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Road Weather Information Systems
Volume 1: Research Report

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British Columbia	Wisconsin

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Washington	

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Abstract

This report provides an overview of roadway snow and ice control practices, the types of road weather information currently available, the means for communicating road weather information, and the uses for such information in roadway snow and ice control. The report presents the results of field tests conducted to answer questions on the location of road weather information systems (RWIS), and to discuss a methodology used to determine possible cost-reduction ranges for RWIS implementation in support of roadway snow and ice control. Finally, the report presents conclusions and recommendations for the use of RWIS by state and local highway maintenance agencies in support of snow and ice control activities.

Executive Summary

In order to better respond to the transportation needs of industry and the travelling public, state highway agencies are seeking new ways to ensure safer driving conditions on major highways during all weather conditions. Highway agencies also are looking for ways to use labor, equipment, and materials as cost-effectively as possible. Weather technologies can help snow and ice control managers make more timely and efficient decisions to enable them to reduce costs and improve service. Several countries in Europe have established nationwide networks of weather data-gathering systems to provide decision information to "roadmasters." These systems are road weather information systems (RWIS).

The range of weather technologies includes meteorological sensors to gather weather information in the highway environment, sensors in the roadway to collect pavement condition information, thermographic analysis of roads to develop temperature profiles of road networks, and forecasts of both weather and pavement conditions.

Under Contract SHRP-87-H-207, Storm Monitoring/Communications, each of these technologies was tested in one or more states. Seven states participated in this study: Massachusetts, New Jersey, Michigan, Minnesota, Missouri, Colorado, and Washington. These states were selected because of their implementation of some of the technology, their use of different snow and ice control practices, and their different climates. Information was collected during the 1990-1991 winter in order to conduct a cost analysis using these technologies for snow and ice control, and to determine what kinds of technologies should be used and where they should be used. In addition, highway agencies in the United States and Canada were surveyed with questionnaires to determine their annual cost for weather information. Highway maintenance managers were interviewed in person. A literature search determined the existing technologies worldwide.

This final report provides details on the conduct of the investigation, describes the development of a methodology for performing the cost analysis, documents the conclusions from the investigation, and lists recommendations for states and other levels of government to consider when implementing RWIS technologies. In addition to this final report, *Road Weather Information Systems. Vol. 2 Implementation Guide* has been produced which supplements the research results presented in this report and which will assist highway agencies in implementing RWIS.

This investigation concluded that the use of RWIS can be a cost-effective method to reduce costs and improve roadway snow and ice control.

- The best return on investment occurs when highway maintenance managers use detailed forecasts of weather events and pavement conditions in their snow and ice control decisions. This is true for highway agencies with large or small snow and ice problems.

- An RWIS that blends data inputs from sensors and thermal evidence into detailed forecasts tailored to the needs of snow and ice control managers offers the opportunity for a significant return on investment close to 500%, *and* significantly improves the service level on the roads, *and* greatly decreases the frequency of decision errors.

    - RWIS sensors provide a generally reliable means to monitor, detect, and assist in the prediction of road temperatures and weather and pavement conditions. Sensor data, when made available to forecasters, allow for much better forecasts of road temperatures and icing. Hence, they allow for an improved snow and ice control service level and reduced decision errors.

    - Because of heat transfer differences among sensors, pavement, road subgrade, and solar energy, pavement sensor temperatures may differ by several degrees from pavement temperature readings under clear sky conditions.

    - Sensor reliability and accurate output require a preventive or routine maintenance program, and at least annual calibration of sensors.

- Road thermal analysis, when combined with sensor data, can be a cost-effective and useful tool for improving pavement temperature and condition forecasts. Road thermal analysis can assist in determining locations for RWIS sensors, reduce the number of locations required, and thereby reduce hardware costs.

- In order for RWIS data to be integrated properly into snow and ice control decision processes, effective communications must be established to ensure the timely flow of information.

    - Sensor data, weather information, and pavement temperature predictions need to get to snow and ice control decision makers. In order to accomplish this in a timely manner, portable computers with modems should be made available to the lowest level of decision makers in the majority of cases.

    - Sensor data need to be available to the agency/firm providing the forecast services. This availability should include on-line and dial-up access.

    - Effective communications must be established between forecasters and maintenance managers to ensure that forecasters understand the needs of the managers, that the managers understand the weather information, and that the forecasters know how well the information satisfies the managers' needs.

- Data dissemination practices designed to hold down communication costs, such as transmitting information only when certain parameter thresholds are crossed, limit the use of RWIS data. Data gaps on the order of days have occurred. These gaps preclude post-event analysis, applied research using the data, and the development of forecast techniques. Such practices should be modified to avoid these limitations and increase the value of RWIS data.

- Philosophical and psychological barriers exist to integrating RWIS technologies into snow and ice control operations. Individual barriers include distrust of weather forecasts, fear of change, and the perception that technology is difficult to implement. These barriers can be overcome through behavioral changes resulting from training. Organizational barriers include problems with management and labor, perceiving RWIS implementation as a top-down-directed initiative, and having little or no participation and support at the implementation level. These barriers require organizational behavior change and also can be overcome with training plus management initiatives.

- Problems exist in contracting for weather forecasting services and acquiring RWIS hardware.

  - Highway agencies frequently contract for weather services using low-bid procedures, resulting in services that inadequately meet the agencies' needs.

  - Many highway agencies interested in pursuing acquisitions write requests for proposals (RFPs) which parrot vendor specifications whether appropriate or not.

Agencies considering investment in an RWIS should consider the following recommendations:

- All highway agencies that perform snow and ice control should assess the benefit of contracting with a value-added meteorological service (VAMS) for weather and road condition forecasting.

- Highway agencies should contract for meteorological services using an RFP, consultant selection, negotiated-price procedure. Highway agencies should use technical evaluation criteria for selection and not just cost. Some highway agencies might consider developing meteorological expertise on their staffs.

- Each highway agency that has either an RWIS in use, or desires to develop one, should obtain weather support from a designated weather advisor who works directly with snow and ice control personnel to assist in the acquisition and implementation of RWIS technologies, to provide guidance on sensor acquisition and siting, to help contract for weather services, and to provide staff training on the use of the RWIS for snow and ice control. The weather advisor should be knowledgeable concerning meteorology and RWIS technologies. He/she can be a part-time, shared, or full-time existing employee, new hire, consultant, or VAMS.

- Highway agencies planning to acquire RWIS sensors should consider using road thermal analysis and road crew knowledge to assist with sensor siting and forecasting of road conditions.

- Any highway agency acquiring RWIS technologies should develop a training program to assist the integration of RWIS information into snow and ice control decision processes and the development of management strategies.

- All highway agencies should require that RWIS data be acquired from sensors at least once each hour. If no data are received for over an hour, action should be taken to correct any problems.

- Data from an RWIS should be archived. Data can be of great value for research, performing local forecast studies, and for records of road and weather conditions and maintenance actions for liability purposes.

- All highway agencies with RWIS hardware should implement a routine maintenance program. Sensors should be calibrated annually. A standard calibration procedure should be adopted.

- Involve the parties affected by change in the process of change. Tap the knowledge of road crews about the roads they maintain, for example. The benefits of such an approach are many: it recognizes the value of the people within the organization; opinions about the new system can be discussed at stages where protocol and design changes still can be made; people involved in change are more likely to understand and actually use the system; and longstanding issues regarding the snow and ice control practices of a highway agency can be addressed. Much as RWIS forecasts must be tailored to an agency, its actual system must also fit the agency.

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Introduction

Statement of the Problem

Controlling snow and ice on roadways requires large expenditures for labor, equipment, and materials. The United States and the provinces of Canada spend over $2 billion annually on snow and ice control. Snow and ice control costs could be reduced by improving the ability of highway agencies to select an appropriate strategy and carry it out in the most timely fashion.

The inability to accurately predict storm conditions and pavement conditions, and to communicate rapidly changing conditions to snow-removal forces and the travelling public, result in excessive and unnecessary expenditures. Calling crews out for prestorm treatment when a storm doesn't materialize is a waste of resources. Delaying treatment to be certain a storm is of sufficient magnitude to warrant attention eliminates the advantages of early treatment and increases the amount of resources necessary to return the road system to a normal condition. An efficient snow and ice control process would provide for the mobilization of just the right amount of personnel and equipment at just the right time.

An emerging technology which uses weather and roadway sensors to provide current information to snow and ice managers could provide timely notice of changing temperature, of snow or freezing rain beginning to fall, or of the amount of chemical remaining on the pavement. At the time this project was initiated, over ten states had installed pavement sensors for snow and ice control, but little information regarding performance or cost-effectiveness was available.

If the information produced by sensors is not integrated into a forecast system and is not used to generate accurate predictions of weather and pavement conditions, sensors have only limited usefulness, and their full potential is not realized. Fragmentary information is not sufficient for proper crew scheduling.

Effective storm management requires the capability to predict the need for snow and ice control four to twelve hours in advance. This capability would enable supervisors to send workers home to rest before a storm hits and to estimate how many workers will be needed and when they should return. It would also enable supervisors to plan routine maintenance work to keep employees as productive as possible when freezing temperatures or snowfall are not forecast.

Rapid communication, both on a regional basis and within the structure of individual jurisdictions, is also necessary for effective coordination of snow-removal efforts.

The precursors to road weather information systems (RWIS) were initially installed at airports in this country. Their information was used to assist airport authorities in their conduct of snow and ice control. Atmospheric and pavement sensors were installed at airfields, usually near the ends of runways, runway intersections, and on parking ramps. These sensors sent their data to processors in airfield operations offices where supervisors made decisions concerning chemical applications for deicing and snow plowing.

The snow and ice control problems of highway authorities only differ in magnitude and methods for treatment. Similar systems were sold to highway agencies and other agencies. Remote processing units (RPU) with atmospheric and pavement sensors were installed along highways, and central processing units (CPU) were installed in highway maintenance facilities. These systems were generally installed on a research or test basis. In simplistic terms, when more RWISs were desired, additional RPUs and a CPU were installed in another maintenance area of responsibility.

Road weather information systems are made up of pavement sensors and other components similar to those in standard weather information systems. An RWIS may contain:

- Meteorological sensors which measure atmospheric temperature, relative humidity or dew point,* wind speed and direction, and precipitation;
- Pavement sensors which measure surface temperature, subgrade temperature, surface condition (wet, dry, or frozen), the amount of deicing chemical on the pavement, or the freezing point of a wet surface;
- Temperature profiles of roadways based on road thermal analysis;
- Site-specific forecasts of weather and pavement conditions tailored to a highway agency's needs;
- Other weather information for use by meteorologists and snow and ice control managers, such as radar images and National Weather Service forecasts;
- Communications and data processing and display capabilities for data dissemination and presentation; and

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* Dew point is the temperature at which the atmosphere would be saturated (100% relative humidity) if cooled. It is used in the calculation of relative humidity.

- Weather support to agency staff that allows for close coordination and consultation between meteorologist and decision maker.

- A plan for an agency to use its RWIS data to create and maintain a preventive activity program for winter weather problems.

Each component of an RWIS is specialized because of its application. It is important to understand their differences and applications. To establish a common basis of understanding, the following sections describe standard and road weather information system components.

Standard Weather Information

There are different types of weather information available to different groups. The general public gets area weather information provided by the National Weather Service, broadcast and print media, and in some cases, specialized television broadcasts such as The Weather Channel, AM Weather on the Public Broadcasting Service, or cable television broadcasts of National Weather Service forecasts and weather radar. Finally, National Oceanic and Atmospheric Administration Weather Radio provides continuous broadcasts of weather observations, forecasts, and in some instances, specialized information such as road conditions. For the most part, all of this weather information is for large areas and defines average conditions or a range of conditions, but not conditions for specific locations.

There are two types of weather information: *observations* and *forecasts*.

Observations

Weather observations provide information on the current state of the atmosphere. These observations are usually provided hourly, or more often if significant changes occur. Typical observations describe sky cover (cloudy, partly cloudy, clear), the type of weather occurring (rain, snow), air temperature, relative humidity, and wind direction and speed. Frequently, the atmospheric (barometric) pressure and the pressure tendency (rising, falling, or steady) is given. Aviation observations contain additional information. Sky cover information is more detailed and includes the heights and amounts of clouds, the visibility distance, and any restrictions to visibility (fog, smoke, dust, snow). Aviation observations also include the dew point, a pressure reading for pilots to use for setting altimeters, and runway information.

Weather observations are also used by the meteorology community to generate forecasts. For instance, a forecast for conditions one hour from now could very well be the latest observation. Observations are monitored to check the accuracy of earlier forecasts. If observed weather conditions begin to deviate significantly from forecast conditions, then the forecasts may require change.

A weather observation usually contains information obtained from sensors such as thermometers for temperature and anemometers for wind direction and speed. Additional observations are provided by instruments borne aloft by balloons in order to obtain upper atmospheric temperature, humidity, and wind data; by weather radars that detect or monitor precipitation and severe weather; and by satellites. Data from these observations are mostly used to provide initial or boundary conditions for meteorological computer models, to assist in severe weather forecasting, and to support aviation.

Additional information must be gathered by human observers of the sky and weather conditions. Humans also have to record the instrument observations and encode observations for dissemination. Both the National Weather Service and the Federal Aviation Administration are in the process of installing automated observing systems around the country. Considerable research has gone into the development of systems to provide information to the aviation and meteorological communities without human interaction.

Forecasts

Weather forecasts describe expected future weather conditions in general terms for an area. For example, forecasts may be issued for urban areas, coastal areas, or mountains. Most public forecasts are issued by the National Weather Service and are frequently retransmitted by broadcast media. Some media either have their own meteorological staffs which produce their own forecasts, or they contract for weather services from value-added meteorological services (VAMS). Public forecasts rarely provide detailed information which can be related to specific locations. In most cases, users must interpret these forecasts to determine the potential impact of the expected weather.

Aviation weather forecasts, on the other hand, are usually site-specific or deal with a particular route of flight. Detailed forecasts are issued by the National Weather Service for larger airports, and in some cases, general aviation airfields. These forecasts contain projections of the same conditions contained in aviation observations, i.e., conditions of importance to aviators who need to know whether they will be able to take off or land at particular locations.

Site-specific forecasts usually require the services of VAMS. VAMS use National Weather Service data and forecasts, specialized observations, objective forecast techniques, and meteorological models to prepare forecasts. VAMS customers frequently have special needs—critical thresholds for decisions. VAMS tailor their forecasts to meet a user's needs.

Road Weather Information

The primary reason for using forecast information is to help make decisions whether to undertake certain activities in a timely manner. Without forecast information, decisions regarding activities must be based on the actual occurrence of weather phenomena, and therefore cannot be made much in advance of the activities.

So it is with snow and ice control on our highways. A supervisor can make resource allocation decisions based on forecasts of weather and pavement conditions (plan ahead, more economical), or rely on observations of those road conditions (react, more costly).

Observations

Road weather observations are similar to standard weather observations in many ways. They provide information about weather conditions in the road environment and the conditions of the pavement. This information is usually gathered by meteorological or pavement sensors.

Meteorological instruments located along roadways gather data on temperature, dew point, wind speed and direction, and the occurrence of precipitation. Sensors placed in the pavement monitor the pavement temperature; determine whether the pavement is dry, wet, or ice-covered; measure the relative concentration of any deicing chemicals on the road surface; and calculate the temperature at which the moisture on a surface would freeze. A temperature probe is also sometimes placed about 20 in. (0.5 m) below the surface. The subsurface temperature is used with other data to determine if heat is flowing to or away from the surface.

These observed parameters are important to understanding what is taking place on the road. For instance, road temperature and precipitation data are key to whether ice or snow can bond to the pavement, or whether ice can exist. Road temperature and dew point are key to whether frost can form on the surface. These data are also important for the development of forecasts of these conditions. It is the forecasts of these weather events that are the key to successful decision making, improved efficiency, and reduced costs of snow and ice control.

Forecasts

Forecasts can and should be obtained for both weather and road conditions.

Forecasts of pavement temperature have been made possible with the development of computer models that use observations of conditions in the road to produce surface temperature forecasts accurately out twenty-four hours in the future. This lead time allows managers to plan allocation of resources during the day for the following night and succeeding morning. Knowledge that the pavement temperature will or will not go below freezing can be critical factor in a snow and ice control decision.

Better decisions can be made with forecasts tailored to a decision maker's needs. Snow and ice control managers need to know not only that a weather event such as snow is expected, but also how much, where, when, and for how long. Managers use some critical thresholds to make resource allocation decisions, such as ≥2 in. (5 cm) of snow for mounting plows, ≥6 in. (15 cm) for calling out contractors, or storm duration greater than twelve hours for emergency shift scheduling.

Much of the information important to snow and ice control supervisors is not available from standard sources of information. If detailed forecasts of weather and road conditions are to be obtained, it is advisable for an agency to acquire a value-added meteorological service (VAMS). A VAMS could be a state agency, a state-funded weather service as is found in avalanche forecasting, or a private meteorological service.

VAMS provide a wide range of forecasting services, including short-range (0-4 hours), mid-range (4-24 hours), and long-range (24 hours or more) forecasts of weather events. Each range has utility in making decisions for snow and ice control. In addition to weather event forecasts, road condition forecasts are necessary. These conditions include snow cover, icing, and frost. Road condition forecasts require pavement temperature forecasts. Road temperature forecasts are somewhat more reliable than atmospheric temperature forecasts. The thermal energy balance at the pavement surface is easier to model than the atmosphere. More predictable temperatures are possible there than for the atmosphere.

Road Thermal Analysis

One form of road thermal analysis, road thermography, was developed simultaneously in the United Kingdom by Dr. John Thornes of The University of Birmingham, and in Sweden by Professor Sven Lindqvist of The University of Gothenburg (Thornes 1972, Lindqvist 1976). The principle underlying road thermal analysis is that if a temperature is known at a specific location, then pavement temperatures can be estimated between sensors. It uses vehicles with downward-pointing infrared radiometers to collect road surface temperatures every few meters. Data are gathered in the early morning hours when surface temperatures tend to be the coolest and solar heating effects are absent. Data are gathered under clear sky, cloudy sky, and wet pavement conditions because the temperature patterns of a road surface differ significantly under each of these conditions. The raw data are used to prepare temperature profiles along a road. Under the same sky and wind conditions, the temperature profiles for a road will have the same shape over time. These profiles supplement sensor data since a sensor only provides pavement temperatures at one location.

Supplemental data are usually also annotated to the profiles to indicate areas where the roadway might be shaded from the sun, or where temperatures may be influenced by such things as buildings, forests, or bridges. An extension to road thermal analysis is used in Sweden to show moisture sources, locations where cold air tends to pool at night, and areas prone to wind and drifting snow. This extension is called road climatology, and it is designed to be used in conjunction with temperature profiles to provide an expanded basis for short-term forecasting of pavement temperatures and road conditions.

Road thermal analysis has been used to help determine optimal locations for RWIS sensors, to develop alternative plowing and spreading routes for snow and ice control, and to prepare forecasts of road temperatures.

Communications

Three paths of communications are required for successful utilization of an RWIS: communication from sensor systems to roadway maintenance centers, communication between snow and ice control managers and private weather services, and communication from highway agencies to the traveling public.

Data Transfer from Sensors

In order for RWIS sensor data to have value, the data must be available to highway agencies and VAMS. A typical RWIS sensor system includes onsite sensors, a microprocessor to collect and format the data in digital form, and a transmitter to send the data to users. The microprocessor/transmitter is called a remote processing unit (RPU) or outstation. RPUs typically communicate with a central processing unit (CPU) or instation, a computer located where data from more than one RPU may be gathered.*

An RPU usually transmits data via radio signal or land line. Radio transmissions require line-of-sight between an RPU and an antenna. In order to get a signal to a CPU, repeater antennas may be required. State-owned microwave systems provide one of the best transmission capabilities. Land lines can be dedicated leased telephone lines or state-owned cables. Data can also be transmitted by cellular telephone in some areas, and these areas are expanding, although the transmission costs may be high.

Once data are sent to a CPU, they can be retrieved by other computers. Supervisors and managers can have real-time access to observations around the clock through the use of portable computers with telephone modem capability. A supervisor can dial into a CPU from any telephone, including at home or while on the road, to monitor data, analyze trends, and acquire the latest forecasts.

Similar capability should also be available to VAMS providing support to highway agencies. Access to observations is key to successful forecasting, and to building a knowledge base of weather conditions in locations of interest.

Information Transfer between VAMS and Highway Agency

A communications link must also exist between a provider of weather support, the VAMS, and the user of the weather information, the highway agency. There are a number of ways for the VAMS to transmit and the highway agency to receive weather and pavement condition forecasts. These include teletype, telephone, facsimile (fax), computer-to-computer, or combinations thereof.

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* For greater detail on communications, refer to the *Road Weather Information Systems. Vol. 2 Implementation Guide* prepared under this contract, and to a Transportation Research Board report entitled *Transportation Telecommunications* (National Research Council, Transportation Research Board 1990).

The format of the forecasts can also vary from detailed word descriptions to forms with boxes checked in menu fashion. The information contained in word discussions can be tailored to the needs of a highway agency, while menu-type forecasts tend to include standard types of information provided to all customers. The latter may also require further interpretation by snow and ice control managers, while the former might provide information in a form ready for decision making.

Another aspect of VAMS-highway agency communication is human interaction. For effective communication to take place, a snow and ice control manager must be able to talk with a meteorologist, and vice versa. For effective communication, the manager must understand what the meteorologist means, and the meteorologist must know what the manager needs. The meteorologist and manager also need to understand each other's capabilities and limitations. This verbal capability is also necessary for evaluative processes so that the VAMS meteorologists can improve their forecasting, and equally important, get notified that their forecasts were correct.

Information Dissemination to the Traveling Public

The primary purpose of snow and ice control activities is to maintain roadways that allow reasonably safe travel for the public. However, before travellers venture forth on the roads, they also need to be prepared for whatever the road conditions might be. Travellers, too, need to make decisions based on road condition reports.

Current road conditions are frequently available. Highway agencies apprise the public of these by one or more of the following:

- Local television and radio broadcasts
- Highway advisory radio broadcasts
- "800" or "900" highway agency-sponsored phone numbers
- Rest-area broadcasts
- Commercial local-area advisory broadcasts
- NOAA Weather Radio in some areas
- American Automobile Association (AAA) via telephone
- Visible indicators, like a wind sock
- Manually controlled message signs (e.g., "chains required" sign)
- Variable-message signs controlled by transportation centers

- Variable-message signs remotely controlled by sensors, e.g., visibility (fog), precipitation (ice or snow), and wind.

This list is not intended to be all-inclusive. It does point out that there are many ways for the public to obtain information, none of which is ideal at all times. It also shows that the potential exists for different information being provided simultaneously. This can lead to mistrust or eventual disuse. However, because of interest, curiosity, or real needs for weather information in routing or timing trips, the public is likely to demand pertinent observations and forecasts when RWISs are more widely established.

2

Conduct of the Research

In order to achieve the stated project objectives of identifying promising RWIS technologies and evaluating their cost-effectiveness, research was undertaken in a number of functional areas. These included pavement and meteorological sensors, road meteorology sources (especially tailored, site-specific forecasts), road thermal analysis, RWIS communications architectures, a computerized cost analysis, and development of an index for specifying winter severity. These investigations revealed a great deal about the ability of RWIS technologies to improve the effectiveness and reduce the costs of highway snow and ice control activities.

The Investigations

The project focused early on information gathering to determine the state of the art in measuring road surface conditions and meteorological conditions in the road environment, to determine the extent of use of road weather information systems within and outside this country, and to ascertain the potential for use of road weather information in support of snow and ice control activities in the United States. Information was gathered from an in-depth search of global literature on the subject of monitoring weather and road conditions, through written questionnaire surveys, through in-person interviews with snow and ice control managers, and through field tests of RWIS technologies.

