updating? (Number of respondents shown in parentheses)

Pumpkin Vine (2)
Vedauwoo (2)
First Divide
Cemetery Separation (Green River)(2)
First Divide
Sage Junction
RR-11
Deer Creek
Sibley Peak
20-Mile Hill
Meeteetse Rim
Vaisala Sites
Bordeaux
I-25 Divide
Beaver Rim
"varies", "not site specific", "sites operated by solar panels"

8. How useful are the following data to you?

Air temperature

67%	Very
27%	Somewhat
1%	Not at all
5%	Could be useful

Pavement Temperature

70%	Very
24%	Somewhat
1%	Not at all
4%	Could be useful

Subsurface Temperature

35%	Very
47%	Somewhat
12%	Not at all
4%	Could be useful

Wind Speed/Direction

75%	Very
18%	Somewhat
4%	Not at all
3%	Could be useful

Dew Point / Relative Humidity

41%	Very
50%	Somewhat
5%	Not at all
5%	Could be useful

Precipitation / Snowfall

70%	Very
19%	Somewhat
1%	Not at all
9%	Could be useful

Road Surface Condition (Dry, Wet, Ice, etc.)

72%	Very
15%	Somewhat
3%	Not at all
10%	Could be useful

Visibility

34%	Very
21%	Somewhat
17%	Not at all
28%	Could be useful

Forecasts provided by vendors

48%	Very
33%	Somewhat
17%	Not at all
16%	Could be useful

Other data or information that you think would be useful if provided: (Number of respondents shown in parentheses)

Televised view of road (16)
Better and more current forecasts (3)
Quantified precipitation (1)
Quantified visibility
Networked RWIS sites (1)
"Black ice notification" [based on temp/dewpoint relationship] (1)
Better and more current forecasts (3)

9. If you don't have visibility information available, how useful would a report on this factor be (in blowing snow conditions)?

16%	Don't know
14%	Not useful
25%	Somewhat useful
44%	Very useful

Give locations, if any, where visibility data would be most useful: (Number of respondents shown in parentheses)

I-80 mp 327 and 330
US 287 mp 416-419, 423.5
Meeteetse Rim
State Line mp 1
I-90 N. of Sheridan
Piney Creek (5)
Mp 42 S. of Sheridan
I-90 mp 96, 102, 109
I-90 mp 182-190
US 14-16 mp 60 and 76
WY 59 mp 170, 150
Beaver Rim (4)
South Pass (2)
Continental Divide (2)
Sheridan area
Buffalo area
Kaycee area
Wright area
Cemetery Separation
Bitter Creek (2)
I-25 mp 218
WY 387 mp 124 (?)
Arlington
"North on 487"
Vedauwoo
Pumpkin Vine
Gun Barrel
At interchanges along interstate
US 191 mp 127 Rim Area
Bordeaux
Sibley Peak
Pathfinder
Hiland
I-25, WY 220
Many locations
Tunnels at Wind River Canyon
US 26-287 mp 24.0
At Section breaks
Togwotee Pass
Chief Joseph

10. Would additional weather stations improve the usefulness of the system?

29%	Don't know
7%	No
63%	Yes

If *yes*, are there specific locations in your area?

[See Question 9 responses + following]:
S. Dak. State Line
I-90 mp 96, 109
US 14-16 mp 60 + 76
WY 59 mp 150, 170
South Pass: WY 28 mp 41 and 59
WY 487 mp 24 or 29
20 miles south of Meeteetse (WY 120/431)
WY 387 between mp 124-132
US 14-16 mp 51 or 52
I-25 mp 100
I-90 mp 82, MT/WY border
Elk Mountain and Cooper Cove (I-80)
North WY 487 mp 18.5
US 85 mp 160 (N. of Lusk)
North of Manville approx. mp 105
WY 270 Mule Creek Jct
US 85 mp 196.6
Lusk Maintenance Yard
Dana Ridge (I-80)
WY 789 mp 10
WY/MT state line
Mile 51-52, US 14-16 E. of Buffalo
Southern or western MT
Tipton
"West and northwest Wyoming to see advancing storms"
I-25 mp 3.2
Mule Creek Jct. (US 85)
US 20/26 west out of Casper
WY 258 (outer drive)
US 85 mp 56, 64, and 124
"Fill in gaps, especially in western WY"
Wind River Canyon
"One on each of my road sections"
Church Buttes on I-80 mp 54 +-
Kemmerer area on US 30
I-80 Superior Intersect.
I-80 mp 383

US 26-287 mp 26.1
WY 120 mp 110 (north of Cody)
At Section breaks on US 30 and I-80
Dana Ridge (I-80)
Cody-Yellowstone Road
I-25 mp 100

11. Would the usefulness of the weather information be improved if one or more weather stations were moved to another location in the same general area?