Literature Search

As soon as this project was initiated, an extensive literature search was undertaken to assist in the determination of the state of the art in RWIS development and use. A large body of knowledge was found to exist in Europe. Two large efforts there were focusing considerable attention on RWIS development and testing.

First, through the European Community's (EUCO) Cooperation in the Field of Scientific and Technical Research (COST) program, member countries first performed an analysis of potential RWIS use to help with snow and ice control. The results were extremely encouraging (EUCO-COST 30 1983), and a project, COST 309, was initiated for sharing information and technology, testing RWIS hardware, and fostering RWIS technology development. Second, under the auspices of the Permanent International Assembly of Road Congresses (PIARC), which meets every four years, a Standing European Road Weather Commission (SERWEC) was formed to enhance the exchange of information and technology within the research community. In 1990, SERWEC was changed to the Standing International Road Weather Commission (SIRWEC) to reflect the inclusion of representatives from countries outside Europe, including the United States.

An extensive bibliography of RWIS-related literature is included with this report. Information from SIRWEC is either published by the individual researchers or appears in the SIRWEC newsletter, *Highway Meteorology.*

It is important to note that for a variety of reasons, very little research into RWIS use or development has been published in the United States. Firstly, the only research conducted in this country was by state highway agencies. Some of this research is published (e.g., New Jersey Department of Transportation 1988, Minnesota Department of Transportation 1989, Michigan Department of Transportation 1988), but frequently it is used only for internal decision making. Secondly, until 1990, there was for all practical purposes only one vendor of RWIS hardware in this country. Much of this vendor's technology is proprietary, whereas in Europe, such technology development is often government subsidized and implemented. Thirdly, most of the meteorological support provided to state highway agencies in the United States comes from value-added meteorological services (VAMS), private companies that provide tailored weather support beyond that which the National Weather Service provides. These VAMS tend to be very operationally oriented, and they conduct studies for their own purposes. They tend not to publish their findings.

Questionnaires

In order to determine the extent of use of RWIS components in support of snow and ice control, questionnaires were sent to all state highway agencies and to the provinces of Canada. In addition, information was sought on the range of snow and ice activities used by highway agencies and the costs of those activities. Responses were received from 82% of the states and provinces. Those that did not respond were contacted verbally to at least obtain their expenditures for snow and ice control.

State Highway Agencies

The large expenditures for snow and ice control were documented through this survey. Data from the survey in 1988 and 1989, plus calls to states which had not responded, indicated that states and Canadian provinces spend over $1.5 billion per year in this area. In addition, 1987 Federal Highway Administration (FHWA) data showed that $700 million more is spent by cities and counties in the United States for snow and ice control (U.S. Department of Transportation, FHWA 1987).

In addition to obtaining cost data, the survey documented the use of various RWIS technologies. This information was used to find agencies which were willing to participate in a formal evaluation of their technologies. These technologies include actual or planned installations of RWIS observing systems, uses of forecast support, actual or planned road thermal analysis, or unique installations which could be used to answer key questions related to the siting of observing systems.

The survey responses described the snow and ice control practices of the states using some form of RWIS. These descriptions proved useful in analysis of the utility of RWISs in support of snow and ice control. For instance, with respect to material use, agencies in certain areas of the country use large quantities of deicing chemicals, particularly sodium chloride. Some use abrasives and little or no chemicals, and others use mixtures of chemicals and abrasives. Figures 2-1 and 2-2 show the amounts of salt and abrasives used by the states according to returned surveys. Additional survey results are presented in Appendix D.

Finally, the survey data was used to select states to participate in the interview process or the field testing program.

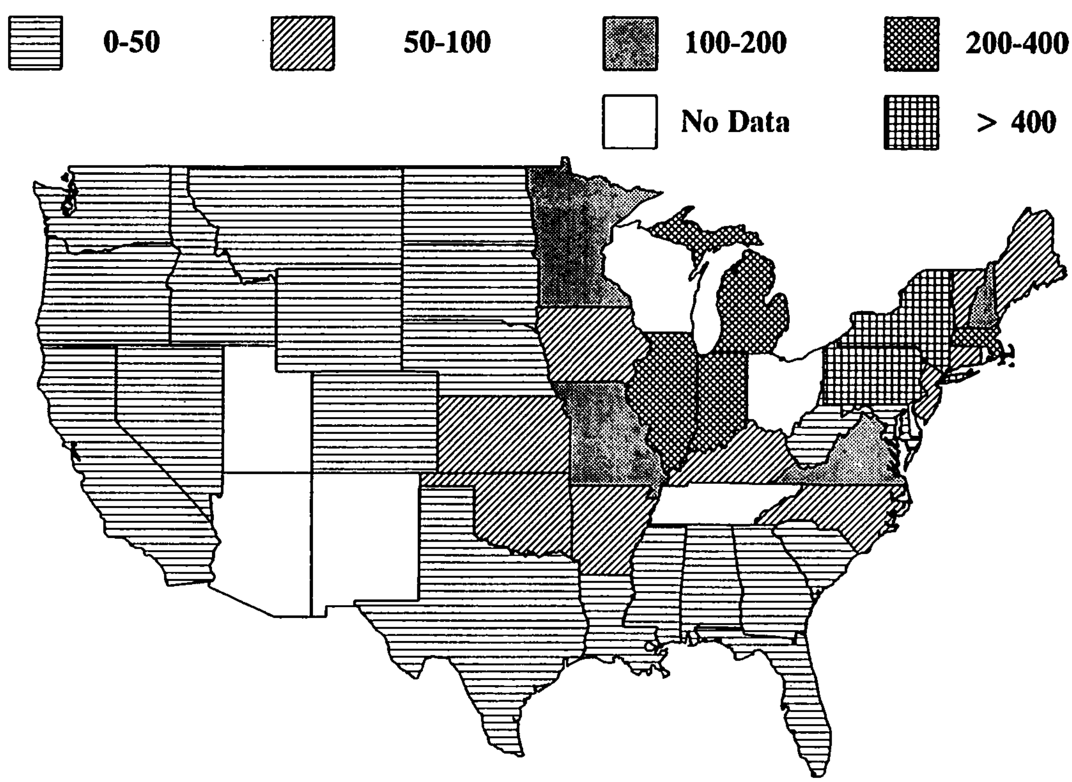

Figure 2-1. Reported annual salt usage by the states (thousands of tons)

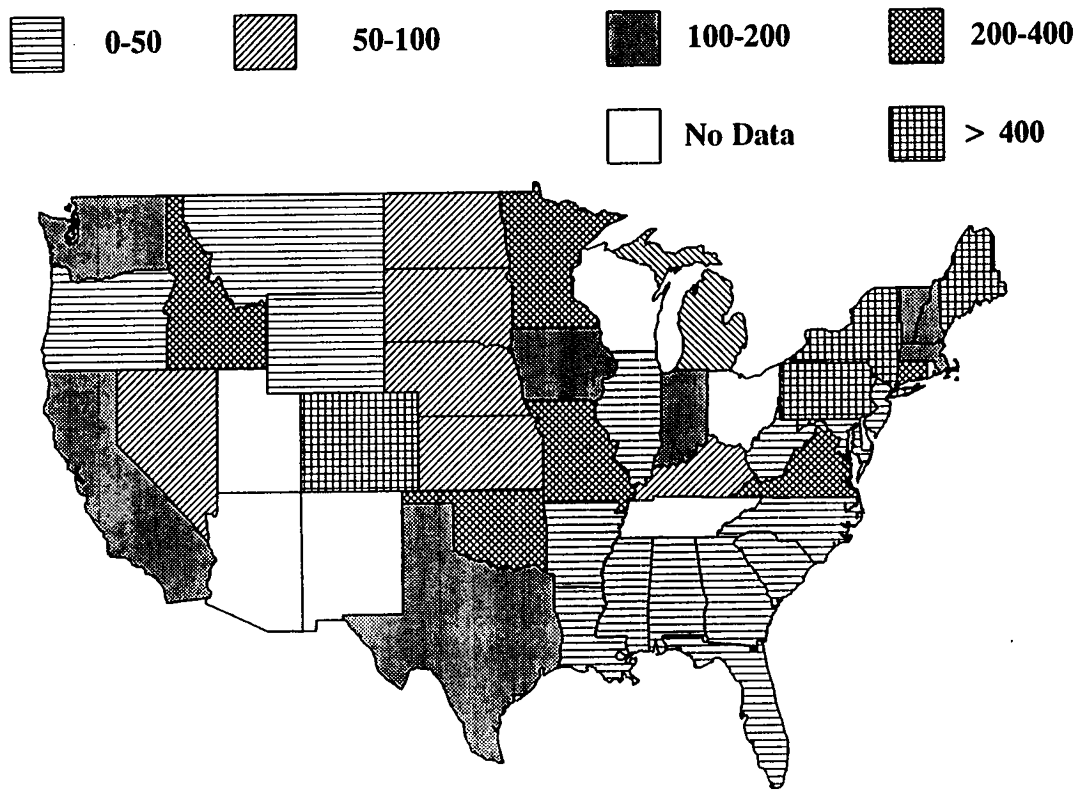

Figure 2-2. Reported annual sand usage by the states (thousands of tons)

Meteorological Hardware and Services Vendors

Questionnaires were also sent to vendors of meteorological and pavement sensing or observing equipment and to private providers of meteorological services. Questions were asked on topics which ranged from the types of forecasting support provided and accuracies of forecasts to the performance specifications of hardware. In general, the private meteorological community was unwilling to divulge information because of concerns over proprietary issues. Some vendors that did provide detailed information requested that the information be treated confidentially. Most of the information related to hardware was provided in advertising materials.

Interviews

Interviews were conducted with state highway agency snow and ice control managers and decision makers and with vendors of RWIS components. The primary purposes of the interviews were to determine the extent of in-place RWIS hardware and how pavement sensors were being used, to assess how weather information was communicated within or outside state highway agencies and how it was being used, and to determine if a state highway agency would be willing to participate in the field trials.

State Highway Agencies

These interviews thoroughly discussed state highway agency snow and ice control programs and their uses of labor, equipment, and materials. This topic was explored in order to determine what effect RWISs could have on their operations.

Ten states—Massachusetts, New Jersey, Pennsylvania, Michigan, Minnesota, Missouri, Colorado, Wyoming, Washington, and Alaska—were chosen for interviewing. Wisconsin was added later. In addition, interviews were conducted in British Columbia, Canada. These states and British Columbia were chosen because they were using or planned to use some RWIS components, represented a cross-section of different snow and ice control practices, and had varied climates. Also, British Columbia's highway ministry had recently carefully documented its maintenance procedures because of an initiative to privatize all highway maintenance, including snow and ice control, and it had some in-house meteorological support. Finally, RWIS uses may vary among state highway agencies according to their different snow and ice control practices and the types and frequencies of winter weather events they experience.

In all cases, interviews were conducted at every level of snow and ice control management. Initial interviews were usually held with state or district headquarters managers. From that point, interviews were arranged and conducted with supervisors who made the decisions to implement snow and ice control activities. Follow-on interviews were also held in most of these states to talk in detail about snow and ice control practices and to discuss possible field testing.

Vendors

Informal discussions were also held with vendors of RWIS components to establish a framework of cooperation in the conduct of this research. An evaluation of each vendor's products was never the intent of the research. The purpose of the research was to determine the utility and cost-effectiveness of the technologies. Operating with those ground rules facilitated the exchange of information between the project team and the vendors.

Field Tests

Although the data gathering and interviewing of snow and ice control personnel provided great insight into the current and potential uses of RWIS, a number of critical questions remained unanswered. These included:

- What meteorological parameters are critical in support of snow and ice control decisions and should therefore be measured?
- What are the optimum heights for weather sensor installations, in particular, wind speed and direction and relative humidity (dew point)?

- Where should weather and pavement sensors be placed along the roadway, i.e., how far apart should sensors be placed and how many are needed to give representative data?

- Where should pavement sensors be placed in the roadway in relation to the centerline, e.g., in a through lane or a passing lane?

- Should pavement sensors be placed in wheel tracks, lane center, or between lanes?

- What types of weather forecasting services can best serve highway maintenance agencies?

- What are the benefits and costs of the weather information options available to highway maintenance agencies?

These questions could best be answered by conducting field tests. Data gathered from in-place sensor systems and from highway maintenance agencies were analyzed to document the answers to the above questions and to determine costs.

Participants

Initially, three states were selected to participate in the field testing program for H-207: Minnesota, Colorado, and Washington. These states were selected because they are located in different climates, they have very different snow and ice control practices, and each had elected to test some forms of RWIS technology.

- The Minnesota Department of Transportation had installed one make of sensor in the Minneapolis area, installed a second make at its research facility near Monticello (Mn/ROAD) which could be used in analyzing variations in pavement temperatures across lanes of traffic, installed a third make and contracted for road thermographic and climatologic analysis in Duluth, had contracted for weather forecasting services to support snow and ice control managers, and had hired a meteorologist as a staff weather advisor.

- The Colorado Department of Transportation had installed a large number of sensors in the Denver area which could be used for analysis of the spatial variability of temperatures and requirements for numbers of sensor sites, and had contracted for weather forecasting services.

- The Washington Department of Transportation had contracted for road thermographic analysis and installed sensors in the Seattle area, had contracted for weather forecasting services for a number of areas in the State, and had participated in a unique, multiagency RWIS sensor system installation in the Spokane area.

It was believed that the combinations of weather technologies, practices used for snow and ice control, and different climates provided by these states would give sufficient information for answering the questions posed above. However, insufficient winter weather could occur in one or more of these locations. To preclude lack of data, four additional states were contacted to assist in data gathering: Massachusetts, New Jersey, Michigan, and Missouri. Each of these states had acquired and was testing or using some form of RWIS technology:

- Massachusetts had installed 16 pavement sensors in the Braga Bridge in southern Massachusetts. The bridge is high and long, prone to icing, and subject to varying surface conditions depending on the weather. The state also contracted with a weather forecasting service for snow and ice control assistance.

- New Jersey was one of the first states to install pavement and weather sensors, and based on in-house research, intended to expand its initial system located in southern New Jersey to other regions in the state, and had contracted for weather forecasting services.

- Michigan had installed sensors in the Lansing and Saginaw areas, the latter on the Zilwaukee bridge where they were also using only an alternative deicer.

- Missouri, in cooperation with the City of St. Louis, had installed a sensor system in Eureka. Missouri also installed RWIS technology in the Kansas City area.

Types of Tests

Three types of data were gathered with the assistance of the seven participants. First, the participants were asked to assess the utility of available weather information in making decisions and to document any cost savings (Figure 2-3). Forms were tailored to each maintenance unit participating. For example, the SCANCAST shown in Section VII of Figure 2-3 is forecast support provided to Michigan DOT by Surface Systems Incorporated.* Second, the participants were asked to make pavement temperature and atmospheric measurements using a hand-held infrared radiometer and portable air temperature/relative humidity instrument in order to determine the representativeness of temperatures measured by pavement sensors and atmospheric sensors (Figure 2-4). Finally, the three original test states were asked to provide diskettes of data acquired from in-place sensors which were used as follows:

- Data from an installation of eight pavement temperature sensors placed in four traffic lanes at the Mn/ROAD research facility near Monticello were used to help determine where temperature sensors should be placed in the road.

- Data from 14 different locations in the Denver urban area were used to analyze the number of sensors required to provide sufficient information for an area.

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* The mention of a brand name does not constitute endorsement of that product.

I-496 WINTER OPERATIONS, MASON GARAGE, MICHIGAN
Maintenance Response Recording Form
SHRP-87-H207 Field Tests

SECTION I

Date: ________ Beginning Time of Event: ________ Ending Time of Event: ________

Crew Configuration Dispatched: O2 ☐ O4 ☐ Decision Maker: Shift Supervisor ☐ Foreman ☐

SECTION II

Current Cloud Condition

Cloudy ☐ Mostly ☐ Partly Cloudy ☐ Clear ☐

SECTION III

From CPU at Time Above:

Roadway Surface Condition: ________

Pavement Temperature: ________

Chemical Factor: ________

Air Temperature: ________

Relative Humidity: ________

Wind Speed/Direction: ________

Pavement Temp Forecast: ________

SECTION IV

Actual Road Conditions at RPU

	Wheel Tracks	All Over
Dry	☐	☐
Damp-Wet-Slush	☐	☐
Ice	☐	☐
Snow	☐	☐
Ice Pack	☐	☐

Other ________

SECTION V WEATHER AND PAVEMENT FORECASTS

	Weather Forecast	Actual	Roadway Forecast	Actual
Fog or Dew	☐	☐	☐	☐
Rain	☐	☐	☐	☐
Freezing Rain	☐	☐	☐	☐
Snow	☐	☐	☐	☐

Road Conditions:	Start of Event	Length of Event	Type of Event
Forecast	________	________	________
Actual	________	________	________

Figure 2-3. Sample maintenance data collection form

Maintenance Response Recording Form
SHRP-87-H207 Field Tests
(Continued)

SECTION VI

Weather Conditions:	Start of Event	Length of Event	Type of Event
Forecast	________	________	____________
Actual	________	________	____________

SECTION VII What source of information triggered this written maintenance operation?

DOT Patrol	☐	Other DOT Maint	☐	Police	☐	NWS	☐
Radio or TV	☐	Forecast Service	☐	SCAN CAST	☐	Sensors	☐

SECTION VIII What winter operation was initiated based on this information?

Do Nothing	☐	Patrol/Watch	☐
Extend Shift	☐	Plow	☐
Call out DOT	☐	Abrasives	☐
Call out Contractor	☐	Chemicals	☐

ACCURACY OF FORECASTS
(place X in appropriate box)

ACTUAL	FORECAST: Winter Weather	FORECAST: No Winter Weather
Occurred		
Didn't Occur		

SECTION IX

Which of the following types of weather information saved money?

Pavement Sensors ☐ Forecast Service ☐ Media Forecast ☐

Estimate the amount of salt saved during this winter operation (Tons)

1-5 ☐ 6-10 ☐ 11-15 ☐ 16-20 ☐ Other ☐ ____________

Did you extend ___ or shorten ___ working hours as a result of the observed conditions ___, forecast weather ___, or sensor information ___?

Please estimate the number of working hours saved on this winter operation. ________

Did you receive any requests for road temperature ___ or chemical factor ___ from road crews?

List any other benefits that the weather information provided. ____________

____

____

Figure 2-3 (continued). Sample maintenance data collection form

Pavement Sensor Recording Form
SHRP-87-H207 Field Tests

Date: ______________ Time: ______________ State: **Michigan**

RPU Location: I-496 Sensor Location: Org: **Mason Garage**

Deck ☐ Service Road ☐

Adjacent Lane?

Yes ☐

No ☐

Outside Lane ☐

Center Lane ☐

Passing Lane ☐

In Track ☐

Lane Center ☐

Outside Track ☐

Radiometer measured <u>sensor</u> temperature (Degrees Fahrenheit) ☐

Radiometer measured <u>pavement</u> temperature: (Degrees Fahrenheit)

Maximum ☐

Average ☐

Minimum ☐

Weather Conditions:

Cloudy ☐ Partly Cloudy ☐ Clear ☐

Windy ☐ Light Wind ☐ Calm Wind ☐

Rain ☐ Snow ☐ Fog ☐

Comments: ____

Pavement Condition: Dry ☐ Wet ☐

Ice ☐ Snow ☐ Frost ☐

Traffic Conditions: Light ☐ Medium ☐ Heavy ☐

If possible, please provide and estimate of the number of vehicles per 5 minutes in lane ______

Figure 2-4. Sample pavement temperature data collection form

- Data from three sensor installations in the Seattle area were used to compare with road thermography data to assess the validity of the road thermography.

The field tests were conducted in all locations from October 1, 1990 through March 31, 1991. In order to establish a common framework for the testing, a meeting was held with the participants in each state to provide guidance on how to fill out the forms and how to use the measuring instruments. Ground rules for obtaining measurements were discussed. For instance, in order to make the workload manageable for the state highway agencies, and since freezing is a critical highway consideration, the state highway agencies were asked to obtain pavement temperature measurements when the pavement temperature was expected to go to or below 32°F (0°C). The state highway agencies were told that safety of workers had to be the foremost concern, and if conditions in the road environment were too dangerous, e.g., not enough spacing between vehicles to ensure being able to obtain pavement temperature measurements safely, then measurements should not be taken. The Manual of Uniform Traffic Control Devices (MUTCD) was to govern in all cases with respect to needed traffic control.

In addition to the data collection by the state highway agencies, the research team conducted its own field tests. Initially, these tests were conducted primarily to gather radiometric pavement temperature data to determine the validity of road thermography which had been conducted in Minnesota and Washington. However, after some early measurements by state highway agencies with the hand-held infrared radiometers indicated that there were some discrepancies between sensor temperature reports and the radiometer reports, additional pavement temperature measurements were taken by the research team and the state highway agencies in order to try to assess the magnitude of likely errors. Details are discussed in the following section, "Investigation of the Use of Sensors."

Finally, after more than one state observed these temperature discrepancies, the vendors of pavement sensors were notified. SSI undertook a detailed investigation of the use of the hand-held radiometer to measure pavement temperatures. The results of their investigation pointed to problems in using the radiometer. It also indicated that the radiometer could be used for measuring pavement temperatures under carefully controlled circumstances and when used in a specific manner by a knowledgeable user (SSI 1991). Guidance is provided in the following section.

Investigation of the Use of Sensors

There were two major objectives in investigating pavement and meteorological sensors. The first was to determine their current and potential uses. The second was to determine where sensors should be placed in the roadway and how many of them are needed in an area.

Uses of Sensors

The following descriptions of the uses of sensors are based on information gathered primarily from the interviews. The field tests did provide some additional insight, although they were designed to address more specifically the issues related to the siting of sensors.

Pavement Sensor Uses

There are two kinds of pavement sensors, in situ or in-place sensors, and remote sensors. Examples of in situ pavement sensors include simple thermistors or thermocouples installed in a road surface to measure pavement temperature. More sophisticated in situ devices provide surface temperature, indications of the concentration of deicing chemicals on the road, and an indication of the state of the surface, e.g., whether it is wet or icy. Because they provide a great deal of information, these sensors can have a number of uses.

Remote sensors provide information from some distance. Weather radar is an example of a remote weather observation. Research is being conducted in Europe on the use of remote microwave sensors installed along roadways to determine pavement temperature and surface conditions. Such observations may prove very useful because in situ measurements represent only a very small surface area, on the order of tens of square centimeters, compared to remote measurements of tens of square meters. The latter observations may be more representative of the road environment than those obtainable from the smaller in situ instruments.

Sensors can also be active or passive. The in situ sensors discussed above are passive. Changes in their electrical properties are used to determine the temperature or condition of the road surface. Active sensors have now been developed: a freezing-point sensor actually cools a surface to determine at what temperature moisture on the surface will freeze, then heats it to repeat the measurement cycle. This information is potentially more valuable than pavement temperature alone since it will measure the effects of any deicing chemical present. If the freezing point is known, then a forecast of minimum pavement temperature can be used to determine whether a surface will freeze.

Pavement sensors are used for three purposes: *detecting*, *monitoring*, and *predicting*.

- First, they are used to *detect* critical conditions or the attainment of critical thresholds for decision makers. They serve an alerting function. For example, alerts include the surface temperature reaching 32°F (0°C), the presence of moisture, or the occurrence of precipitation. Each of these can be a critical piece of information on which a manager wishes to take action, or at least be notified. Without sensors, such notification must come from observations from highway crews, police, or the traveling public. Unfortunately, many times, the notification comes from the police providing "constructive knowledge" of a situation that requires attention because an accident has occurred and the highway agency must take action. Some highway agencies use road patrols to detect critical conditions, but this turns out to be a costly alternative.

- Second, pavement sensors can be used to *monitor* current conditions. Although monitoring and detecting may be similar, detecting is associated with alerting and reacting. Monitoring sensor output allows a manager to assess the progress of weather conditions or snow and ice control activities. A pavement sensor provides the ability to monitor road temperatures and compare them to forecasts, to monitor road conditions "upstream" in the weather pattern or prior to a weather change, to assess the progress of weather as road conditions change, and even to assess the progress of maintenance work. For example, a pavement sensor that measures the conductivity of the surface, i.e., the amount of deicing chemical present, provides information to a manager concerning whether chemicals should be applied, or even when they were applied. There were situations revealed in the interviews where supervisors had cross-checked maintenance logs against pavement sensor data to determine when chemicals were applied on a specific route. Also, such data become a valuable resource for documenting maintenance actions if faced with liability claims.

- The third use of pavement sensors is for *prediction.* The most savings in snow and ice control will come from maintenance managers making timely and effective decisions about snow and ice control activities. To do this, managers need to know what conditions are expected. One of the important forecast parameters is pavement temperature. A critical input into pavement temperature forecast models is subsurface temperature. A subsurface temperature probe assists in forecasting surface temperatures. A surface temperature sensor also allows for fine-tuning or updating surface temperature forecasts.

Meteorological Sensor Uses

Meteorological sensors can also be used for *detection*, *monitoring*, and *prediction* purposes.

- For ice *detection* purposes, the dew point is critical. If the pavement surface temperature falls below the dew point, moisture will condense on the pavement. If the ambient temperature is less than or equal to the freezing point of the road surface, then ice or frost will form on the pavement. The dew point measurement then becomes part of the detecting/alerting system.

- Meteorological sensors also play a large role in *monitoring* current conditions. Although the pavement temperature is important, monitoring the weather conditions upstream or downstream helps in the decision to initiate or suspend maintenance actions. For example, in areas of prevailing westerly winds, data from an RPU to the west can be the first indication that predicted weather will or will not occur. A precipitation detector might sense the first snowfall. Temperature drops and wind speed and direction changes can indicate that a weather system is progressing. In other areas, monitoring the wind speed and direction may provide clues to what kind of road conditions will occur and what maintenance activities may be needed.

- Meteorological sensors also aid in *predicting* road and weather conditions. Accurate forecasts require knowledge of current conditions. Wind, temperature, and moisture patterns determine what will take place in terms of weather and road conditions. A weather forecaster who has meteorological data available will make a more informed and accurate forecast. The data can also be used for special studies of weather phenomena to improve forecasting. Such "local forecast studies" are extremely valuable in improving forecast capability.

Field Testing of Sensors

Several field tests of sensors were conducted. These dealt with the representativeness of pavement sensor reports, optimum sensor placement in the roadway, and locating RPUs and weather sensors along roadways.

Representativeness of Pavement Sensor Reports

The states and the research team gathered data using hand-held radiometers to determine pavement sensor report representativeness. It was decided to use infrared pavement temperature measurements because contact devices require too much time to be used safely in many of the highway test locations. Sensors at selected RPU locations were to be checked whenever the temperature reached 32°F (0°C). This temperature was selected because sensors should be most representative when the surface temperature is near freezing. Each state highway agency was provided a Raytek PM-4* radiometer to take pavement temperature measurements. A radiometer indicates the temperature of a surface in terms of its infrared radiation; the readout is directly in degrees Fahrenheit (°F) or degrees Celsius (°C). The state crews were instructed to point their radiometers vertically at sensors in the pavement to measure their temperature. Then the radiometers were pointed at the pavement surrounding the sensors, and the average, maximum, and minimum temperatures were recorded. Finally, and if conditions permitted, the average, maximum, and minimum temperatures from an adjacent lane were recorded. Records of the pavement temperature sensor outputs were also annotated. All measurements were documented in °F.

Temperature Reporting Accuracy. It was never the intent to check the accuracy of individual pavement temperature sensors. However, it soon became apparent that some discrepancies existed. The first two state highway agencies to receive their radiometers found that they were frequently getting radiometer-reported pavement temperatures 5-7°F (3-4°C) lower than the sensor-reported temperatures. The research team conducted its own investigation using a site in Washington State and found the same discrepancy. The team

* The mention of a brand name does not constitute endorsement of that product.

had also used a contact probe as a backup, and this confirmed the discrepancy. Subsequent measurements by the research team using another vendor's sensors produced the same discrepancy. This indicated that there was more of a problem with temperature reporting than just whether sensor temperatures were representative of road temperatures.

There are a number of reasons why this discrepancy can occur.

- A sensor is thermally isolated from the pavement by the mastic used to cement the sensor into the pavement.
- The backfill materials under a pavement sensor may change the thermal flux beneath it.
- A subsurface sensor may be installed beneath a surface sensor providing a thermal conduit below the latter different from adjacent pavement.
- A sensor exterior is thermally different than the pavement due to its construction and materials.
- The thermal characteristics of an entire sensor, including its electronic components, are different from those of pavement.

Each of the three major vendors of pavement temperature sensors was notified that these discrepancies had been observed. The team was informed by one manufacturer that the sensor was designed to report "accurately" when the road surface condition is wet and the sky condition is either cloudy or dark. This was a conscious decision by the manufacturer because it believed that wet and dark/cloudy conditions presented the worst situation for snow and ice control decision makers.

Under sunlit conditions and dry pavement, these sensors may register temperatures higher than the surrounding pavement. This means that for frost or black-ice situations, pavement temperature sensors may report temperatures too high. However, under some sunny conditions and wet pavement, or even recently wet appearance, these sensors can report pavement temperatures accurately.

Sensor Calibration. It is sometimes impossible to tell how representative pavement sensor readings are of the pavement temperature because in general, there is no record of sensor calibration after installation. The discrepancies discussed above can only be described in relative terms because of a lack of knowledge of actual sensor maintenance. Based on the SSI evaluation of the Raytek PM-4 radiometer, Mr. Robert Hart (personal communication, 1991) suggest that a procedure could be developed to use such an instrument to calibrate surface temperature sensors.

Radiometer Use. Some of the temperature discrepancies noted earlier may have been due to problems in using the radiometer. Problems arise from:

- Taking a warm radiometer into the cold exterior environment and inducing it to thermal shock. All participants were asked to keep their radiometers in a cold vehicle trunk or pickup bed. If that were not possible, the instruments were to be placed outside in the cold to stabilize. The research team's radiometer was always stored in a trunk overnight before measurements were taken.

- Measurements taken too high above the pavement. A detailed investigation conducted by SSI showed that the Raytek radiometer was accurate if placed just at the pavement surface (SSI 1991). Temperature differences of up to 2°F (1°C) were introduced by holding the radiometer 20 in. (0.5 m) above the pavement.* For absolute temperature measurements, this could be a problem. For relative differences, it should not be. All participants were instructed to take measurements at knee height to obtain relative measurements.

Based on the research conducted by SSI and the research team, the following general instructions should be followed when using a radiometer to measure surface temperatures:

- Always keep the radiometer in a cold environment, such as the trunk of a vehicle, in order to minimize the thermal shock the instrument will experience if moved from a warm environment to cold. Thermal shock produces erroneous readings.

- If the instrument cannot be stored in a cold place, when arriving at a measurement site, place the instrument outside but not exposed to solar radiation for at least 30 minutes to allow it to cool to ambient temperature.

- Take a measurement by holding the radiometer vertically 1 in. (about 2-3 cm) above the pavement. Resting the instrument on the toe of a shoe and pointing it at the surface provides a reasonably consistent method of measurement.

- Take measurements before sunrise to avoid solar radiation entering the instrument.

- Take at least four temperature measurements at each location. Compute the sample mean and standard deviation of the measurements. The sample standard deviation should be less than the error of the instrument (as specified in the manufacturers' literature).

The radiometers were acquired to collect relative temperature measurements, and to determine the representativeness of sensor measurements of the roadway temperature. Experience with the radiometers suggests that careful procedures need to be established for their use, they should be used by trained personnel, their measurements should **not** be considered absolute, and they should be calibrated carefully.

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* The research team was not able to verify the discrepancy positively. The SSI measurements were taken using a radiometer and a thermistor implanted in the pavement. Research team measurements were taken using a radiometer and a contact probe. Differences of up to 2°F (1°C) were noted when taking measurements at about 20 in. (0.5 m) and 1 in. (2-3 cm) above pavement. However, the two-degree difference is within the combined errors of the two instruments.

Data Reporting Frequency. It is very difficult to verify data from pavement sensors that do not provide data on a regularly-scheduled basis. In most RWISs, if no critical thresholds are crossed, no data are reported. This condition can exist for hours. A data user is unable to tell if there are no data reports because of no change or because of malfunctions. The values of parameters such as surface temperature can only be estimated during this condition.

Sensor Placement in the Roadway

Hourly data from Mn/ROAD were used to assess where sensors should be placed in the roadway. The Mn/ROAD consists of approximately five kilometers (three miles) of Interstate Highway 94 (I-94) west of Minneapolis near Monticello. There are four lanes of rural commuter highway, with an average daily traffic (ADT) of 25,000. The eastbound asphalt lanes carry inbound (toward Minneapolis-St. Paul) commuter traffic; the westbound portland cement concrete lanes carry outbound commuter traffic.

Two surface sensors are located in each lane, one in the center of the lane, the other in the outermost wheel track. Sensor locations in the roadway are shown in Figure 2-5. The sensor located in the westbound inside lane wheel track (#6 in Figure 2-5) was selected to be the reference against which the other sensors were compared. This sensor was selected because it is located in what was anticipated to be the coldest location. Research in Sweden had indicated that vehicles can affect pavement temperature, and that the greatest influence is in the center of a lane (Gustavsson and Bogren 1990). In addition, data provided by the Washington State Transportation Center indicate traffic volumes tend to be larger in the outside lanes, especially during inclement weather (personal communication with Scott Rutherford, 1991).

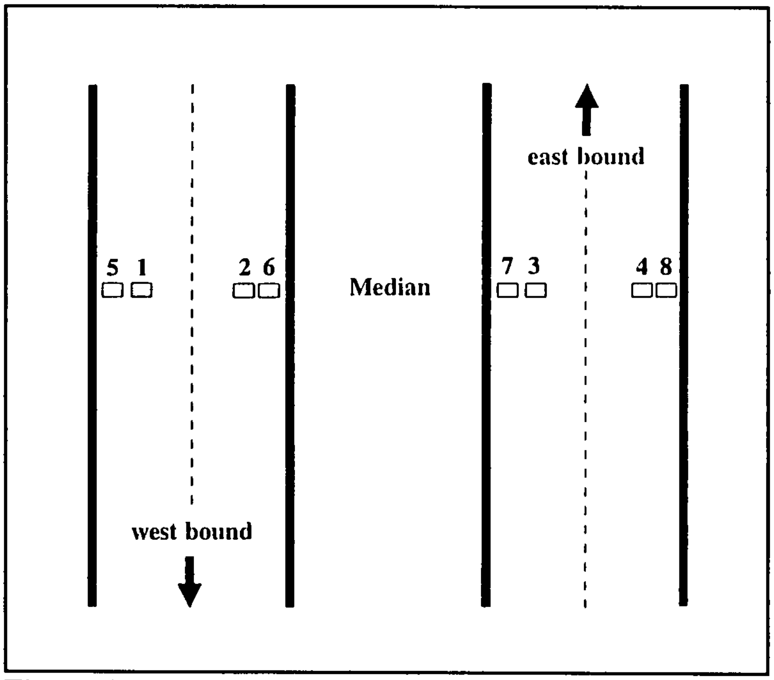


Figure 2-5. Sensor locations in the Mn/ROAD pavement

A large volume of data was obtained from the Minnesota Department of Transportation on computer diskettes. Three months of data were processed to analyze the temperature differences between the seven sensors and the reference. The statistics for January and February are given in Table 2-1.

The statistics indicate that the temperature differences, when averaged over a long period of time, show little difference, except for sensor #8.* However, there were other possibilities for temperature differences that would be masked when considering the long-term averages. Daily fluctuations in traffic and atmospheric phenomena, as well as changes due to pavement conditions (wet, dry, frozen), could also influence the sensor temperatures.

First, the temperatures were compared by time of day to determine the extent of diurnal influences. Because of the large volume of data, observations were processed for three-hour periods from 5:00 a.m. to 9:00 p.m. These times were selected because 5:00 a.m. covers the cold period before any influence from traffic, 8:00 a.m. covers the morning commute inbound to Minneapolis-St. Paul, 3:00 p.m. picks up any solar influence, and 6:00 p.m. covers the evening commute. Data for two time periods are shown in Figures 2-6 and 2-7.

Table 2-1. Deviation of sensor pavement temperatures from reference sensor (#6), January-February 1991

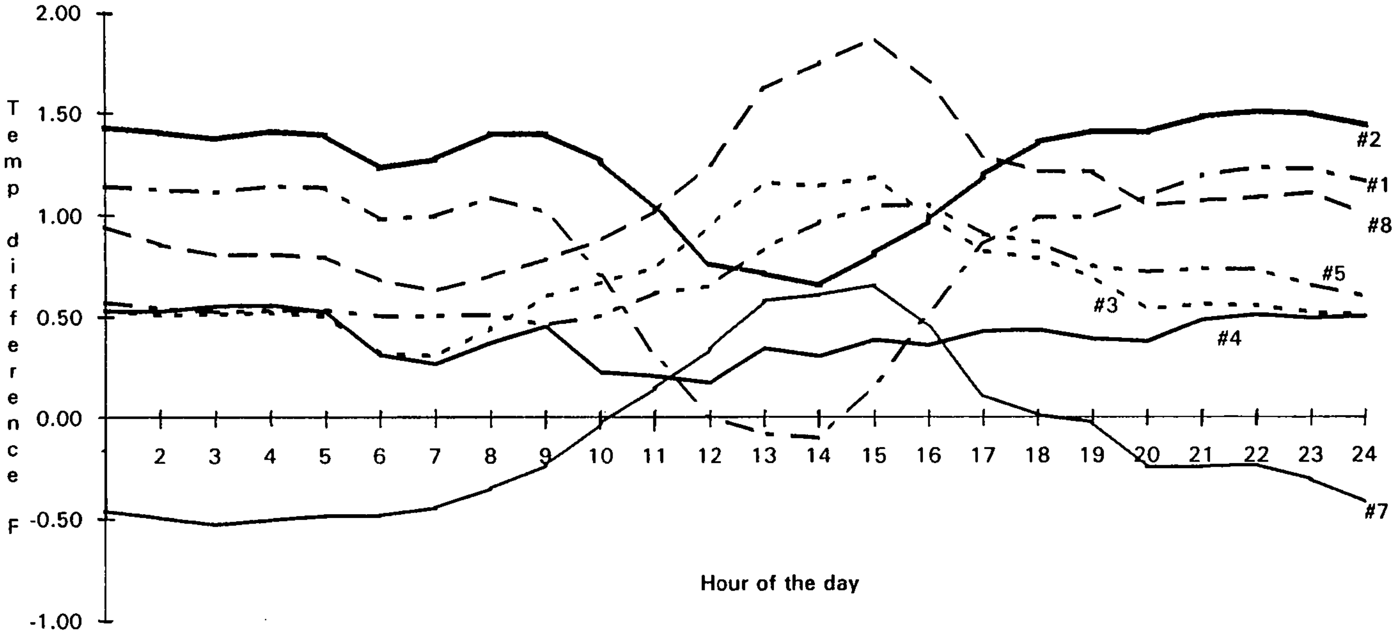
	Temperature Deviation (in °F)						
Sensor #	1	2	3	4	5	7	8
Mean difference	0.6	1.1	0.7	0.4	0.6	-0.1	1.2
Standard deviation	1.1	0.9	0.7	0.8	0.4	0.7	0.8
Maximum	4.3	5.3	3.7	3.0	2.0	3.8	4.8
Minimum	-5.1	-3.7	-1.0	-3.6	-3.4	-2.5	-1.2
Variance	1.2	0.7	0.5	0.7	0.2	0.5	0.7

The data indicate that temperatures in the center of the lanes are warmer than in the wheel tracks, and that traffic volume influences the temperatures. However, it is the experience of most snow and ice control people that wheel tracks clear first. This is due to tire grinding, pressure, and friction, which overcome the tendency for the wheel tracks to be cooler. It should also be pointed out that these temperatures are measured without snow or ice cover.

In order to relate temperature differences to traffic, volume data were requested from Mn/ROAD. Temperature differences resulting from traffic could not be obtained because only daily ADTs were available; no data were available by hour.

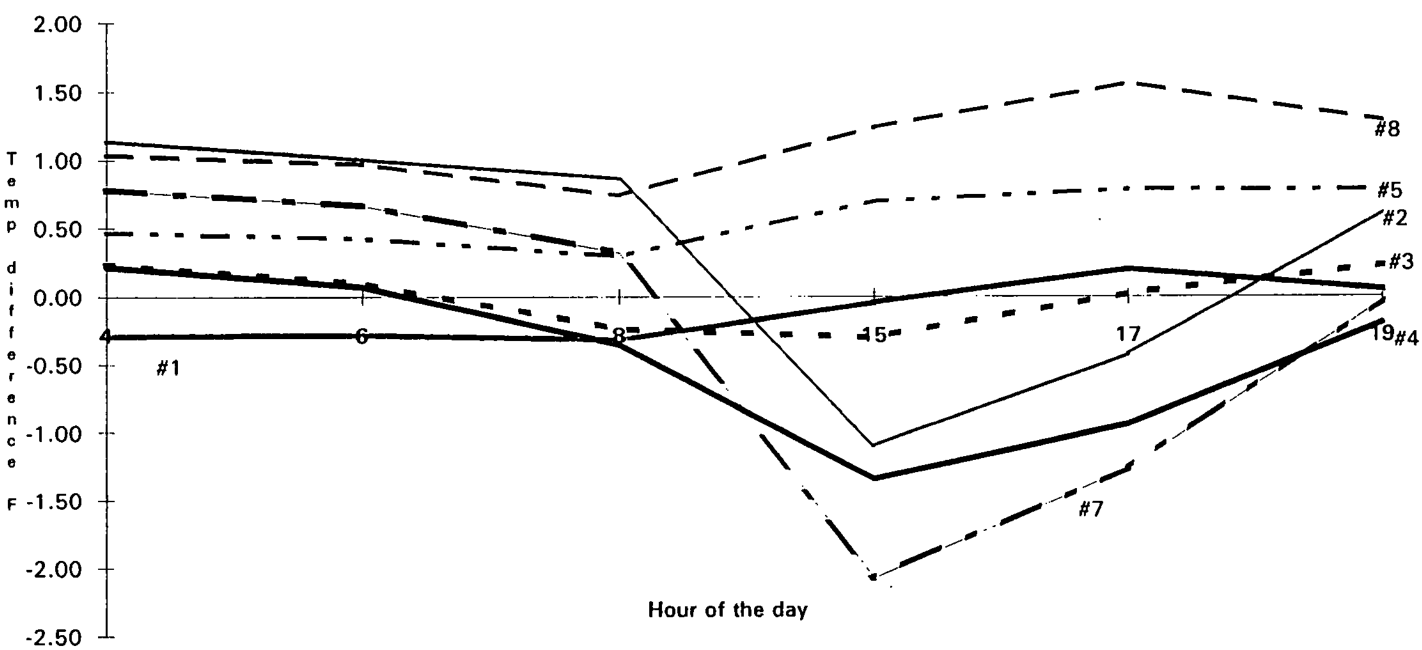
The team also attempted to determine the influence of pavement surface conditions on the temperatures. Each sensor provided an output indicating whether it was wet or icy. Solar radiometer measurements indicated whether it was clear or cloudy. The pavement temperature observations were classified into wet, dry and cloudy, and dry and clear cases.

* Separate measurements with a radiometer and a contact probe at the site indicated that sensor #8 was consistently reporting temperatures too warm.



Based on average temperature differences between sensor #6 and other sensors during January 1991

Figure 2-6. Sensor temperature differences at Mn/ROAD facility, January 1991



Based on average temperature differences between sensor #6 and other sensors during the period 3/1/91-3/25/91

Figure 2-7. Sensor temperature differences at Mn/ROAD facility, March 1991

However, in the middle of January, the sensor system stopped reporting the pavement condition properly. The vendor was contacted to see if the data could be corrected. No response was received by the end of the field test.

Recommendations for Sensor Placement in the Roadway

Maintenance engineers frequently disagree on precisely where pavement sensors should be placed in the roadway. Several different options exist which depend on the type of road surface, traffic volume, and the purpose of the sensor information.

Pavement sensors are used to *predict, detect,* and *monitor* road and weather conditions. For *prediction* purposes, sufficient sensor installations are needed to provide reliable information to whoever is making the road temperature and/or weather forecasts.

Care should be taken to ensure that the slope of a road at any location is such that there is no drainage onto sensors from the shoulder or the median. Sensors should not be placed in the roadway on curves.

Placement within Lanes. There is also a range of opinions on where sensors should be located within lanes. Table 2-2 provides a matrix of options for sensor placement within lanes. Figure 2-8 depicts these locations graphically. Placing sensors for *prediction* of pavement temperature and *monitoring* of forecasts should be the primary criteria. When *detection* of current conditions is desired, installing an additional sensor at a location selected for prediction offers the opportunity to obtain both prediction and detection information.

Placing sensors in wheel tracks is another possibility. Wheel tracks tend to get cleaned out by tire friction, and may not be representative of the rest of a roadway. Heavy vehicles such as trucks can disturb the pavement surrounding a sensor. Also, with significant road surface wear, water can pool and ice can form first in the wheel tracks. In other circumstances, particularly in high traffic volume areas, wheel tracks can dry out first.

The centers of lanes in urban environments can be affected by vehicle heat. Pavement temperatures can be as much as 2°F (1°C) higher in lane centers. Since vehicle heat influences pavement temperature, placing sensors in the center of lanes is not recommended.

Another possible location for pavement sensors is between lanes. This area is probably the least disturbed, but it is also subject to increased concentrations of deicing chemicals and debris. In addition, sensors here could be accidentally covered with paint during striping operations.