55%	Don't know
32%	No
14%	Yes

If *yes*, give present location and any suggestions for better location:

Pumpkin Vine to mp 423.5, 419, & 416
Vedauwoo to mp 327 or 330
Belle Fourche to mp 75.5 +/-
Dead Horse to mp 76-80 (mp 76-80)
Arlington to Cooper Cove, possibly
Cemetery
Move Teton Pass RPU to top of mountain where originally requested or extend mast
Green River was better on Peru Hill--move back?.

12. In your experience, is the road surface condition information from the sites in your area:

42%	Usually representative of actual conditions
63%	Sometimes representative / sometimes misleading
3%	Usually not representative

What specific locations, if any, are the most likely to be unrepresentative?

Pumpkin Vine
Vedauwoo
Pathfinder
20-Mile Hill
Cemetery Separation
First Divide
Dead Horse
"Any - all"
"Bridge decks"
"A lot of false snow-ice alerts"
Deer Creek (comm. failure)
Dead Indian Summit
"False readings at Beaver Rim (?)"
"Information given me by all foremen"

13. In your experience, is the precipitation information from the sites in your area:

46%	Usually accurate
52%	Sometimes accurate but sometimes misleading
1%	Usually inaccurate

What specific locations, if any, are the most likely to be inaccurate?

Vedauwoo
Pumpkin Vine
Cemetery Separation
Dead horse
"Any-all"
"Depends on whether talking about amount, or yes/no"
Piney Crk
"All"
"Weather station calls fog snow"
"Wind can cause false readings"
Meeteetse
"Y/N is worthless"
"Blowing snow identified as snowfall"
"Sometimes sensor output is misunderstood due to inadequate training"
"Green River forecasts".

14. In your experience, are the wind data from the sites in your area:

78%	Usually representative of actual conditions
17%	Sometimes representative
5%	Usually not representative

What specific locations, if any, are the most likely to be unrepresentative? (Please specify wind speed, direction, or both):

Pumpkin Vine
Vedauwoo
Cemetery Separation
Dead Horse ("needs to be relocated")
"Wind direction Teton Pass is blocked by the mountain and wind speed reduced by trees".

15. If you have sites with visibility data, are the data:

33%	Usually representative of motorist visibility
67%	Sometimes representative but sometimes misleading
0%	Usually not representative

What specific locations, if any, are the most likely to be unrepresentative (if any)?

Pumpkin Vine
Vedauwoo
"If I do [have visibility monitor], I've never seen a reading".

16. Would the RWIS be more useful to you if the method of displaying the weather station data and forecast information were improved (better graphic displays, easier to read and interpret, etc.)?

42%	No
58%	Yes

If yes, any specific suggestions?

Doppler radar
More and better weather forecasts
Long range forecasts
Instructions on how to read graphics
Could be better
Data are lumped together and hard to read
Include video or slow-scan image of road (3)
Weather maps
Vaisala's graphs are good
Graphical point & click maps--pop-up data
Integrate radar and satellite data
Use latest technology for graphics packages
Improve forecasts
Improvement needed
Color graphics
Up-to-date weather maps
Bar graphs on histories.

17. Would the RWIS be more useful to you if current weather radar, satellite, and weather map information were also available for immediate display?

15%	Don't know
0%	No
85%	Yes

18. What other weather information, if any, would be useful if always available and updated hourly? (Number of respondents shown in parentheses)

Doppler radar (3)
Weather map (1)
Only better accuracy (2)
Long-range forecasts--5-day (2)
Summer reports (1).

19. How accurate are the local weather forecasts provided by the vendors? Please distinguish between "SCAN*Cast" (use "S"), and "IceCast" (use "I"):

1%	Not at all
68%	Somewhat
13%	Very
10%	Don't know or not sure

20. How timely are the forecasts? Please distinguish between "SCAN*Cast" (use "S"), and "IceCast" (use "I"):

12%	Not at all
74%	Somewhat
14%	Very

21. How useful could these forecasts be to you if their accuracy and timeliness were improved?

0%	Not at all
21%	Somewhat
67%	Very
12%	Don't know or not sure

22. How much training have you received in obtaining, interpreting, and using the RWIS information?

16%	Considerable
73%	Some
10%	None

23. Do you think that you could use the RWIS to better advantage if you received more training?

30%	No
53%	Yes
17%	Don't know or not sure

24. Please list any other suggestions to improve the usefulness of the RWIS system: (Number of respondents shown in parentheses)

Video (2)
Tie R&T into RWIS
Weather map for all stations, not just District Office
More sites (4)
Better maintenance of equipment (3)
More training (4)
Improve transfer of information from foreman to crew
Better forecasts (4)
More timely forecasts (3)
Upgrade computers (2)
Better maintenance of computers
Satellite weather info (2)
Coordinate with other sources of weather information (airports, DTN, NWS) (2)
Windows software
Quantify precipitation instead of Y or N
Increased reliability (5)
Compatibility between systems
Easier access to data
Change location of RPU (2).