Table 2-2. Suggested placements of pavement sensors in roadways

	Location of Pavement Sensors within Lanes			
	Urban (Commuter Route)		Rural (Non-commuter Route)	
Primary Use of Sensors	Multilane Road	Two-lane Road	Multilane Road	Two-lane Road
Prediction	Just outside of outside wheel track of outbound passing lane	Just outside of outside wheel track of outbound lane	Just outside of a wheel track of a passing lane	Just outside of a wheel track of either lane
Detection	Just inside of outside wheel track of inbound through lane	Just inside of outside wheel track of inbound lane	Just outside of a wheel track of a through lane	Just outside of a wheel track of either lane
Monitoring	Use prediction placement whenever possible			

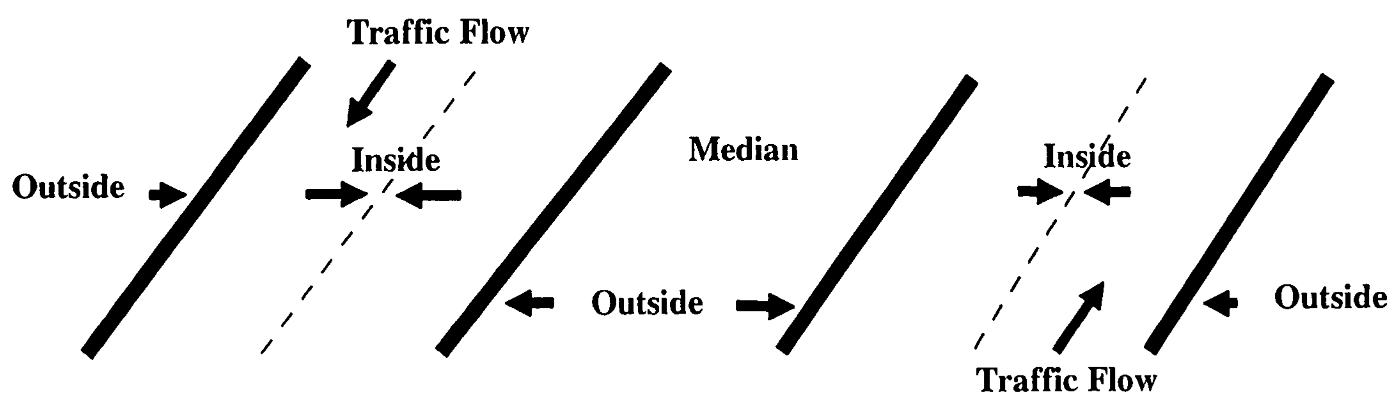


Figure 2-8. Lane orientation

Placement within Wheel Tracks. There is considerable discussion among highway engineers as to just where sensors should be placed in wheel tracks. Some prefer the center of tracks because that is where most of the vehicles run; others prefer just off-center to get out of the bottom of the track. In portland cement concrete surfaces, the precise location may not be as crucial as in asphalt because PCC pavements do not generally rut as deeply as asphalt surfaces. Whatever lane is chosen and for whatever purpose, it is suggested that pavement sensors be placed approximately 8-12 in. (0.2-0.3 m) from a wheel track center. This will keep the sensor away from vehicle influences in the center of the lane, outside the possible pooling of materials in the wheel track bottom, yet close to where engineers want to know what is going on. Figure 2-9 provides a cross-sectional view of preferred sensor placement in a lane.

Care should also be taken to ensure proper placement in grooved pavement. The top of a sensor should be flush with the top of grooves so that groove runoff does not flow onto the sensor.

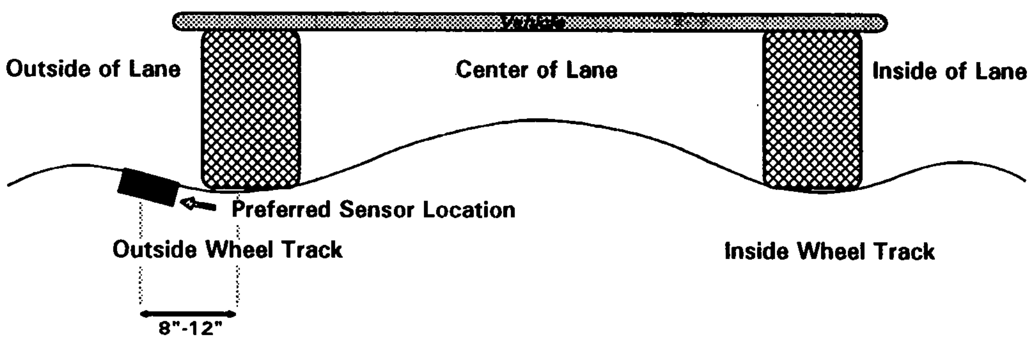


Figure 2-9. Sensor placement in a lane

Location of RPUs and Weather Sensors

There can be no hard and fast rules for RPU station location in relation to an area or roadway. Each situation must be decided based on agency needs, weather and road conditions, trouble spots, traffic volume, and snow and ice control policy. In general, any siting analysis needs to weigh operational considerations against meteorological needs. Analysis of RPU siting indicated that state highway agencies frequently make siting decisions more on cost than on representativeness of observations.

RWIS sensor data can be used for *predicting*, *detecting*, and *monitoring* weather and road conditions. For *predicting*, from a statistical perspective, a minimum of four RPU stations is required based on the simple assumption that if the pavement temperature is distributed normally, four samples are needed to assure a 95% probability that the sample mean is within one standard deviation of the actual mean (Larsen and Marx 1986). Using this same statistical assumption, if more than five degrees of pavement temperature variation are expected, six sensors should be installed: one sited to sense the warmest temperature expected, one which will sense the coldest, and four located to sense temperatures close to the mean.

The mean is important for predicting purposes. If the RPU sites are all forecast (predictive) and "mean temperature" sites, they can be used to provide confidence in the accuracy of forecasts. The warm and cold sites, also predictive sites, establish the outer limits of temperature ranges predicted.

This statistical basis for siting may be outweighed by operational needs because of a requirement to monitor trouble spots. Thermal analysis can help locate representative predictive sites near trouble spots. A site can then become dual-purpose.

In the Denver area, RPU stations are installed at 14 locations with a total of 56 pavement sensors in roadways and bridges. The sites are placed to supply data from all quadrants of the urban area. For an analysis of the number of sensors needed in an area, five sensors were selected to compare to a reference sensor. The six sensors selected were located in four quadrants of the Denver area, plus one near the center of the area.

Data were to be acquired during the period December 1, 1990 through March 31, 1991. The CPU at the Colorado Department of Transportation became inoperative for a period during December and January. However, the Colorado Department of Transportation had sensor data for all of the winters their system had been in place. Data for the 1989-1990 winter were then analyzed to investigate sensor spacing requirements.

Considerable effort was required to process the data. First, the Colorado Department of Transportation data are transmitted to the CPU from the RPUs when critical thresholds of the measured parameters such as 0°C are crossed. If none is crossed, no data are transmitted. Frequently, no data are available for certain hours, and hourly analysis is hampered. In addition, there is no separate record of sensors being inoperative or inaccurate. The data had to be viewed manually and determinations made that sensors were or were not working properly. Sensors that were not functioning had "out-of-range" values to indicate they were inoperative. The out-of-range values had to be manually located, then stripped from the archived data for each nonfunctioning sensor.

The temperature variations were extraordinary. Under sunny conditions in October, average temperature *differences* ranged from +43°F (+24°C) in the early morning hours to -33°F (-18°C) in the afternoon over ten consecutive days. Under cloudy skies and with snow/ice or wet pavement, the variation ranged from +10°F (+6°C) in the early morning to about -2°F in the afternoon. Analysis of the actual temperatures revealed that most of the variation came from comparing a sensor in the deck of an elevated roadway to a sensor in a road on grade.

Sensors were then divided into bridge-deck and road-on-grade categories, with 19 sensors in each category. A sunny day was selected for analysis. The deck sensors showed the greatest variation, with the standard deviation reaching nearly 20°F at 2:00 p.m., and about 2°F at 5:00 a.m. This indicated the variability in the influence of the sun and variation in deck construction. The on-grade sensor standard deviation varied from about 3°F at 5:00 a.m. to about 7°F at 2:00 p.m. From a statistical standpoint, the large standard deviations indicate that the sensors in the Denver area provide more variance than is desired for determining mean temperatures. Four sensors sited in locations that represent the mean would provide better confidence in measured and hence predicted pavement temperatures. Deck sensors are installed for monitoring and detecting, not predicting the mean.

If the starting point for site selection is the experience of maintenance crews, they frequently identify more places to locate sensors than there are funds available, and they do not always suggest the best places. When sensors are relied on only to *detect* snow and ice problems, managers are forced into reactive maintenance, and they frequently spend more time and resources than if the maintenance decisions were based on forecasts. The cost savings are greater when detailed, site-specific forecasts are made and used, even for trouble spots.

Recommendations for Location of RPUs and Weather Sensors

Prediction of road temperatures and conditions should be the primary purpose for siting RPUs and weather sensors. However, if *detection* and *monitoring* are the principal reasons, then decisions have to be made on how many RPUs are needed to give sufficient knowledge of road conditions. Highway agencies that use deicing chemicals may find that pavement sensor information, including chemical factor and surface temperature, is critical. Highway agencies that use abrasives may not find the chemical factor as useful. Highway agencies with few winter weather events may find that forecasts are sufficient, rather than establishing a network of sensors. And regions where conditions are rather uniform may also get by with fewer sensors than an area with significantly variable terrain and weather patterns. As will be discussed later in an economic analysis, placing sensors only for detection at many trouble spots becomes expensive because of the relatively high cost of sensors compared to the cost of forecasts, and the greater reductions in the costs of snow and ice control that are possible with detailed forecasts.

It is impossible to describe every possibility for RPU siting. The criteria discussed below have to be adapted to individual situations. The following paragraphs describe some of the factors to consider in selecting RPU and sensor sites:

Terrain Variation. Local terrain variation provides the greatest challenge for snow and ice control. Higher terrain can increase precipitation, and the location of roads relative to terrain can determine whether they will be subject to rain or snow, ice or frost, blowing and drifting snow, cold air pockets, and sources of moisture. Depending on the road and the elevation change, a manager might wish to have RPUs and sensors at a high point, a low point, and/or somewhere in between.

Weather Patterns. Analysis of the weather impacts in an area will usually reveal that the majority of snow and ice control problems occur under certain weather patterns. Siting of RPUs should include locations which assist in the identification and prediction of those patterns and the resulting road conditions. An example is placing a sensor system on the west or southwest side of an urban area because that is the prevailing direction from which weather comes.

Trouble Spots and/or Bridge Decks. Although such locations may be obvious from an operational standpoint because maintenance personnel need to know what is going on there, prediction of future conditions at such locations may be just as important as data about current conditions, and certainly would provide information for timely and efficient decisions. Near bridges, sensors for prediction need to be placed in roadways.

Crew Knowledge of each of the above can significantly contribute to effective pavement sensor location.

Thermal Analysis. Thermal profiles of roadways assist in determining the warmest and coldest locations along those roadways. Thermal profiles also identify locations suitable for specifying average temperatures, especially locations which may be at or close to trouble spots or bridge decks of concern.

Statistical Analysis, such as that described above to be able to specify the mean pavement temperature.

RPU Spacing. Analysis of RWIS data from the Denver area, and monitoring the use of data from other locations, show that four to six RPUs in an urban area can provide sufficient information for snow and ice control. Spacing of about 20 mi (30 km) along a road or in an area can be used as a guide. The 20 mi (30 km) spacing also matches the smallest-scale forecasting models planned for use in this country.

Cost. Certainly the cost of each RPU installation—which can cost between $20,000 and $40,000—has to be a consideration when determining the number of installations. This cost varies depending on such variables as the number of pavement sensors, the types of atmospheric sensors included, or whether a tower is included. Additional costs can be incurred for manufacturer or contractor installation. The cost simulation conducted in this project shows that one can easily spend more acquiring sensor systems than can reasonably be expected to be saved on maintenance costs in an area. However, incurring such costs may be deemed necessary to provide the proper service level to road users. Cost considerations also include proximity to power and communications. This will be discussed in more detail below.

Whenever possible, highway agencies locating RPUs and their associated sensors in the highway environment should consider standard atmospheric sensor siting criteria. For example, wind speed and direction sensors—anemometers—are typically placed 33 ft (10 m) above the ground. A standard 33 ft (10 m) tower is commercially available. However, buildings, trees, structures, and road cuts can prevent representative observations. Anemometers should be located to minimize the influence of obstructions. A standard rule requires that anemometers be located twice as far from an obstruction as the height of the obstruction. For example, if trees are 65 ft (20 m) tall, anemometers should be located at least 130 ft (40 m) from them. If an obstruction is very broad, then the distance from it should be four times its height.

Air temperature and dew point (humidity) measurements are usually taken at a height of 5-6 ft (1.5-1.8 m) over a grassy surface. The moisture content of the atmosphere, as indicated by the humidity, governs whether dew or frost will form on pavement. Pavement temperature is influenced by air temperature. Therefore, it is important to get representative air temperature and dew point measurements as close to the highway as possible. The RPU and meteorological sensors should be far enough from the road, though, to avoid road splash.

It is frequently impossible to find an RPU location which meets all of these criteria when having to deal with highway rights of way, so finding the most appropriate location is important. If an agency has a choice of locations, but one is in a tree-lined roadway and the other is fairly open, the latter might be the better choice. A meteorologist should also be involved in site selection.

Because of limited roadside space or fear of damage or vandalism, some highway agencies mount all of their atmospheric sensors on top of sign bridges or gantries or light standards. It is difficult to get temperature and humidity measurements representative of the pavement environment where vehicle exhaust can be an important contributor to humidity. If no space is available at a desired location for installing a meteorological tower, then an alternative location might prove better in the long run. A location often overlooked is the gore of an on-ramp. On-ramp gores are frequently protected by barriers and can often provide a more representative site than a sign bridge. Off-ramp gores are the most frequently encroached areas on freeways, and as a result, are not suitable for locating weather sensors.

If vandalism is a concern, one possibility is to enclose RPUs with fences. Erecting a tower with instruments and electronics on a small concrete pad, then erecting a wire-mesh fence not only provides protection against vandalism, but also provides protection for maintenance and repair of the equipment.

Less-than-desirable locations are sometimes selected because of the availability of power or communications. The cost of digging a trench or cutting pavement to install cables may seem very high. However, the proximity to a source of power should not be a driving force in siting an RPU. If power is available within about 500 ft (150 m) of an ideal location, then the money should be spent for trenching ($10 per foot or $3 per meter is assumed to be an average trenching cost). If power is not available within about 800 ft (240 m), then solar power can be used. Even during winter, there is sufficient sunlight to power RPUs, and the cost of solar cells is comparable to the cost of trenching. Locating an RPU for line-of-site radio communication may be a problem in some areas, but when used in conjunction with a state radio system, only a repeater may be required.

In the same manner, many RPU sites are chosen to avoid long trenches to reach sensors. However, the economics of RPUs and sensors often makes long runs cost-effective. More than one sensor can be used with each RPU. Since a sensor represents only about ten percent of the cost of an RPU installation, RPU locations should be selected to make maximum use of sensors. Sensors can be placed up to one-half-mile from an RPU.

It is far better to dig a long cable trench to reach a sensor than it is to settle for an installation which from either a meteorological or operational point of view will not provide representative information.

In summary, ideal RPU locations for *predicting* would include, at a minimum:

- one in a low spot where temperatures tend to be cold when skies are clear.

- one at a higher elevation where temperatures tend to be cold when skies are cloudy.

- two additional stations to be able to specify the mean temperature to a minimum of a 95% confidence level.
- sites to cover trouble spots.
- sites on bridges, overpasses, near moisture sources such as rivers or lakes, or on structures that require special care (e.g., bridges where no salt is used).

Additional RPU stations could also be needed for *detection* and/or *monitoring*, but these could be sited to fit the other requirements. For instance, if a bridge deck is of concern, an RPU could be sited with sensors in the roadway near the bridge to report mean temperatures, and an additional sensor could be located on the bridge deck to report extreme temperatures there.

Though the primary purpose for installing RPUs and sensors is to acquire information about the road environment, other purposes can also be served. One reason to identify meteorologically representative locations is the potential for building databases to use in developing forecasts. The better the siting, the more useful the data.

Conclusions Regarding Sensors

This research project showed that the best opportunity for reductions in maintenance costs when implementing an RWIS comes from accurate, tailored forecasts of weather and road conditions. It is therefore important that sensor locations be considered that allow prediction data to be collected. In like manner, it is important to recognize the ability of sensors, properly located, to assist in the development of tailored forecasts.

Forecasts are only as good as their initial data. Wind and temperature patterns, the presence of atmospheric moisture, and the occurrence of precipitation can all be identified with the assistance of in situ sensors. These are key elements for forecasting weather and road conditions. Without in situ sensors, a forecaster must use his or her best meteorological analysis and forecasting techniques to project the weather over a specified area. This may involve the use of remote sensors (radar or satellite), but even these sources of weather information need to be supplemented by ground truth.

Pavement and meteorological sensors are being used successfully to assist highway snow and ice control managers to make more timely and efficient decisions. They provide important information needed by these managers to aid in selecting the resources needed, determining where they are needed, and deploying them.

These sensors provide important information to meteorologists who must make tailored weather forecasts for these managers. These sensors provide baseline information for generating forecasts, for monitoring the progress of conditions relative to these forecasts, and for developing forecast studies.

Recommendations

- Every agency that performs snow and ice control should consider acquiring RWIS sensors to assist in snow and ice control decision making.
- RWIS sensors should be sited to provide data to forecasting services as well as to provide detection and monitoring information to snow and ice control managers.
- Sensors should be sited with the assistance of meteorological analysis, input from maintenance supervisors for operational considerations, and road thermal analysis, if available.

Evaluation of Road Meteorology Sources

As used here, a road meteorology source is a provider of weather information. It does not include sensors, but data from sensors are important in assessing the capability of the sources to provide detailed weather and road condition information.

Types of Meteorology Sources

Weather information comes from a number of sources. Each source offers a different level of detail in the information it provides. The timing of the receipt of the information by road managers and the age of the information when received also vary by source. Following are the major sources of weather information.

Media

Newspapers. The print media frequently provide great detail on weather events in a local area, a state, the nation, or the world, but usually in a retrospective fashion. There is an inherent lag between the recording and writing of weather information and the printing, distributing, and digesting of that information. Weather data are perishable. Observations of what is going on weatherwise do not always provide clues to what is about to happen. Forecasts of weather, because of the "state of the art" in forecasting technology, are also perishable. A forecast issued in the morning may require changing by the afternoon. Newspapers therefore provide forecasts which may be up to twelve hours old by the time they are read. In addition, they can provide little more than expected general conditions in an area. Because of this lack of timeliness and detail, newspaper forecasts are a poor source of weather information for snow and ice control decision making.

The Weather Channel. The broadcast media have an advantage over print media in providing more timely weather information. They modify forecasts based on current weather, and update their viewers and listeners frequently. The Weather Channel provides the latest National Weather Service forecasts for local areas many times each hour. It provides overviews of regional and national weather patterns, shows radar and satellite imagery, and highlights areas of severe weather. Although the radar and satellite imagery have some utility for roadway maintenance managers, the relayed forecasts are Northwest Weather Service zone or area forecasts, and these do not provide a great deal of detail about the weather, and usually none about road conditions. Snow and ice control managers are left to interpret the most likely conditions in their areas of responsibility.

Local Radio and Television tend to provide more detailed weather information for a local area than does The Weather Channel. Unless the station is a "news-only" station, weather reports occur perhaps in the morning, at noon, during the evening, and later at night. They have more detail, but frequently lack timeliness. There are also two types of weather broadcasts: those given by meteorologists and those presented by reporters, who usually read prepared text. The meteorologists use their expertise to provide more detailed information. However, the media would rather have people pay attention than miss a weather event. There is therefore a tendency to forecast weather events conservatively. If two to four inches of snow are forecast, the television may indicate "four," as related by Mr. Ken Siemek during a general session of the 1990 North American Snow Conference.

Special Television. Some cable television systems provide continuous weather information to customers. These broadcasts can consist of radar imagery or teletext of National Weather Service forecasts. Additionally, educational channels are used to broadcast weather information. The continuous broadcast of radar information has some utility for roadway maintenance managers to monitor precipitation events in a large area.

AM Weather. The most meteorologically-oriented weather broadcasts are provided by the National Weather Service on the public broadcasting system in the morning. AM Weather focuses on national weather for aviation purposes, but for the weather aficionado, there is ample display of meteorological products to interpret. A meteorologist could use the information to make general forecasts, but there is insufficient detail for snow and ice control.

The National Weather Service

The National Oceanic and Atmospheric Administration's National Weather Service (NWS) provides public forecasts and issues watches and warnings of severe weather which can affect life or property. The NWS provides forecasts of general conditions for zones within each state. In areas where there can be considerable variability in the weather, the NWS will provide more detail in its forecasts, or subdivide a region into smaller areas. Each state has one or more NWS offices which provide forecasts for the state. Through river forecast centers, the NWS also provides special hydrological forecasts for flood considerations.

The NWS typically does not provide the kind of detailed forecasting necessary for snow and ice control decision making. Forecasts of winter weather events usually contain general predictions of what amounts of snow or ice will accumulate. The time of onset and the duration of events are also frequently general because the forecasts cover a large area of terrain.

In areas near commercial aviation airports, more detailed forecasts are provided by the NWS. Called aviation forecasts, they include the time of significant (to aviation) changes in weather events. These changes can be in wind speed and direction, cloud cover, visibility, as well as the occurrence or cessation and intensity of precipitation. No forecasts of precipitation amounts are provided.

NOAA Weather Radio offers continuous broadcasts of the latest weather forecasts, advisories, and observations prepared by the NWS. Available in almost all areas, these broadcasts can be obtained on VHF receivers. Special NOAA Weather Radio receivers can be purchased for about $15, and upgraded versions, which are turned on automatically by a tone alert, can also be purchased. A patient listener can glean a great deal of information from NOAA Weather Radio about current and expected weather conditions, but with little site-specific detail.

In most cases, snow and ice control decision makers are left to interpret these forecasts in order to make decisions. The general nature of this weather information tends to lead to conservative (and possibly expensive) decisions.

Other Government Sources

Other federal agencies besides the NWS and NOAA provide forecasts, but usually for special purposes. For instance, the U.S. Forest Service employs forecasters for fire danger forecasting. In some mountain areas, these or other forecasters are employed during the winter for avalanche forecasting. Where avalanches are a problem for highways, a state highway agency can also fund a portion of the forecast cost.

This state forecast support serves as a model for obtaining contract weather services within a state. The state pays for detailed, specialized forecasts which are used in making decisions for taking action related to avalanches. These services can be obtained using either contract or permanent employees. A full-time seasonal state forecast agency may not be necessary or even desired for snow and ice control. Although existing forecast services might be expanded, obtaining specialized professional commercial forecasting services requires contracting.

Value-added Meteorological Services

The term value-added meteorological services (VAMS) usually refers to commercial meteorological businesses services that take meteorological information from the NWS or other sources and use it to construct specialized information of use to particular clients. Sometimes called private weather services, private meteorological services, or value-added weather services, VAMS offer detailed forecasting services to individuals, businesses, or governmental agencies to assist them to do their work. VAMS may also be provided by government agencies, or agency-funded utilities.

VAMS range from large companies with dozens of forecasters and weather centers with large computer capabilities, to one person with a microcomputer. They provide their forecasting services in many ways. Some VAMS provide only weather data to subscribers. They purchase NWS products and repackage them for use by individuals, companies, agencies, or other VAMS. Some VAMS provide forecasting services to customers. These VAMS provide their forecasts year-around, seasonally, or on an as-needed basis. Still other VAMS provide services related to the environment, climate, meteorological instrumentation, or forensic issues.

Evaluation of Sources

All types of the above sources of meteorological information are used by highway agency snow and ice control decision makers. For analysis purposes, the sources of information provided by VAMS were divided into three groups: meteorological data, weather forecasts, and pavement temperature forecasts.

In order to determine how effective this information is, procedures were developed for the state highway agencies supporting the field tests to record the types of weather information they used in making snow and ice control decisions, and to document the actual weather compared to that which was forecast. Participants were asked to record the types of winter weather event which occurred; what weather information or other information triggered their snow and ice control action; how well a forecast specified an event in terms of type of weather, timing of the onset, and duration of the event; what action took place; and the kind and quantity of resources saved by using the information. Figure 2-10 shows a completed form for collecting this information.

Training sessions were conducted with personnel in each of the seven field-test state highway agencies. The training was designed to promote consistency in recording information, especially since most of the recording would be accomplished by shift supervisors or foremen and not people specifically trained in observing and interpreting weather. In each training session, suggestions were made for adapting the forms to the particular needs of each state highway agency. Documenting the weather and snow and ice control activities was not accomplished until each state highway agency agreed to the form. Completing forms began in most state highway agencies in December, 1990, but was delayed in Colorado due to RWIS computer problems, and in Missouri due to the RWIS installation being destroyed by an automobile accident and not restored until February, 1991.

Field Testing Results

Unfortunately, the amount of data acquired from the state highway agencies was greatly reduced by a significant lack of winter weather in all areas. In addition, some maintenance

I-44 WINTER OPERATIONS, EUREKA SUBAREA, MISSOURI
Maintenance Response Recording Form
SHRP-87-H207 Field Tests

SECTION I

Date: 2-14-91
Beginning Time of Event: 16:00
Ending Time of Event: 18:30

Crew Configuration Dispatched: 6
Decision Maker: Reports on slick pavmt.
RPU Location: Times Beach

SECTION II

Current Cloud Condition

Cloudy ☑ Mostly ☐ Partly Cloudy ☐ Clear ☐

SECTION III

From Computer at Time Above:

Roadway Surface Condition:	Isolated patches of ice
Pavement Temperature:	30°
Chemical Factor:	0
Air Temperature:	26°
Relative Humidity:	50
Wind Speed/Direction:	11-18/300-360
Pavement Temp Forecast:	28°

SECTION IV

Actual Road Conditions at RPU

	Wheel Tracks	All Over
Dry	☐	☐
Damp-Wet-Slush	☐	☐
Ice	☐	☐
Snow	☐	☑
Ice Pack	☐	☐

Other: Note - sensor site was dry a 1 mile wide band of snow covered pavmt. 1 mile west of sensor

SECTION V WEATHER AND PAVEMENT FORECASTS

	M & T Forecast	Actual	SCANCAST Roadway Forecast	Actual
Fog or Dew	☐	☐	☐	☐
Rain	☐	☐	☐	☐
Freezing Rain	☐	☐	☐	☐
~~Snow~~ scattered snow flurries	☑	☑	☐	☐

Road Conditions:	Start of Event	Length of Event	Type of Event
SCANCAST Forecast			
Observed Actual	16:00	18:30	scattered light bands of snow

Figure 2-10. Completed maintenance data collection form

Maintenance Response Recording Form
SHRP-87-H207 Field Tests (Missouri)
(Continued)

SECTION VI

Weather Conditions:	Start of Event	Length of Event	Type of Event
M & T Forecast	16:00	2:30	Scattered Light Bands of Snow
Observed Actual	16:00	2:30	"

SECTION VII What source of information triggered this winter maintenance operation?

DOT Patrol	☐	Other DOT Maint	☑	Police	☑	NWS	☐
Radio or TV	☐	M&T Forecast	☐	SCAN CAST	☐	Sensors	☐

SECTION VIII What winter operation was initiated based on this information?

Do Nothing	☐	Patrol/Watch	☐
Extend Shift	☐	Plow	☐
Call out DOT	☑	Abrasives	☑
Call out Contractor	☐	Chemicals	☐

ACCURACY OF FORECASTS
(place X in appropriate box)

ACTUAL	FORECAST: Winter Weather	FORECAST: No Winter Weather
Occurred	X	
Didn't Occur		

SECTION IX

Which of the following types of weather information saved money?

Pavement Sensors ☑ M & T Forecast ☑ Media ☐ SCANCAST ☐

Estimate the amount of salt saved during this winter operation (Tons)

1-5 ☐ 6-10 ☐ 11-15 ☐ 16-20 ☐ Other ☑ 50 TON

Did you extend ✓ or shorten ___ working hours as a result of the observed conditions ✓, forecast weather ___, or sensor information ___?

Please estimate the number of working hours saved on this winter operation. ________

1-5 ☑ 6-10 ☐ 11-15 ☐ 16-20 ☐ Other ☐ ________

Did you receive any requests for road temperature Yes or chemical factor ___ from road crews?

List any other benefits that the weather information provided. Showed that this was an isolated area needing treatment and we were able to greatly reduce size of our operations.

Figure 2-10 (continued). Completed maintenance data collection form people did not record data. Little recording occurred prior to midwinter. This was doubly unfortunate since the worst weather across the country took place from mid-December into January. In Missouri, a long stretch of ice storms in January was missed.

In order to obtain some data, interviews were scheduled with maintenance supervisors at the testing locations in March and April to try to verbally obtain results from or perceptions of the use of weather information during the testing period. The findings that follow are based on both the forms returned and these interviews.

Uses of Meteorological Data

Interviews of state highway agency maintenance managers indicated that meteorological data provided as a subscription service are of limited value to decision makers and are frequently an unnecessary cost.

The successful use of meteorological data is related to the degree of centralization of snow and ice control activities. Centralized decision support, such as found in states with "snow rooms," provides a greater ability to select appropriate products for use and/or further dissemination.

The ability of maintenance supervisors or dispatchers to integrate available meteorological data into highway agency snow and ice control decision processes is limited. At the foreman/superintendent level, there is usually little time available to look at weather maps or to use other weather data effectively. Some radar imagery and satellite data can be used, however, to monitor the progress of precipitation.

With the present state of the art, meteorological data, in general, are best left for meteorologists to interpret. Highway maintenance managers in areas prone to shower activity, such as lake-effect snow showers around the Great Lakes, can use NWS radar data to monitor the progress of storms and to direct snow and ice control resources. Most weather radars, though, do not provide good information on light precipitation events and snow. Once data are available from the Next Generation Weather Radar (NEXRAD), computer-generated *products* will provide more useful tools for highway agency decision makers.

Weather Forecasts

Snow and ice control decision makers who use weather forecasts will generally make more timely and efficient decisions. There is a hierarchy of potential benefit, which is related to the type of forecast services used.

- Public forecasts from the NWS are too general in nature and require further interpretation by decision makers.

- Some VAMS provide forecasts similar to the NWS, but which, they argue, are more accurate or more detailed. Although this may very well be the case, remembering the limitations inherent in general area forecasts, decision makers are still left to interpret what forecasts mean in terms of snow and ice on the roads. More accuracy is not the need; tailored forecasting is.

- The most useful forecasts for highway agencies are provided by VAMS who issue detailed, *tailored* forecasts which are based on weather and road conditions meeting or exceeding critical thresholds which are established by the highway agency and understood by the VAMS.

- The best weather support is attained when the detailed, *tailored* forecasts are provided in a consultant-client relationship where the consultant (the VAMS) and the client (the highway agency) communicate through whatever medium is established for providing the forecasts (e.g., teletype, telephone, facsimile, computer link) *and* verbally to ensure mutual understanding of VAMS limitations and capabilities, highway agency needs, the significance of VAMS forecasts, and the confidence the VAMS has in the forecasts.

Field test reports from the participating states provided seventy-five instances of response to various types of winter weather. These responses are summarized in Table 2-3. Of these seventy-five responses, twenty-five listed savings as a result of weather information. Only one response indicated lost time due to weather information: productive time was lost waiting for a storm that didn't happen.

Table 2-3. Results of use of RWIS data from field trials

Maintenance Action Reported	RWIS Information Used	Saved Labor Hours	Saved Materials
Shorten shift	Radar data	✓	✓
Shorten shift	Pavement sensor	✓, NE	NE
Shorten shift	Sensor and forecast	✓, ✓	✓, ✓
Extend shift	Sensor and forecast	✓, NE	✓, NE
Extend shift	Sensor		✓
Apply chemicals	Sensor	✓	✓
Apply chemicals and abrasives	Forecast	✓, ✓	✓
Apply chemicals and plow snow	Forecast		✓
Apply no chemicals	Sensor and forecast		✓
Change callout	Sensor and forecast	✓	✓
Do nothing	Sensor and forecast	✓, NE	✓, NE
Do nothing	Forecast	✓	✓

✓ = one event reported NE = no explanation

The savings ranged from 1-5 hours (labor and equipment) to 50-75 hours per event from using pavement sensor readings or forecasts. Savings in salt usage were also documented, ranging from 1-5 tons to 50-75 tons per event, and resulted from both sensor and forecast inputs. These savings apply to one maintenance location only; 75 tons of salt is a large cost savings for one maintenance unit. Nearly all the weather instances involved precipitation events, either rain, freezing rain, or snow; three involved frost. One of the cost-saving instances was related to a frost situation. Forecasting services, with sensor data to tailor the support, can reduce the costs of snow and ice control.

	FORECAST: Winter Weather	FORECAST: No Winter Weather
ACTUAL: Occurred	84%	2% TYPE I ERROR
ACTUAL: Did Not Occur	10% TYPE II ERROR	4%

Figure 2-11. Accuracies of weather forecasts documented during field trials

The forecasting accuracies were computed as shown in Figure 2-11. These data show that the forecasts were correct 88% of the time (44 of 50 events). Ten percent (5 out of 50) of the forecasts were "bad" forecasts, i.e., winter weather was forecast but none occurred (Type II error). This type of error usually incurs costs for taking action when none was required. Only 2% (1 out of 50) were "very bad" forecasts, i.e., no winter weather was forecast but some occurred (Type I error). This is the dangerous kind where accidents can occur because no snow and ice control action was taken.

It is encouraging that only 2% of the forecasts were of the Type I variety, and that the overall accuracy was so high. It is impossible, however, to say any more than that. The forecasts were made by many different forecasting organizations. It is likely that forecasts from some agencies are better than those from others. It is also interesting, however, that the British Road Transport Association has established 85% as the minimum level of acceptable forecasting support. Agencies may wish to include this figure in requests for proposals for forecasting services.

Tailored forecasting services have the highest payoff in terms of their cost versus savings in snow and ice control for any of the RWIS technologies. The primary reason is that the cost of VAMS forecasting services is minimal compared to the cost of snow and ice control for two reasons:

- Highway agencies tend to contract for weather services by using cost alone as the selection criterion, i.e., going with the lowest bid.

- VAMS have been forced to reduce the cost of their services, and in some cases their service level, to accommodate the low-bid environment.

Highway agencies frequently base their assessment of the utility of forecasting services on perception or intuition rather than generating even simple statistics such as percentage of correct forecasts. This lack of objective evaluation is often compounded by too infrequent interaction between highway agencies and VAMS to discuss good and bad forecasts. Highway agencies need to perform critical reviews of their forecasting support. Simple logs which describe the forecast, resultant conditions, and the timeliness of the forecasts provide a minimal basis for technical evaluation.

Like snow and ice control managers, weather forecasters tend to be conservative. This results from a tendency to minimize Type I errors, those that occur when a bad road condition is not forecast and does occur. In turn, this usually results in an increase of Type II errors, where resources are deployed for an event that does not occur. The net result is unnecessary expenditure of funds.

Weather forecasters do not always have access to data from RWIS sensors, and therefore cannot always forecast weather as well as they might. VAMS should have access to RWIS sensor data.

Weather forecasting is not and should not be expected to be an exact science. However, VAMS forecasting accuracy of over 90% for detailed, tailored forecasts has been documented and can be expected.

Pavement Temperature Forecasts

One key piece of information available to snow and ice control managers from RWIS pavement sensors is current pavement temperature. Pavement temperature is critical to the bonding of ice or snow to pavement and the accumulation of snow. Even more valuable are forecasts of pavement temperatures. A number of models have been developed and are in use in North America and abroad to forecast pavement temperatures. These models describe the heat budget of the pavement surface and provide reasonably accurate forecasts of pavement temperature out to 24 hours. Accuracies of $\pm 1°C$ 90% of the time are possible with the latest models (Thornes and Shao 1991).

Good snow and ice control decisions can be and have been based on forecasts of pavement temperature. Even if snow is forecast to accumulate or is accumulating in some areas, if the pavement temperature is forecast to remain above freezing, chemical applications may not be necessary and plowing may not be required. One of the most cost-effective decisions is the one which points to taking no action. Pavement temperature forecasts can provide a basis for those decisions.

Pavement temperature forecasts are also particularly useful in helping to select the appropriate chemicals for deicing. All too often, managers have used existing air temperature or air temperature forecasts for deicing chemical decisions. With the advent of pavement sensors, better information is available. The best decisions are based on what the pavement temperature is going to be when the chemicals are applied or after they are applied. Pavement temperature forecasts also have the potential to help make anti-icing a viable, acceptable practice.

Conclusions

Weather information, which includes meteorological data and weather and pavement temperature forecasts, provides valuable assistance to snow and ice control managers for resource allocation decisions. Weather and road condition forecasts, combined with pavement temperature forecasts, are the most cost-effective tools agencies can use to allocate snow and ice control resources. Meteorological data allow managers to monitor conditions and to check the progress of weather with respect to forecasts. However, most meteorological products available from vendors, such as weather maps, have limited utility because they require interpretation for decision making, a practice best left to meteorologists. Meteorological radar and satellite data, however, can be used by decision makers in monitoring the progress of precipitation events.

Recommendations

- Agencies should acquire and use road weather information in their snow and ice control resource allocation decisions.
- Contractual arrangements between agencies and VAMS need to make clear the need for the consultant-client relationship to foster communication and mutual understanding of needs and capabilities, and to provide feedback on forecast accuracy.
- Agencies with RWIS sensors in place should ensure that pavement temperature and other sensor data are available to VAMS and that pavement temperature data and forecasts are available to in-house decision makers at the lowest levels.
- Agencies should develop an evaluation program to measure the performance of VAMS in support of highway agency needs.

Evaluation of Road Thermal Analysis

Thermal analysis of the pavement surface is most often accomplished by what is generally referred to as road thermography. This usually involves driving an instrumented vehicle over a road network to measure pavement temperatures. An infrared radiometer on the vehicle measures road surface temperatures, and these are correlated to distance along a road. Data are gathered about every ten meters. Typically, notations are made of important features in the road environment which can affect road temperatures, such as road elevation and sky-view blocking by trees, buildings, cuts and fills, and overpasses.

The rationale for road thermography is that road temperatures tend to have similar patterns under similar conditions. When skies are clear and winds are light, radiational cooling reaches a maximum. Cold air pools in valleys or low spots, and the coldest pavement temperatures tend to occur in the low spots, while the warmest tend to be at higher elevations. Under these conditions, temperature variations will be the greatest. When cloud cover exists, the clouds absorb much of the outgoing radiation and then reradiate thermal energy back to earth. When clouds are present, radiational cooling does not occur, and road temperatures tend to mirror the standard atmospheric temperature profiles, with the warmest temperatures occurring at lower and the coldest at higher elevations. Temperature variations are also not as great under cloudy conditions. When precipitation occurs, temperature profiles are further damped.

Road thermography is usually conducted under the conditions described above, with most emphasis on clear-sky conditions. Road temperatures are measured in the early morning hours when the temperatures tend toward the coldest. These profiles will show the greatest variation and set the bounds for the maximum cold and warm deviation from the mean temperatures. In Wisconsin, road maintenance supervisors said sensors should be located at average surface temperature sites because the problem spots are already known (Stephenson 1988).* Figure 2-12 shows examples of profiles under varying conditions. The data only apply to dark hours.

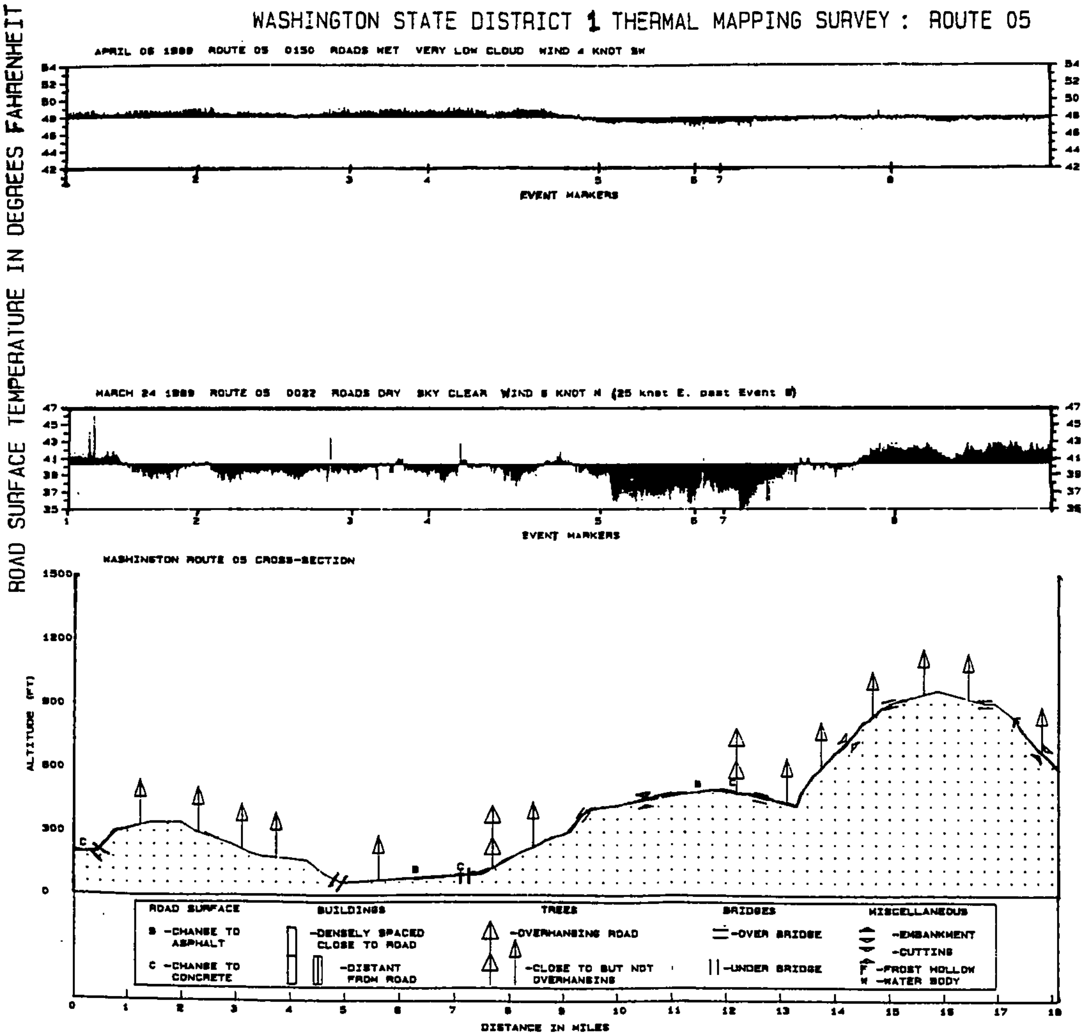


Figure 2-12. Examples of thermal mapping under varying conditions (used with the permission of Vaisala, Inc.)

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* David Vieth of the Wisconsin DOT, in response to questions about how the DOT used thermal profiles, said that the thermal profiles were obtained for a CMA test. They were conducted after RWIS sensor sites had been in place, and to the best of his knowledge, have not been used in selecting sensor sites and have not been used operationally.

Another use for thermal profiles has been to assist in the determination of road surface temperatures at locations where there are no pavement sensors. Temperatures can be interpolated between sensors using profiles for the proper weather conditions. In addition, pavement temperature forecasts can be constructed for entire road segments or networks rather than just for sensor locations.

An extension of road thermography called road climatology has been developed in Sweden (Gustavsson 1990). In addition to producing surface temperature profiles, it also gathers atmospheric temperatures at two heights above the road as well as humidity and wind information. Road climatology data are used as inputs to a prediction model which automatically provides pavement temperature forecasts out to four hours for road networks.

Little road thermal analysis has been conducted in North America. One reason may be the apparent high cost, which can approach $200 per mile ($120 per kilometer). Another reason appears to be a lack of clear understanding of the potential cost savings the technology may provide by assisting in the placement of RWIS sensors at strategic locations. Finally, no clear evidence exists that thermal profiles provide general patterns with broad applicability rather than instantaneous glimpses of road temperatures.

Testing of Road Thermal Analysis

In order to determine whether road thermal analysis is valid and has utility, three paths were explored. First, interviews were conducted with snow and ice control managers in locations where thermal analysis had been conducted. These included Vancouver, British Columbia, and the states of Washington and Minnesota. These interviews were geared to learn about uses of thermal profiles, their perceived or realized value, and the validity of the process.

Second, in-place sensors were used to determine the general applicability of thermographic data. Temperature differences between pavement sensor readings were compared to the temperature differences extracted for the same locations from thermal profiles under different atmospheric conditions. Multiple thermal profiles had to be used along a road segment in order to build a continuous profile between sensors at the ends of the segment. For example, one profile might cover from a sensor at point A to point B, a second profile would cover from B to C, a third from C to D, and a fourth from D to the sensor at Point E. Not all of the profiles were developed on the same day, although care was taken to ensure that the weather conditions were as similar as possible when all profiles were made.

Third, the project team conducted its own form of road thermal analysis in an attempt to determine if thermal profiles can be reconstructed or repeated. A handheld radiometer, a Raytek PM-5, was connected to a portable computer, and readings of pavement temperature were acquired by holding the instrument out a car window every 0.1 mile (0.2 kilometer) while the car travelled at a speed of about 20 mph. The instrument reported surface temperature to 1.0°F (0.5°C). Investigation showed that the thermal temperatures acquired at this speed and at the car-window height compared to within less than 1°F with

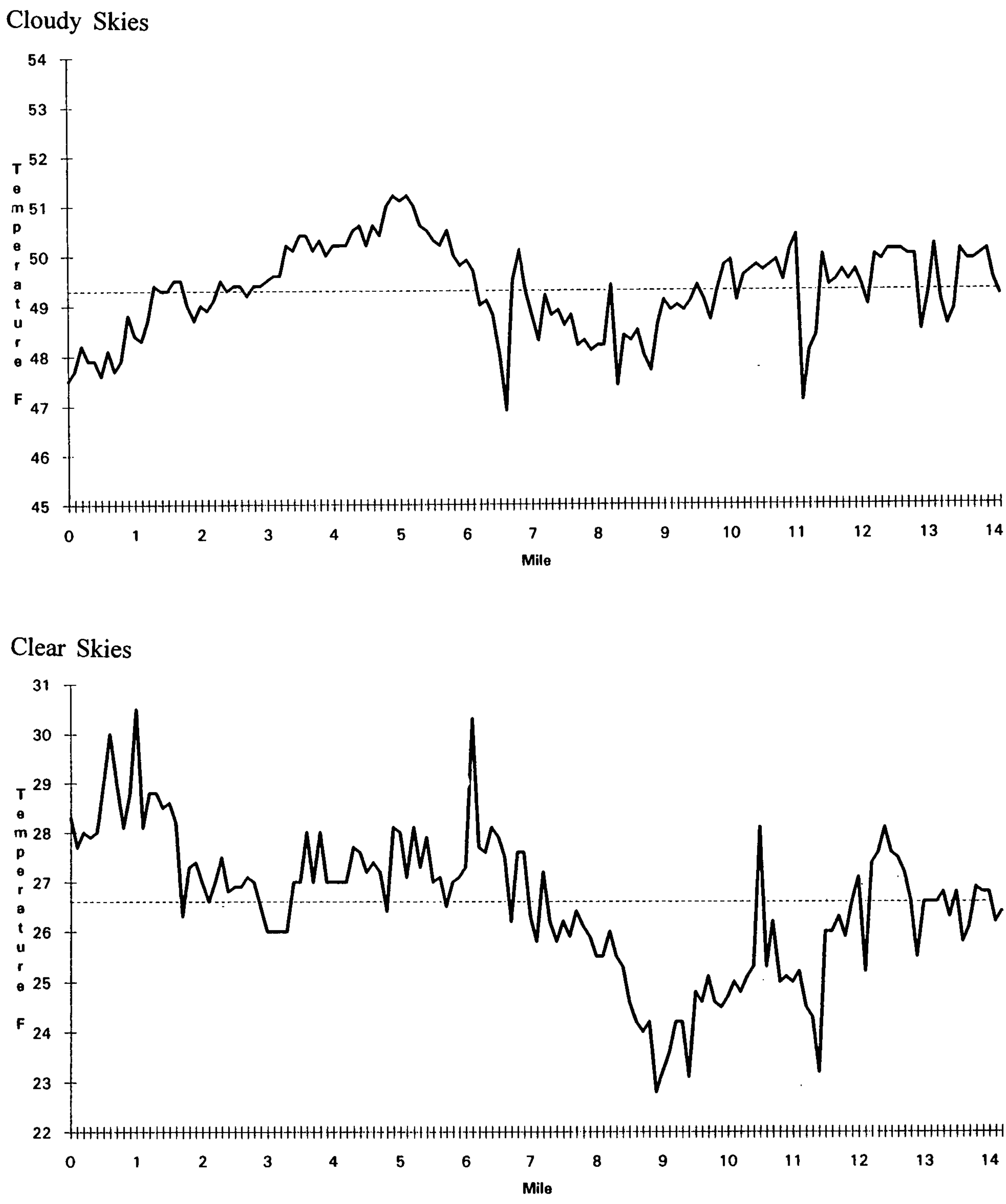

Figure 2-13. Thermal profiles constructed from hand-held radiometer measurements. Data are from the same road segment, under different atmospheric conditions

temperatures obtained from stationary readings taken at about knee-height. The data were recorded in the computer, and thermal profiles were constructed at a later time. Figure 2-13 shows examples of such profiles.

It should be noted that these profiles were obtained at a fraction of the cost of commercial road thermography. The radiometer used, with an optional feature allowing it to work at temperatures below 32°F (0°C), cost $1,900 and it can store sixty-four observations internally for later processing. A model without this feature costs $150 less. The cost for this thermography was less than $10 per mile ($6 per kilometer), including salary and mileage, but not counting the instrument and computer. The cost for these, however, coulo be spread over many miles, and in fact, many uses.

Findings

The interviews, in most cases, provided favorable assessments of thermographic profiles and their use. The Assistant City Engineer in Vancouver, British Columbia, indicated that thermal profiles were used to revise snowplow routes. Based on temperature patterns, he discovered that they had been plowing the warmest roads first, the coldest roads last. They reversed this sequence to improve plowing efficiency and to minimize bonding of snow to the pavement. The profiles also indicated that certain bridges were actually warmer than surrounding roads. The city had been spreading chemicals on these structures first. Based on the profiles, city personnel now delay chemical applications on these bridges.

The Washington State Department of Transportation (WSDOT) used its thermal profiles to assist in determining locations for RWIS RPUs. In addition, when WSDOT personnel contracted for pavement temperature forecasts, they required the successful responder to use the profiles to construct temperature forecasts of an entire road network. During interviews in 1990, managers indicated that they used the network temperature forecasts and found them very representative of what was transpiring on the roads. They did not understand why some of the thermal profiles provided information that conflicted with their experience. For example, the profiles showed that some bridges that normally ice up first were warmer than surrounding roads. (A possible explanation of this discrepancy is that these bridges were over a river which provided moisture for ice formation. During the measurements, they may have been exposed to warm, downslope winds flowing under them.)

In Minnesota, road climatology conducted in the Duluth area was used to help identify suitable locations for RWIS RPUs, although the recommendations for RPU sites came solely from the vendor. The thermography and atmospheric data were provided to Mn/DOT on computer diskettes. The software provided for creating the profiles was too cumbersome for Mn/DOT to use effectively, so no further use was made of the thermographic data. Also, these data were viewed as the initial step in what the vendor hoped would be the creation of an automated road temperature and ice forecasting model. The model would provide forecasts out to four hours. This period was deemed too short for Mn/DOT needs.

Based on the few interviews concerning road thermal analysis that were conducted (because of the limited amount done in this country), it appears that thermal profiles have limited use by themselves. They are not a product one would use every day, and they require analysis and interpretation by engineers, meteorologists, and snow and ice control practitioners. They did prompt one agency to revise snowplow routes, and are being tested in Europe for their ability to establish levels of snow and ice response based on forecasts of pavement temperatures for networks of roads. For instance, if only a small portion of the roads were expected to be at or below freezing and to have ice or snow problems, decision makers would call out the first level of forces; if much of the network would be at or below freezing, they would call out the next level; and if all of the roads were expected to be at or below freezing, they would call out all the forces. The value of road thermal analysis for this purpose has yet to be demonstrated.

The attempt to validate road thermography using in-place pavement sensor data for comparing with thermal profiles was made more difficult because of the need to piece together profiles from different days or months. There was potential for subsurface temperatures, which are not profiled, to affect the surface temperatures differently at different times. Nonetheless, temperature differences between sensors were computed for clear sky, cloudy, and damp conditions.

Weather conditions over a four-month period (January through April, 1991) were categorized as clear, cloudy, or damp, based on weather observations for the period at Seattle-Tacoma International Airport. Pavement temperatures were obtained from archived RWIS data for each of three sensors. The sensor locations are shown in Figure 2-14. Pavement temperatures were selected as close to 5:00 a.m. as possible for those days for each of the three sensors operational during the period. The pavement temperature data are shown in Table 2-4.

Thermal profiles were selected which matched the general weather conditions and which included each sensor site. As described above, as many as four separate profiles were used to compute the radiometrically-measured temperature differences between each sensor location. The profiles were obtained during the 1989 winter and early spring. Most of the measurements were acquired in March. Table 2-4 shows the temperature differences computed between sensor locations using the thermal profiles. These temperature differences were then compared with the reported temperature differences from the sensors. Table 2-5 shows the results of this comparison.

The pavement sensor-thermal profile comparison provided surprisingly good results. The profiles used are only relative temperature differences. The sensor data are actual measurements from which absolute differences are calculated. In each comparison, the sign of the difference is the same for each source. This indicates that the thermal profiles can be used to project pavement temperatures at locations other than sensor sites under similar atmospheric conditions.

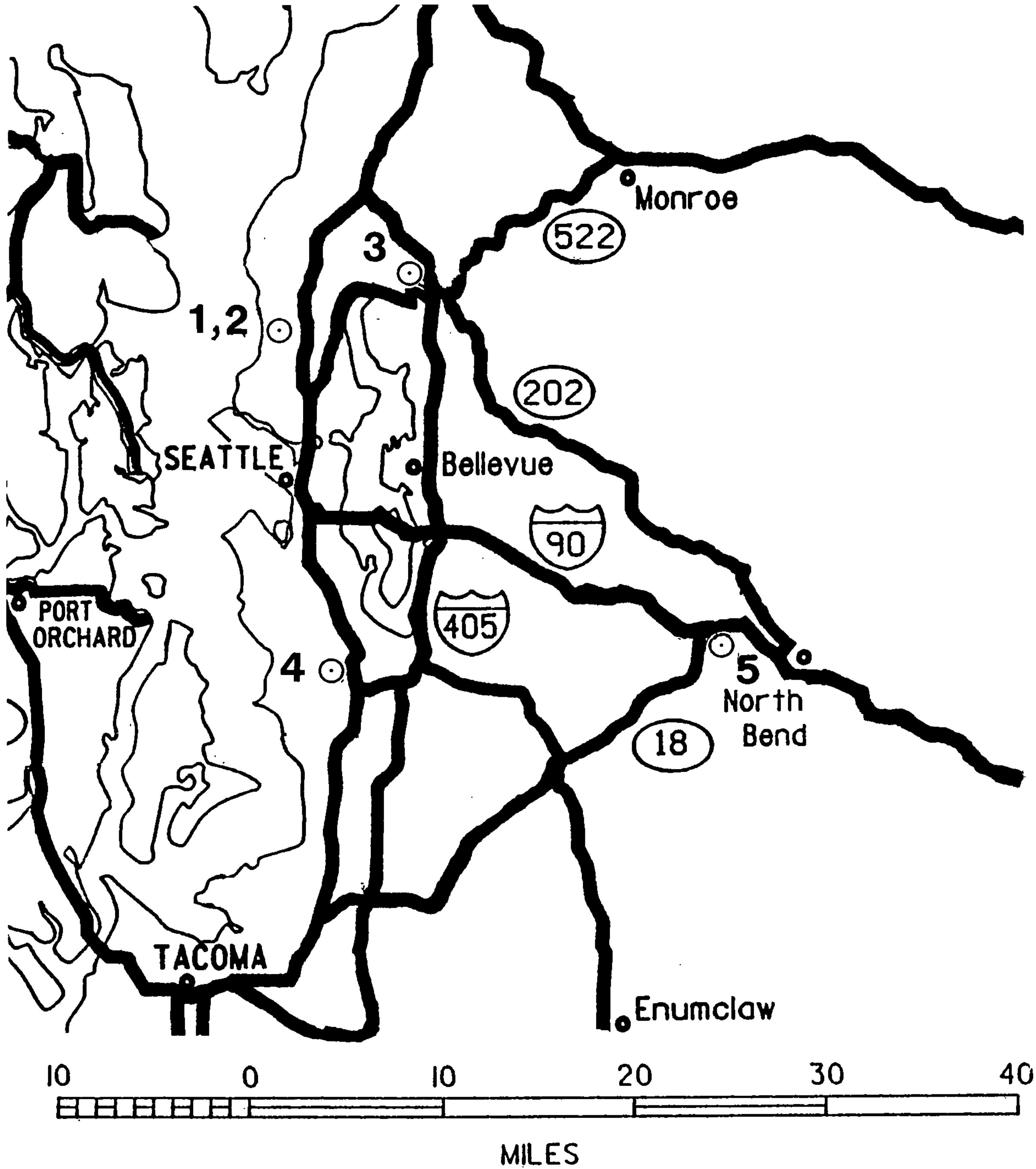

Figure 2-14. Locations of sensors used in comparing reported sensor temperatures with thermal profiles

Table 2-4. Temperature measurements from pavement sensors

Cloudy Days

Date (1991)	Temp #5	ΔT 5-4	Temp #4	ΔT 4-3	Temp #3	ΔT 5-3
1 Feb	44	—	M	—	45	-1
2	46	-4	50	+3	47	-1
3	44	-2	46	+1	45	-1
4	46	-4	50	+2	48	-2
5	42	-4	46	0	46	-4
6	34	-2	36	+1	35	-1
7	41	-4	45	+2	43	-2
8	46	-2	48	+1	47	-1
9	38	-6	46	+1	45	-7
10	37	-9	46	+4	42	-5
11	46	-2	48	+4	44	+2
12	46	0	46	0	46	0
13	46	—	M	—	46	0
14	48	-6	54	+2	52	-4
15	51	-3	54	0	54	-3
1 Mar	39	-2	41	+3	38	+1
2	42	-3	45	+2	43	-1
3	42	-3	45	+1	44	-2
4	35	-6	41	+2	39	-4
5	32	-5	37	0	37	-5
6	36	-5	41	+2	39	-3
7	37	-6	43	+1	42	-5
1 Apr	52	-1	53	+1	52	0
2	45	-3	48	+1	47	-2
3	39	-5	44	0	44	-5
4	M	—	51	+3	48	—
5	M	—	50	-1	51	—
6	M	—	43	0	43	—
7	41	-1	42	-4	46	-5
8	37	-5	42	+5	37	0

Clear Days

Date (1991)	Temp #5	ΔT 5-4	Temp #4	ΔT 4-3	Temp #3	ΔT 5-3
23 Feb	M	—	37	+3	34	—
24	M	—	41	+3	38	—
25	M	—	39	+4	35	—
26	M	—	42	+7	35	—
27	M	—	39	+3	36	—
28	M	—	41	+5	36	—
17 Mar	M	—	M	—	32	—
26	M	—	37	+5	32	—
27	34	-1	35	+4	31	+3
16 Apr	M	—	47	+2	45	—
17	44	-3	47	+1	46	-2
18	48	—	M	—	48	0
19	M	—	46	0	46	—
20	M	—	51	+4	47	—

— = derived value; data not available
M = missing value

Table 2-5. Comparison of thermal profiles to sensor readings

	Sensor Compared					
	#5-#4		#4-#3		#5-#3	
Weather	ΔT_P	ΔT_S	ΔT_P	ΔT_S	ΔT_P	ΔT_S
Clear	-3.1	*	4.2	3.4	-5.0	*
Cloudy	-3.8	-3.6	1.7	1.4	-3.4	-2.1

ΔT_P is the temperature difference determined by comparing thermal profiles (°F).
ΔT_S is the mean temperature difference between sensors for all cases under these conditions (°F).
* Insufficient data from sensor #5

The final evaluation compared thermal profiles provided by vendors with those obtained by the team using a hand-held radiometer. In this case, absolute temperature differences were not considered; it was the repeatability of patterns and the relative differences that mattered. It is for this reason that the hand-held radiometer has potential for conducting a thermal analysis because of the interest in relative temperature changes along a road.

Figure 2-15 provides a side-by-side comparison of thermal analyses conducted commercially and by the project team under *clear* sky conditions, two years apart. Although the level of detail is considerably greater in the commercial product, the patterns are quite similar. Note the corresponding spikes, crossovers from warm to cold, and relative patterns.

Unfortunately, no measurements were obtained in order to compare profiles for this stretch of road for *cloudy* conditions. In the clear-sky case of Figure 2-15, the pavement at start is warm; in the cloudy case, it is cold.

Costs

Road thermal analysis is not inexpensive. When one considers the number of miles of roads in a given area, spending perhaps $200 per mile ($125 per kilometer) for thermal profiles may seem like a large expense. However, some of the high cost of road thermal analysis is related to the small amount that has been conducted in the United States. The vendors of the service have had to pay relatively high costs to outfit vehicles and to pay for insurance. It is conceivable that the cost could go down if more thermal analysis is conducted.

In order to reduce costs, Mn/DOT personnel conducted the thermography in Minnesota. The contractor leased to Mn/DOT the infrared radiometer, computer, and other monitoring equipment so that Mn/DOT could do its own data collection. The raw data were then provided to the contractor for analysis. Mn/DOT also asked for the raw data for possible future use. Unfortunately, this data set is extremely hard to use, although profiles can be constructed using it. (Mn/DOT received no plotted road temperature profiles. Such a problem could easily be solved in an RFP by explicitly requiring profiles.) Figure 2-16 shows an example of a profile constructed from the raw Mn/DOT data.

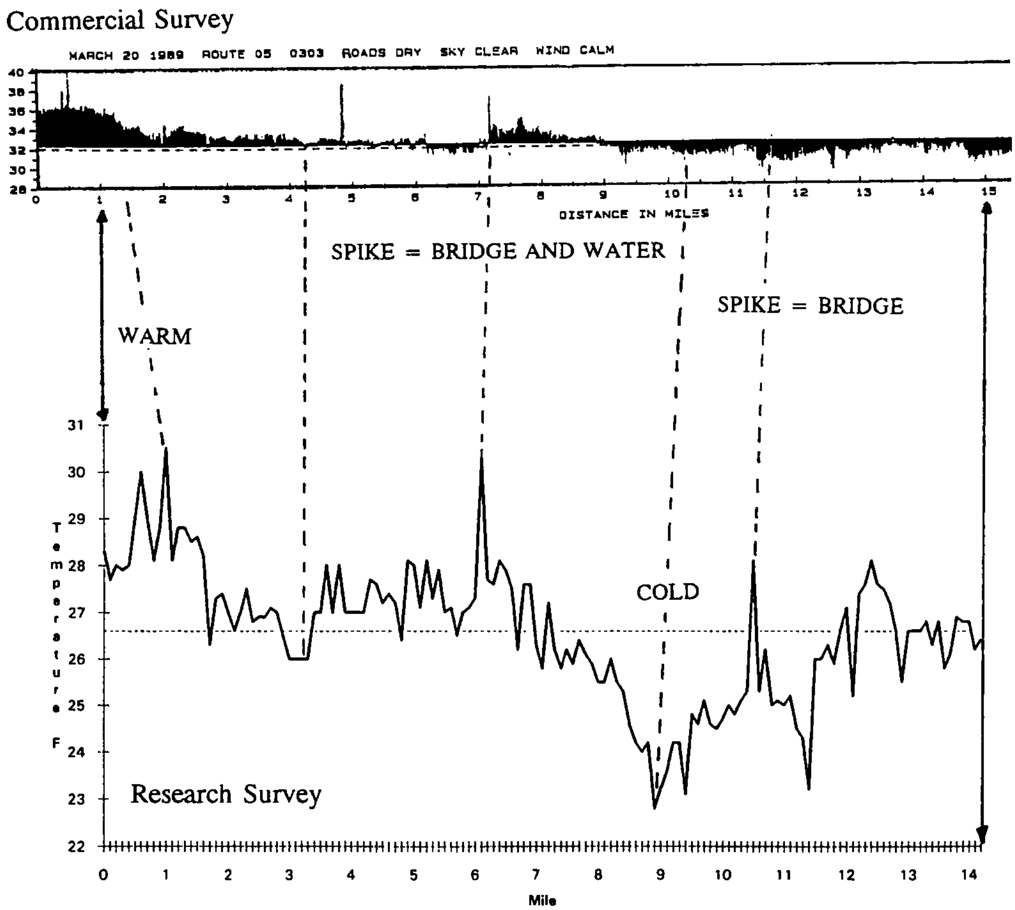

Figure 2-15. Comparison of commercial and research thermal analysis on a stretch of eastbound I-90 under clear skies (Used with the permission of King of the Road Map Service, Inc.)

The Matrix Management Group explored the potential for a third, less expensive methodology for conducting road thermal analysis. Using a hand-held radiometer, thermal profiles can be prepared which have sufficient detail to make sensor siting evaluations. The cost for such analysis is about one-tenth the cost of commercial thermography, although computer processing time would also be required. This research shows that this could be a viable process if an agency is willing to devote the resources to accomplish the task. It is something that could be done when other requirements are not pressing.

As of this writing, two highway agencies are installing RWIS sensors at ten to fifteen locations, each along roads about 150 mi (250 km) long. Commercial thermography over 250 km would cost about $30,000. If these agencies used thermal profiles to assist in selecting sensor locations for warmest, coldest, and up to four mean-temperature locations plus a few trouble spots, as recommended earlier, six locations (plus trouble spots) might be sufficient. The cost of one RPU station can easily exceed $30,000.

Based on these costs, the thermal analysis would pay for itself and would ensure that the sensors were strategically located to maximize the information available relating to pavement temperature. In addition, based on the National Ice Prediction System experience in the United Kingdom, thermal analysis enables more precise forecasts for entire road networks rather than just for individual locations. This has the potential for reducing costs of snow and ice control by providing better information for decision making.

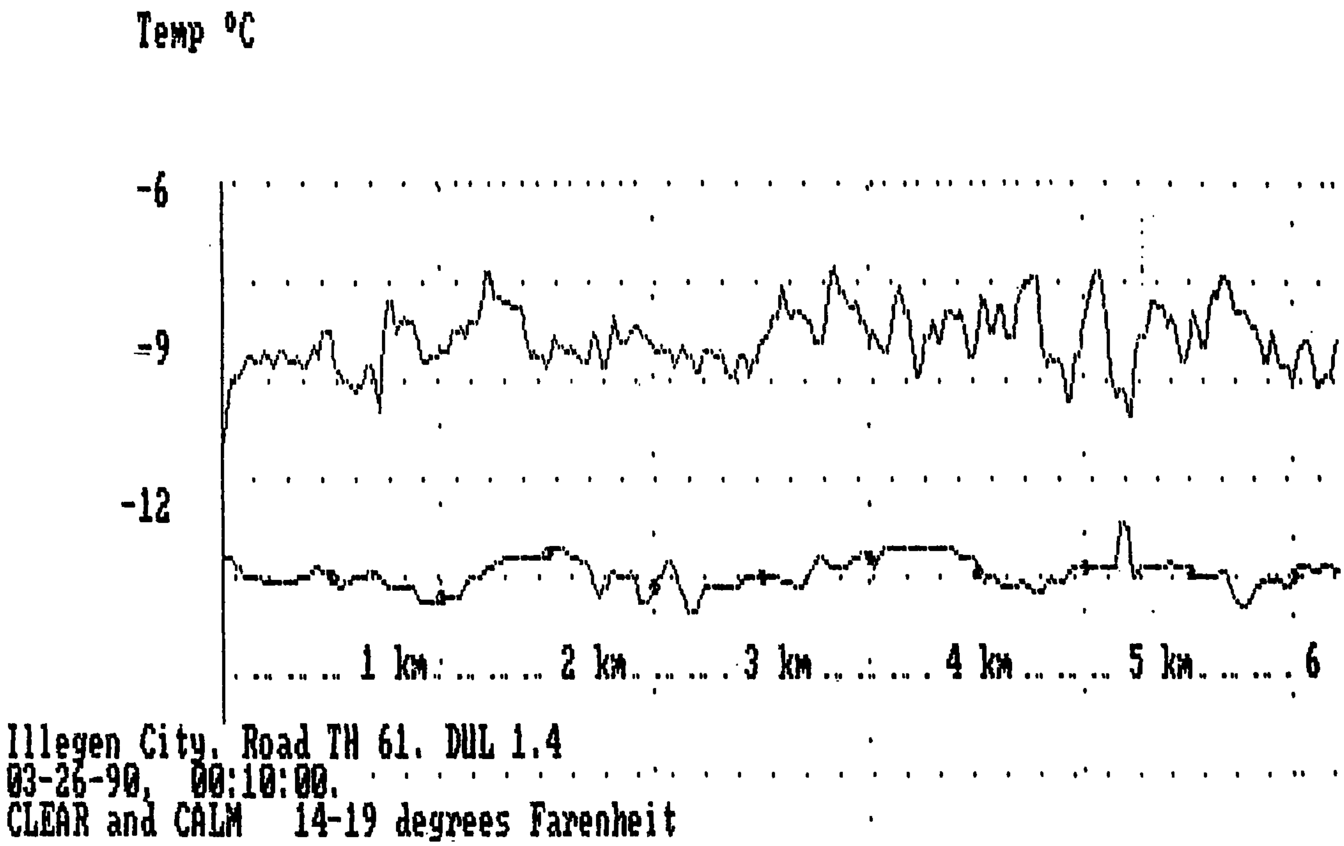

Figure 2-16. Sample road thermal profile from Mn/DOT data. Data are represented as obtained from Mn/DOT computer files

Conclusions

Road thermal analysis can be a valuable tool. It provides useful information for siting RWIS sensors and additional information on the distribution of road temperatures. Based on European and extremely limited North American experience, it can also have value in the analysis of snow and ice control routing and priorities, and for producing road temperature forecasts. It can help to reduce the cost of RWIS hardware as well as the costs of snow and ice control. However, the full economic value of thermal analysis has not been demonstrated conclusively in North America, and it should be considered only as one of the many aspects of implementing an RWIS.

Recommendations

- An agency considering installing a network of RWIS sensors should also consider having road thermal analysis conducted to assist in the siting of these sensors, and to assist the forecasting of road conditions.

- An agency considering analysis of snowplow routes to improve efficiency, either with in-house resources or using consultants who perform route analyses, should consider using road thermal analysis as one technique in order to ensure that proper attention is given to roads in a manner consistent with the thermal profiles, namely, plow the warmest roads last, if possible.

- If the climate shows sufficient variability and labor rules will allow it, an agency should consider using road thermal analysis to establish staged response to snow and ice control.

RWIS Communications

Communication is a significant component of road weather information systems. Communications are required to receive and disseminate road weather information. RWIS communications consist of:

- the transmission of data from sensors to RPUs, from RPUs to CPUs, and from CPUs to user workstations.

- the acquisition by VAMS of weather information, which includes NWS-disseminated data, RWIS data, and data from other remote monitoring sources.

- the communication of road weather forecasts from the forecasters (VAMS) to the snow and ice control managers who make resource allocation decisions, and the exchange of information between them.

- the dissemination of information to police, road users, and the public.

System incompatibility is an issue facing highway agencies implementing RWISs. In some cases, the people using an RWIS at one location are unable to access the data from another location because the CPU equipment or software is incompatible. For example, state highway agencies may want to exchange data with surrounding states. Unless compatibility is made a priority, this exchange of data may not be possible.

The incompatibility issue has magnified since more than one vendor now offers RWISs for highway use. If a highway agency has RWIS equipment in place from one vendor and wishes to add equipment from another vendor, its CPUs cannot exchange data. Furthermore, if a highway agency wants to add one more RPU to an existing system, an RPU from one vendor is incompatible with the CPU of another vendor. The following section discusses available alternative structures for RWIS communications.

Options for RWIS Communications

Two basic options exist for RWIS architecture: proprietary (closed) and nonproprietary (open) systems. Each type has advantages and disadvantages for a particular agency or situation.

A proprietary RWIS is a system developed and sold by a single manufacturer. Proprietary systems usually contain proprietary, vendor-developed software, data formats, and communication protocols for data exchange. Examples of proprietary systems include the SCAN System sold by Surface Systems, Incorporated (SSI); the ICECAST System sold by Vaisala; and the Surface Ice Prediction System (SIPS) sold by Climatronics.

An open RWIS is a system in which data formats and communication protocols are either in the public domain, or can be obtained and used for data dissemination. Such a system may have components from a single vendor or multiple vendors.

Proprietary RWISs have certain advantages over open systems. These advantages include:

- Proprietary systems are relatively easy to procure. Proprietary systems exist, so acquiring such a system primarily involves establishing the number of RPU stations, number and types of sensors, the mode of communications, and the methods of data access for decision makers. The systems are basically off-the-shelf, although the combination of components is tailored to an agency's needs.

- Considerable prior private-enterprise funds and energy have been invested in developing the technologies which are suited to agency needs. Purchasing proprietary systems benefits from that investment.

- The systems are quickly expandable, both to serve inter- or intra-agency needs. Adding an RPU station, additional sensors, or access capability can be accomplished with ease.

- Proprietary systems are proven technology. A system to be acquired will likely be just like one installed somewhere else; other RWIS users can be contacted to review the utility of the system.

- Use of proprietary systems simplifies system quality control. Components from only one vendor are likely to be interchangeable and easily linked.

- With like components, system maintenance should be easier than if components from different vendors are present.

However, proprietary systems have certain drawbacks. Disadvantages include:

- RWISs from one manufacturer have difficulty communicating with RWISs from other manufacturers. This lack of connectivity or interoperability results from proprietary communications protocols and data formats. Figure 2-17 portrays the lack of interconnectivity among systems from different manufacturers.

- Proprietary systems lack flexibility for designing and tailoring to highway agency needs. Each vendor's system may have some desirable feature, but without interoperability, a highway agency is limited to the offering of a particular vendor, or acquiring two or more systems, perhaps with overlapping capabilities.

- With proprietary systems, it is impossible to exchange data with other sources. A proprietary system may not allow access to other weather information systems, or be able to disseminate, process, or display data from them.

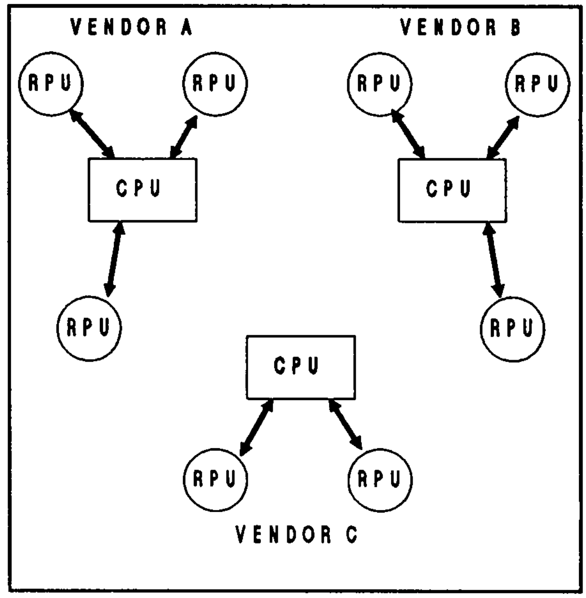

Figure 2-17. Example of a proprietary RWIS communications architecture

- If an agency wants to install different vendors' RPU stations or sensors, even in the same area as existing sensors, the agency will have to have multiple CPUs to access and process the data.

- Proprietary systems may require a dedicated, single-user radio frequency for data transmission. This means that even if multiband communications already exist, an additional radio link will have to be installed for RWIS data collection.

- If a vendor should go out of business, and its software is not in escrow, there is generally no provision for continuing, long-term software support.

Open communication systems also have advantages and disadvantages. Advantages of an open architecture include the following:

- An open system enhances opportunities for interoperability and connectivity among RWISs from different vendors, e.g., across state lines and among different agencies. Figures 2-18 through 2-20 show alternatives for open system communications:

- Figure 2-18: RPU-CPU protocol: RPUs from any vendor can interface with any CPU if there is a standard communications protocol. A companion requirement, however, is a standard data format so that the data can be processed and displayed.

- Figure 2-19: CPU-CPU protocol: RWISs from different vendors can communicate at the CPU level with a standard CPU-CPU communications protocol. There likely would be no direct access to other vendors' RPUs. All data could be used by each system if a standard data format were used.

- Figure 2-20: State communication system: if a standard RWIS communications protocol is specified in a statewide communications system, any workstations connected to the system could access RWIS data.

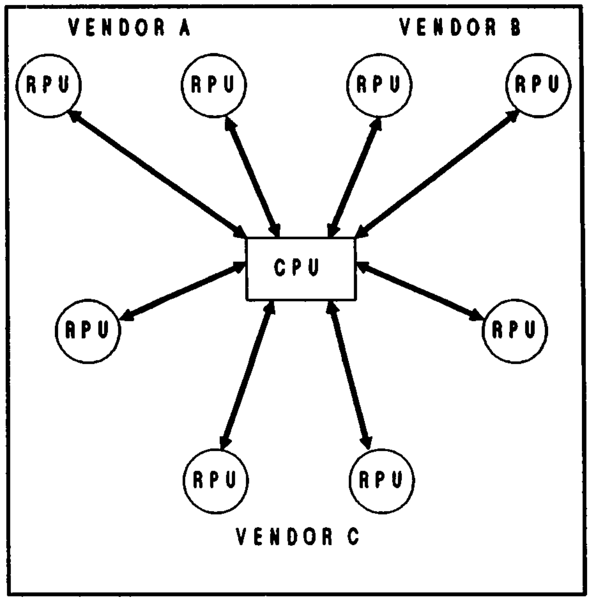

Figure 2-18. Example of an open RWIS communications architecture with RPU-CPU standard protocol

- There is potential to foster RWIS technology development due to competition. A purchaser can buy the best system available rather than having only one choice.

- An open system will provide more flexibility in acquiring RWIS technologies. If a highway agency wants to mix types of pavement sensors, or replace obsolete sensors with new technology, the opportunity to do so is enhanced with open systems.

- Data exchange with various sources can be effected with open communications, especially with a standard data format. Meteorological data from another system may have utility for highway maintenance decisions. Without an open system, these data might not be accessible or useable.

- An open system can be designed to operate with existing, multiple-frequency radio transmission capabilities, eliminating the need for additional, special-use radio equipment and frequencies.

- If an open system is specified in an RFP, control of system software can also be specified, providing the opportunity for long-term software support and maintenance.

Certain disadvantages are also likely with open systems. These disadvantages include:

- If an open system is specified, and no standard protocols exist that meet the specifications, a significant development effort may be required. A proprietary system may need to be redesigned to meet the specifications, or a new system may be required. Either case could increase the initial cost and the time required to acquire the system.

- Vendors of proprietary RWISs may not respond to the RFP. Certain requirements such as RPU-CPU standard communication protocols and requirements for delivery of proprietary software are issues some private companies will not accommodate.

- Some people think that product liability may be an issue when dealing with open systems. If a government is unwilling to indemnify an open-system vendor, that vendor may choose not to respond to an RFP.

- The implementation of an open communications system requires an agency to establish standard communication protocols and standard data formats. This requires knowledge of the possibilities, an understanding of the implications of requiring them, and the means to work with the selected vendor to effect a successful implementation.

- A true open system with components from more than one vendor may complicate system maintenance. A simple analogy: acquiring ten different items from different vendors, rather than ten of one item from the same vendor, increases maintenance and administrative requirements significantly. Some system vendors are also unlikely to want to maintain, even under contract, components from different vendors. On the other hand, other vendors may want to do this in order to expand their business.

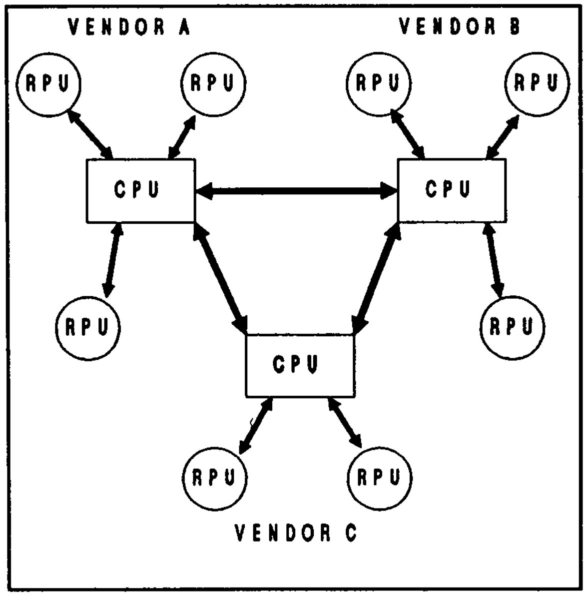

Figure 2-19. Example of an open RWIS communications system architecture with CPU-CPU standard protocol

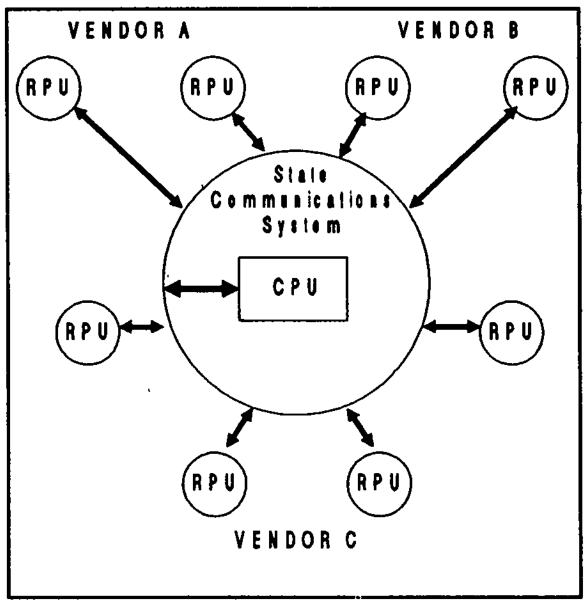

Figure 2-20. Example of an open RWIS communications architecture using a state communications system

Communications Protocols and Data Formats

Access to RWIS data is sometimes limited by a lack of interconnectivity among RWISs due to incompatible hardware and software in different vendors' systems.

Standard communication protocols are available to correct software incompatibility. Standard protocols could be used for RPU-CPU, CPU-CPU, RPU-state system, or CPU-state system communications.

A standard protocol for RWISs would establish an open system concept rather than a closed system. The RPU-CPU option (Figure 2-18) requires vendors to allow other vendors' hardware to work within their systems. Concerns have been expressed over vendor liability on this issue. Without an open RPU-CPU option, agencies are forced to buy another CPU if different RPU hardware is wanted. However, an open CPU-CPU system (Figure 2-19) would allow adjacent states, areas, or agencies to share information, whether they had different vendors' equipment or not.

Another ingredient in obtaining free interchange of RWIS data is a standard data format. This is required if a standard communication protocol is established. An analogy is to consider the protocol as an envelope in the mail. The standard protocol allows the envelope to reach its destination. However, the information in the envelope needs to be understood. If it is in an unknown language, the information cannot be translated. Similarly with RWIS data, if the format is unknown, the data cannot be decoded, or separate decoders need to be developed for each RPU. As with the standard communication protocols above, established international meteorological data codes exist.

Intrastate Communication

Many states have established statewide radio or telephone communication systems. These systems frequently have data transmission capabilities and are accessible by state highway agencies, or arrangements can be made for access. Using an existing statewide network would allow access to any RWIS CPU from any computer tied to the network. This means that other state agencies could have access to RWIS data.

With standard protocols and data formats, an RWIS could assist any state agency which needs meteorological or other environmental information. For example, RPUs in the road environment could include air-pollution sensors whose data are of interest to air-quality program personnel. RPUs installed at bridges or other locations with water flow concerns could include stream gauges whose data are needed by hydrologists. Other highway information such as vehicle counts and weigh-in-motion data could also be included. In addition to the expansion of data use, such tie-ins to state networks can help reduce costs. If leased telephone lines, for example, are used exclusively for communicating with RPUs, the costs can be high, especially if long-distance charges are included.

Data Ownership

Meteorological data have routinely been exchanged freely within the international meteorological community. However, some of the RWIS data currently provided to state highway agencies are considered proprietary by the vendors, even though the data are produced by sensors and disseminated by equipment purchased with public funds. Although rulings are not universal, one state's attorney general indicated that if the RWIS procurement contract specifies that the data are proprietary, then the state must honor that condition. This problem can be prevented if the acquiring agency specifies in the request for proposal that data will be considered in the public domain.

Data Archiving

Data are needed to develop weather prediction models and to determine how well an RWIS works. Archived data are also essential for performing objective forecast studies that weather advisors and VAMS can use to improve forecasting for particular locations. Archival data, along with maintenance logs, will also provide a record of highway agency activities for claims purposes.

Few state highway agencies retain RWIS data. Those that do basically keep the data on diskettes in boxes. All states are involved in data collection and management in some form. For example, state climatologists work to coordinate data archiving activities. RWIS data are potentially as valuable as any other meteorological data. RWIS data, along with hydrological, agricultural, aviation, environmental, and forestry data sets, should be available for sharing for research and operational applications. This means that RWIS data should be managed, organized, filed, and accessed with the same care and precision given to other types of data.

Recommendations

- In order to improve data exchange among agencies which might have different proprietary RWISs, or to establish future interoperability among RWISs, a CPU-to-CPU standard communication protocol should be adopted. An industry standard protocol, such as ISO X.25, should be used.
- A standard data format needs to be established so that RWIS data decoding can take place at any CPU or agency computer.
- State highway agencies should consider using existing or developing statewide communication systems for the dissemination of RWIS data and information.

- Agencies should decide whether RWIS sensor data should be in the public domain in order to facilitate their widest distribution and use. If an agency decides that RWIS data will be in the public domain, the requirement should be included in RFPs for RWISs.

- RWIS data should be archived with the assistance of state climatologists. Data should be archived in a format to enhance their sharing for research and analysis.

The use of open RWIS architecture, a statewide communication network, and having RWIS data in the public domain, have potential benefit beyond interconnectivity of RWISs. Access to these data by VAMS should improve forecast support. Data may be of use to other agencies, or data from other agencies may be used by highway agencies. These recommendations should provide a synergistic improvement in the total weather support provided to highway agencies.

Methodology for the Cost Analysis

Assessing the cost-effectiveness of various road weather information technologies was one of the objectives of this project. The research team developed a cost-reduction simulation model to accomplish this objective. A statistical simulation model was used because the methodology had to deal with different snow and ice control strategies, and with different weather regimes having localized effects due to factors such as terrain. Since the occurrence of weather events can be described statistically (climatology), a model using frequencies of weather events and road conditions was used. This model computes the costs of allocating snow and ice control resources, and monitors the service level achieved with each allocation decision.

The model is written in FORTRAN and runs on IBM-compatible microcomputers with a graphics card and math coprocessor. The model has not been documented for general release because it was developed expressly for the analysis required in this project.

Determining Costs

To ensure maximum objectivity, the model focuses almost entirely on direct costs of various snow and ice control technologies. These include costs for labor, equipment, and materials. Direct costs were computed by using actual expenditures for snow and ice control.

Indirect (societal) costs and benefits were excluded because they are subjective, difficult to quantify, and potentially controversial. Examples of indirect benefits of improved snow and ice control technologies include improved traffic flow, reduced fuel consumption from smoother traffic flow, reduced accident rates, lower insurance premiums due to fewer accidents, and a reduction of the costs of delays in starting work or early release from work due to snow and/or ice on the roads (one company reported a cost of $25,000 per half-hour of delayed work start[*]). An example of why such benefits and costs were excluded is that the causes of accidents are frequently disputed, and whether an accident that didn't occur didn't occur because of snow and ice control is conjecture. Any societal benefits—though not quantified in this model—would increase the attractiveness of a road weather information system beyond the level shown by the model.

In the model, "cost reductions" are defined as the differences in direct snow and ice control expenditures produced by alternative RWIS options (like snow and ice control costs with tailored forecasts as compared to those costs without tailored forecasts). "Weather costs" are those expenditures required to implement various RWIS options (such as acquiring tailored forecasts).

The model compares pairs of road weather information systems and assesses their *marginal costs* (i.e., the *differences* in cost between two specific weather information options). The model uses equivalent annualized costs reduced to a daily basis. When weather information options involve one-time, up-front costs such as installing pavement sensors, those costs are converted to amortized, annual and daily costs. Operational costs of snow and ice control activities are expressed directly as daily costs.

In addition to cost savings, improved snow and ice control also improves the service level provided to road users. For the purpose of this study, "service level" is a subjective evaluation of the ability of the road to carry traffic safely. In the simulation, snow and ice control savings should not be, and are not achieved at the expense of road users. Therefore, the model tracks the service level to determine whether it would be reduced by various weather information options.

Use of this simulation model provided a helpful and objective check on conclusions derived from field observations, surveys, and interactions with numerous maintenance managers and meteorologists over a three-year period. Although the assumptions used, as in any simulation, are somewhat idealized and simplified—like always choosing to dispatch snowplows when snow on pavement is the forecast condition—they are always conservative. Each assumption was derived by an experienced meteorologist and maintenance manager working in tandem. Weather events are randomly generated, but the sum of all such events is the actual climatology for each locale. Both the probability of forecast accuracy, and of actual weather conditions at each road segment varying from that declared for the official reporting station, reflect how different weather patterns produce different results in marine areas, mountainous areas, and other areas with special climatologies. The model's assumed reliability of forecasts never exceeds 75 percent; the effects on service level and cost due to errors resulting from bad forecasts are fully included.

The projected effects of rapidly improving weather observation (e.g., NEXRAD), weather analysis (e.g., AWIPS-90), and weather forecasts (e.g., NOWCASTING, artificial intelligence) are not included, but can be expected to raise the threshold capabilities of every

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* Reported in a conversation with a Washington State Department of Transportation maintenance superintendent responsible for snow and ice control in the vicinity of a Boeing company plant.

scenario. Nevertheless, the provision for forecast probability in the model allows it to be run using any level of accuracy an analyst thinks appropriate.

Model Inputs

In order to compute cost reduction, data must be entered into the model's data base. These model inputs are what calibrate the model for different agency practices, weather information strategy costs, and road conditions requiring action (or no action).

Regional Practices

The model accounts for differences in snow and ice control practices in various regions. For example, chemicals (especially sodium chloride, or "salt") are heavily used to remove snow and ice in the Northeast and Midwest. Further west, proportionally fewer chemicals are used while more abrasives (such as sand) are applied. Each of these practices has its own effectiveness, cost, and associated weather-related thresholds for decision makers. The model accounts for those variations.

Climate

Because climates in the United States vary greatly from east to west and from north to south, the analysis was designed to include evaluations of practices in various climates. Standard climatological data available from local National Weather Service forecast offices were selected as the best descriptors of climate for each area. Annual climatological summaries were obtained for Seattle, Washington; Minneapolis, Minnesota; and Denver, Colorado.

These climatological summaries outline the frequency of various weather phenomena on a monthly basis. The weather events considered in this analysis include snow or ice, rain, and fog (for frost formation). The summaries provide the frequencies for these events in days per month. It was assumed that the winter season runs from October through March. The weather event frequencies during that period were added to obtain seasonal frequencies.

Road Conditions

Of course, highway maintenance decisions are based on road conditions as well as the weather. National Weather Service data refer to a specific point, usually an airport from which meteorological measurements are taken. However, road conditions can vary considerably in a small region due to the influence of topography, the presence of water, orientation of a road toward the sun, cuts, and other exposure considerations. While the climatology of an area can be described fairly easily from National Weather Service public records, a more detailed breakdown for road conditions is needed by the model (and reflected in the daily judgments of snow and ice control managers). For example, while it may be snowing at an airport, road conditions in the area may vary from dry, to wet, to snow-covered. The model was designed to provide a distribution of conditions over a road network based on realistic climatological input provided by the researchers for the real road sections analyzed by this model. Table 2-6 shows the distribution of forecast probabilities used in the model. For example, if the road condition is clear, it was 75% probable to have been forecast clear, 5% probable to have been forecast frost, 10% wet, and so on.

Probability values were assigned to each element in the array based on a meteorologist's evaluation, the ability to forecast the phenomena, and input from a maintenance engineer on forecast accuracy. The 75% forecast accuracy, used as the maximum figure, is, in reality, a conservative number. The field tests showed 84% accuracy for forecasting the occurrence of winter weather, and 83% has been documented in an independent evaluation of private meteorological services (McDonald 1990).

Table 2-6. Example of an array of forecast probabilities given road condition for road segment one, based on tailored forecasts

	Forecast							
Road Condition	Clear	Frost	Wet	Ice	Snow <2"	Snow >2"	Clear to Ice	Clear to Snow
Clear	.75	.05	.10	.05	.03	.02	.00	.00
Frost	.00	.50	.10	.10	.03	.02	.25	.00
Wet	.15	.02	.70	.04	.05	.04	.00	.00
Ice	.00	.10	.15	.55	.03	.02	.15	.00
Snow	.00	.00	.00	.10	.35	.35	.00	.20
Packed Snow	.00	.00	.00	.05	.30	.45	.00	.20

Model Operation

The model selects snow and ice control actions based on the weather or pavement conditions it forecasts. For example, if two or more inches of snow are forecast, the model will select the use of trucks with plows. If wet or dry roads are forecast, the model will either select taking no action or assigning road patrols. The action selected is based on the quality of the forecasts available. This process is intended to mimic the real world, where a maintenance manager with access only to media forecasts might select patrols, while a manager with tailored weather support might take no action. Figure 2-21 shows the flow of information that generates the output.

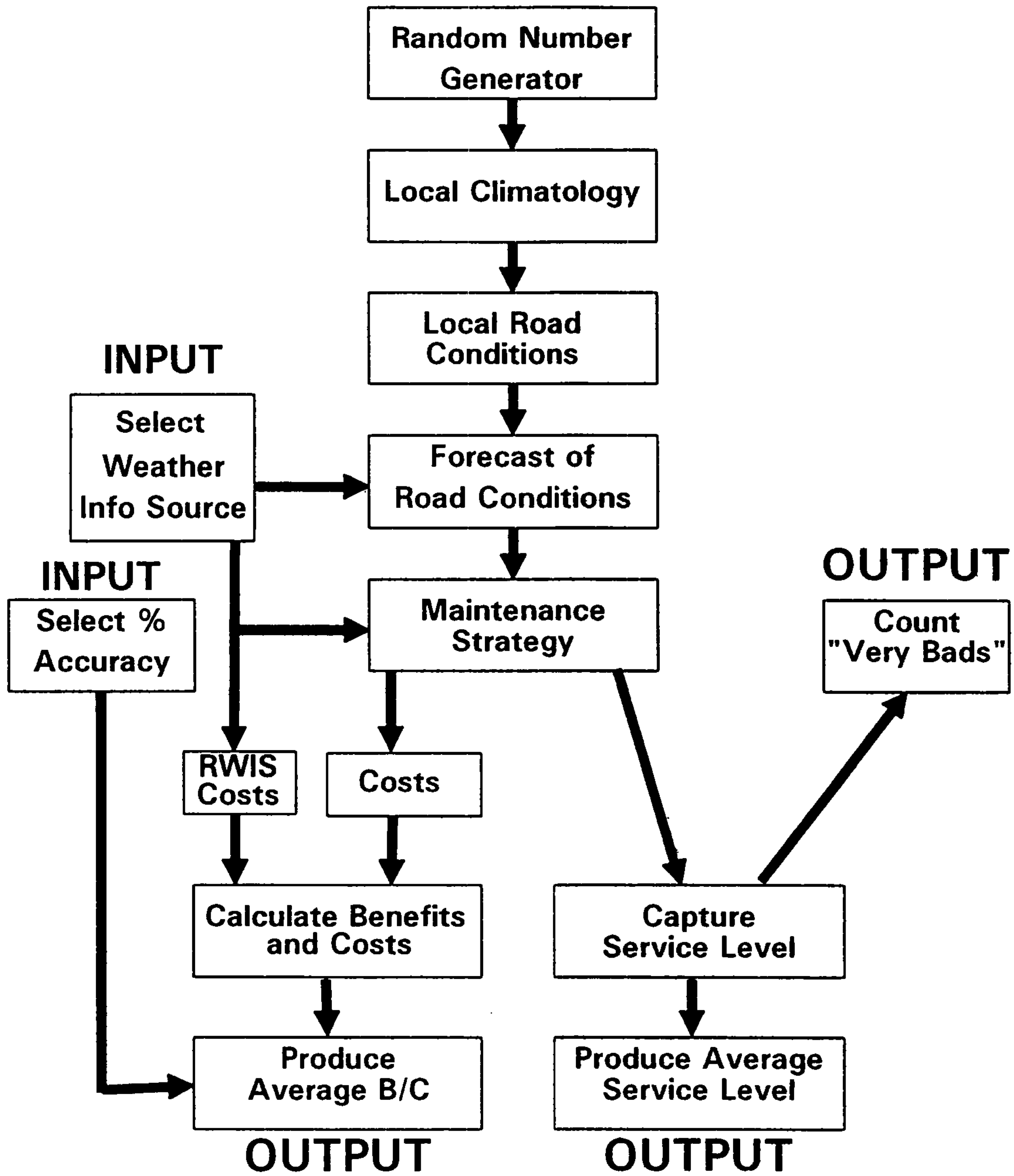

Figure 2-21. Flow of information in the simulation model

The first piece of information generated by the model is a weather event. The model uses a random number generator applied to the climatology distribution. Over time (i.e., over a large number of runs), the distribution of weather events generated will approximate the climatological distribution of the events for the actual region being used. For example, a snow event may be predicted to occur 5% of the time at a given location based on its climatology. Over a large number of iterations, the model will also generate a snow event 5% of the time. Figure 2-22 shows how a frequency distribution of weather events is generated by using a computer's random number generator. The example shows 0.67 generated. On the linear distribution of random numbers compared to climatology distributions, 0.67 equates to "No Significant Weather".

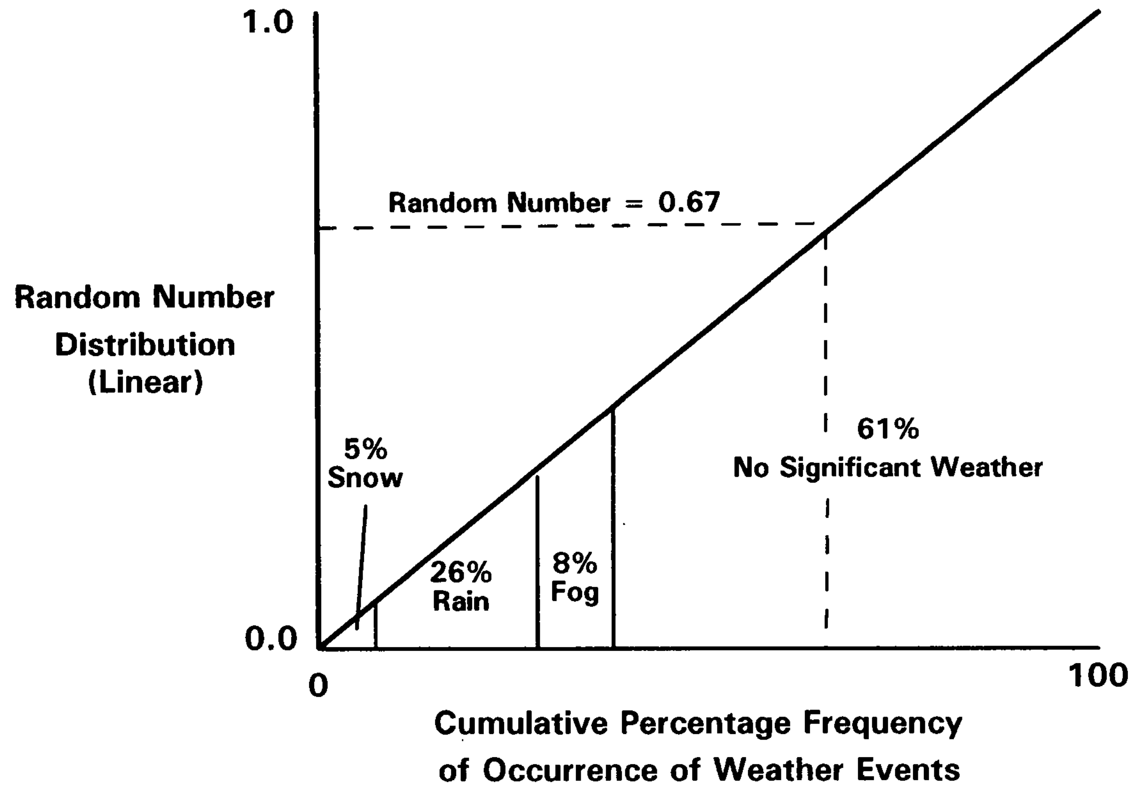

Figure 2-22. Weather events generator

The weather event generator is used to produce a distribution of road conditions. In the example above of "No Significant Weather" (at the reporting station), the road segments in the model will have been given ice, snow, clear, or wet conditions based on their percentage in the climatology. Then, another routine designates the likely accompanying forecast of wet, dry, or snow-covered roads. The forecast designation is based on a probability distribution of likely forecasts—accurate and inaccurate—for the generated road conditions.

This forecast probability is based on reviews of actual tailored forecasts provided to snow and ice control activities (Table 2-6). Based on the road weather information system inputs thus generated, a maintenance action is selected. For example, if the forecast calls for snow, deploying trucks with plows is selected as the response.

Once a decision is made regarding what resources to mobilize, the model provides the cost of allocating that resource and the service level associated with the action. The service level is evaluated on a subjective scale of "1" to "5," with "1" being "best" and "5" being "worst". If roads are dry, any maintenance action selected is a "1." However, there is a cost associated with the action. On the other hand, if no action is taken when the road is icy and the forecast was for wet pavement, the service level would be "5."

At this point, the model compares a specific maintenance action with the actions selected using different weather information. One scenario used by the model is actions based on weather information from the media and other informal sources. The decisions made with that information are then compared with decisions made based on tailored, site-specific forecasts. Site-specific forecasts are assumed to be more accurate and useful than generalized forecasts from the public media.

The costs of each snow and ice control action are calculated and compared. Savings one alternative generates over a more costly one are compared to the increased weather information costs for achieving them by computing a cost-reduction ratio. The cost-reduction ratio is computed by dividing the operational savings by the difference in weather information costs as follows:

$$\textbf{Cost-Reduction Ratio} = (DC_2 - DC_1) \div (IC_1 - IC_2), \text{ where}$$

DC_1, DC_2 = Direct Costs of snow and ice control incurred from using weather information options #1 and #2, respectively, and

IC_1, IC_2 = Information Costs incurred to implement weather information options #1 and #2, respectively.

For a valid order-of-magnitude ratio to emerge, the model must be run for a number of iterations. A subroutine was devised to compute at every hundredth iteration how many iterations are required to achieve either 2 or 5% accuracy in the ratio with a 95% confidence level. Except for a few cases where the number of iterations required was extraordinarily high, the ratio is computed to an accuracy level within 5%.

Model Structure

All of the information used in the model is contained in arrays of information. The model uses the following arrays to simulate a snow and ice control manager making cost-effective decisions:

One-variable arrays:

1) Climatology of weather events
2) Costs of snow and ice-control resources
3) Costs of weather information technologies

Two-variable array:

1) "Strategy matrix" (assigns resources to a strategy, i.e., snow and ice control activity)

Three-variable arrays:

1) Road conditions, over particular roads, reflecting a given weather condition
2) Weather information (used to make resource-allocation decisions), probability of forecast accuracy, and source of the weather information

3) Road condition forecast, source of weather information, and snow and ice control strategy
4) Service level, for various response strategies, given various road conditions

Each element of an array is a value assigned to an item of information. For example, the item may be a weather event called "snow" and might occur "10%" of the time (value). A snow and ice control measure defined as a "truck with plow attachment" might cost "$19 per hour" (value) to operate. The arrays used in this model are explained below:

One-Variable Arrays

The one-variable arrays are lists of items that have values assigned to them. These arrays include the climatology of weather events, the costs of snow and ice control resources, and the costs of weather information technologies.

The *climatology of weather events* is nothing more than the list of possible winter weather events that were extracted from standard climatological summaries for a location and their frequencies of occurrence. A typical climatology list contains the values shown in Table 2-7.

Table 2-7. Climatology of weather events

Weather Event	Frequency of Occurrence
No significant weather	0.60
Rain	0.20
Snow	0.12
Fog	0.08
Total:	1.00

Another array contains the *snow and ice control resources and their associated costs.* Typical resources include *people* (i.e., equipment operators); *vehicles* (pickup trucks, trucks with spreaders, trucks with plows); and *materials* (abrasives, chemicals). Table 2-8 shows a typical screen display of resource costs.

The third one-variable array provides the *costs associated with the weather information options* to be used in the decision-making process. A typical range of options includes information obtained informally (from public media, supervisor, personal observation, etc.), in-place meteorological and pavement surface sensors, detailed forecasts from private meteorological services, road thermal analysis, and combinations of these technologies. Each option has a cost value assigned based on its average costs including overhead and fringe benefits. These costs are reduced to a daily rate. For technologies that involve a one-time cost, a daily rate is calculated using a five-year amortization and 180 days of winter per year. Table 2-9 shows a screen display of daily costs for a weather information option.

Table 2-8. Resources matrix

Unit	Value
Person-hours	$18.00
Truck-hours	$19.00
Sand/ton	$7.00

Two-Variable Array

The model employs one two-variable array. This array generates *snow and ice control costs* when it *assigns the resources to a maintenance strategy.* The costs of resources assigned are based on the assumption that the snow and ice control activity (strategy) will require eight hours, and that the resources must deal with 100 miles (160 kilometers) of four-lane highways during that eight hours. Examples of resources for one strategy could be three people driving three trucks with spreaders applying chemicals at the rate of 300 lb (136 kg)/lane-mile for an ice event, or one person driving a pickup truck for winter patrolling, or combinations of these and other approaches.

Table 2-9. Daily cost of weather information options

Information System	Value
No weather information	$0.00
Sensors	$222.00
Forecasts	$25.00
Sensors + forecasts	$247.00

Table 2-10 is a screen display of resource requirements for a response strategy. Resources are assigned to the strategy shown on the left. The .08 person shown for "No response" assumes a dispatch person works eight hours for each 100 miles each day. The Delay Cost column was established to capture societal costs for delayed responses, but is not used. The "Patrol, late sand" and "Patrol, late plow" strategies were devised to capture the increased costs when delayed response allows a storm to get way ahead of snow and ice control. It is assumed that if response is delayed, adverse road conditions will take 50 percent longer to correct. Patrol, however, is not affected. Given this, the person-hours for "Patrol, late sand" example is explained as follows: The usual person-hours required for sand trucks is .48, which includes .08 hr for a dispatcher. The sand truck time alone is thus .40. At 1.5× for delayed response, .60 person-hours are required to operate sand trucks. In addition, Patrol is required at .32 (includes dispatcher). The total person-hours for "Patrol, late sand" is $.60 + .32 = .92$ person-hours. Truck hours ($.40 \times 1.5$ + Patrol $.24 = .84$) will also be needed; and the amount of sand (1.6 tons $\times$ 1.5 = 2.40 tons) is also increased by the delay.

Three-Variable Arrays

Four arrays comprised of three variables are used in the model. These arrays generate distributions of road conditions, weather forecast probabilities, and snow and ice control actions, and assign a service level to the action taken.

The first array *distributes road conditions over the road network.* Since each model calculation is initialized by climatology, the *weather condition* is the first variable of this array. The second variable in the array is the *road condition.* The array is constructed using local knowledge to estimate a frequency of occurrence of road conditions since no climatology of road conditions is available. For example, in the Seattle area, if it is snowing at Seattle-Tacoma International Airport (the local reporting station), there is likely to be snow on some local roads. However, others may only be wet, and still others may be dry. The array is constructed to provide the frequency of occurrence of a road condition given that a weather condition is specified. The third variable of the array is the *road segment*. Being able to specify the road segment allows the model to account for roads that pose greater challenges in snow and ice control because of terrain and other effects.

Table 2-10. Strategy resource requirements

	Units (#/mile/day)			
Strategy	Person-hours	Truck-hours	Sand (tons)	Delay Cost
No response	.08	.00	.00	--
Random patrol	.32	.24	.00	--
Trucks, sand	.48	.40	1.60	--
Trucks, plow	.48	.40	.00	--
Patrol + sand	.72	.64	1.60	--
Patrol + plow	.72	.64	1.60	--
Patrol, late sand	.92	.84	2.40	.00
Patrol, late plow	.92	.84	.00	.00

The second three-variable array is as shown in Table 2-6. The array *generates the weather information* used to make resource-allocation decisions. The first variable is a *forecast of a weather event*. The array assigns a probability to the forecast based on the *road condition experienced* (second variable). For example, the road condition generated by the array in Table 2-6 might be "snow," and the forecast probability that snow was to accumulate on the road might be 0.70. The third variable of the array is the *weather information source*. One source is a maintenance manager's supposition based on information heard over the media, in National Weather Service forecasts, from staff observations, or from pavement temperature sensors. An alternative source is a contracted meteorological service. Since the methodology assumes that the resource allocations for snow and ice control are based on information received, this array is used with the next array to generate the strategies whose costs are calculated.

The third three-variable array *generates the snow and ice control action*. An example of this array is shown in Table 2-11. If a *road condition* (first variable) is forecast, a *resource-allocation response* occurs (second variable). For example, if the expected road condition is "snow > 2"," then snowplows are called for. If only wet roads are expected, taking no action is the appropriate response. The values in the array are either zero (0) or one (1). A "1" selects the strategy for the specified road condition being forecast. All other elements of that row are "0." In other words, only one strategy is selected for a given road condition. The third variable of this array is again the *source of the weather information.* The source of the weather information is shown in the upper left corner of Table 2-11, "Weather Information Source: Sensors + tailored forecasts." The "Clear to ice" and "Clear to snow" conditions were devised to generate actions that cause additional costs when bad forecasts cause delays.

The last three-variable array *assigns a "service level" value* to the *response strategy* (first variable) recommended for a given *road condition* (second variable). An example of this array is shown in Table 2-12. The values range from "1" (very good) to "5" (very bad). They are assigned subjectively, but the assignments are based on experience. For example, "very good" (1) to "good" (2) would be assigned to any strategy selected when the roads are dry. "Very bad" (5) would be assigned to doing nothing when snow or ice is expected to

Table 2-11. Snow and ice control strategy array

Weather Information Source: Sensors + tailored forecasts — Strategy

Predicted Road Condition	No response	Random patrol	Trucks, sand	Trucks, plow	Patrol + sand	Patrol + plow	Patrol, late sand	Patrol, late plow
Clear	1	0	0	0	0	0	0	0
Frost	0	0	1	0	0	0	0	0
Wet	1	0	0	0	0	0	0	0
Ice	0	0	1	0	0	0	0	0
Snow <2"	0	0	1	0	0	0	0	0
Snow >2"	0	0	0	1	0	0	0	0
Clear to ice	0	0	0	0	0	0	1	0
Clear to snow	0	0	0	0	0	0	0	1

accumulate on the roads. Since this strategy may be appropriate for some low-priority roads, the third variable is the *road segment.* This allows an appropriate service level to be specified for each road segment. Between the two extremes described above, a "2" or "3" is assigned to such activities as chemicals applied to ice in a timely fashion. Applying chemicals as a reactive measure would be assigned a "4."

If the service level were decreased by the use of a road weather information system, the use of that technology would not be prudent—even if a cost analysis produced a positive return on investment. This array allows the model to keep track of the average service level so comparisons among weather information options can be made. The model also counts the number of "5" ratings. The service level array is constructed using "5" to reflect Type I errors (those that occur when someone should have taken action, but didn't). Monitoring Type I errors evaluates the effectiveness of the road weather information system in reducing them. Figure 2-23 provides an explanation of the Types I and II errors in the context of using forecast road conditions.

From a service and liability standpoint, no Type I errors should occur. When attempts are made to minimize Type I errors, Type II errors may increase. Type II errors increase cost but are not likely to engender additional liability. Site-specific, tailored forecasts with sensor data support and interaction between forecasters and decision makers will help to minimize this cost increase.

		Observed: Ice	Observed: No Ice
Forecast	Ice	Good	Bad (Type II)
	No Ice	Very Bad (Type I)	Good

Figure 2-23. Forecast decision matrix

During early model runs, it was discovered that the lowest cost was being generated by choosing to "do nothing." If taking no maintenance action were selected because of bad

Table 2-12. **Response strategies service levels for road segment one**

Segment One				Strategy				
Road Condition	No response	Random patrol	Trucks, sand	Trucks, plow	Patrol + sand	Patrol + plow	Patrol, late sand	Patrol, late plow
Clear	1	1	1	1	1	1	1	1
Frost	5	4	2	5	1	5	3	5
Wet	1	1	1	1	1	1	1	1
Ice	5	4	2	5	1	5	4	5
Snow	5	4	4	1	4	1	4	3
Packed snow	5	4	3	2	3	1	5	4

information, the service level in icy or snow-covered conditions would be "very bad." However, there was no cost associated with doing nothing. To correct this discrepancy, new response strategies were devised to simulate reality more closely. These included "Patrol, late sand" and "Patrol, late plow." In actual practice, it usually takes longer to remove snow when resources are not mobilized in a timely fashion. Likewise, if chemicals or abrasives are not applied quickly, ice can take longer to control. Each of these situations reduces the quality of service, costs the highway agency more, and may increase costs for the traveling public. The model incorporates strategies for measuring the additional costs of incorrect decisions.

Model Runs

Demonstration Runs

Simple scenarios were created to demonstrate and better understand the model. These included a one-segment road network 100 miles (160 kilometers) long; simple two-element lists of climatologies, weather information strategies, resources, and actions; and arrays truncated to 2x2 for all of the other inputs. An example scenario contained a climatology of snow/no snow, and response strategies of winter patrol used with media-only information compared to no patrol with tailored forecast support. The values assigned to items in the arrays were varied to help analyze the sensitivity of the model to various inputs. The analysis also included a look at using perfect forecasts for setting a limit to the cost reductions obtainable.

Data Runs

Following familiarity runs of the model, realistic scenarios were developed for Washington, Minnesota, and Colorado. Arrays were built to reflect each state's snow and ice control practices, weather information sources, climatologies, and characteristic road condition distributions. Examples follow of how savings are generated in the model by the establishment of an RWIS, and how such data are used in comparing costs.

The cost for routine patrolling is estimated for model use to be 8 hours × $18 (salary and benefits) plus 8 hours × $19 (cost per hour for the truck) for a total of $296 each night. The cost for one or two shifts on Saturday and Sunday is also added. If the area is large, complex, or has high traffic volumes and/or multiple weather patterns, more than one patrolling person may be used.

If patrols are replaced by RWIS data, the cost reduction from the RWIS will be $296 saved per night per patrol for the duration of the winter. If tailored weather forecasts cost $500 per month, the cost-reduction ratio for using the forecasts is almost 18 per patrol person ($296 × 30 nights = $8,880, ÷ $500 (cost of forecasts) = 17.8).

Under a typical union contract, bringing people into work after they have left for home (callback) requires a two-hour pay bonus, pay for travel time to and from work, and pay at 1.5 times a person's normal rate of pay. This means that the cost for each callback will be about $54* in bonus and $27 in travel costs (assuming ½ hr each way) for a total of $81 per person before anything is accomplished. Each workhour costs $46 per person ($27 in wages plus $19 for truck rental). A two-hour minimum, which is often a union requirement, means a callout costs on the order of $173 per hr (callout $81 plus 2 hr @ $46). Given this cost, an area or statewide mobilization can be extremely expensive.

Another option is splitting the total crew into day and night groups. Night shifts, based on the same rates, cost between $720 (on duty but not driving) and $1,480 per shift for a five-person crew, depending on the amount of patrolling involved. In mild winters, unless normal maintenance work can also be conducted at night, the night crews soon run out of productive or cost-effective work to do. Even during normal winters, night crews frequently have little to do. The costs of these crews occur every night. In some areas, however, the frequency of bad winter weather is high enough that such an arrangement is cost-effective.

Unit costs for weather information used in the analysis were based on actual costs in the states providing data. The cost of value-added meteorological services (VAMS) can be as low as $10 per day. The cost of $25 per day for forecasting services assumed in the model is an average of known contracting costs plus daily communications costs. A conservative daily cost of about $200 to $500 is obtained when the amortized costs of sensors are added to the VAMS cost.

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* For simplicity, the $54 applies the time-and-a-half rate to the salary unit cost even though it includes benefits.

Table 2-13 shows a typical model run output screen. This output shows the results of a comparison of an integrated weather information system (sensors and tailored forecasts) with "media weather," e.g., listening to a radio, watching TV, or reading a newspaper.

This display is a "snapshot" of the 1,016th iteration (N). For each of nine road segments, the actual road condition is given for the weather event produced ("Rain") by random number generation. For example, Segment eight has "snow," while Segment one is "wet." The "media" weather supposition for Segment one was for ice on the road. With the integrated system forecast, the site-specific forecast was for "wet" road. Each forecast generated a maintenance action. In the first case (supposition of ice), sanders would be dispatched. The service level is high (1), but the action is costly. In the second case (wet), no action would be taken. The service level again is high because no action is required. At the same time, the cost is low. Note that a bad forecast occurs for segment six. This is a Type II error which results in an unnecessary expenditure of funds.

Table 2-13. Typical model run output screen

N = 1,016 822 5% 5,141 2%		Media weather		Sensors + forecasts	
Rain	**Actual Condition**	**Forecast Condition**	**Service Level**	**Forecast Condition**	**Service Level**
Segment one	Wet	Ice	1	Wet	1
Segment two	Wet	Wet	1	Wet	1
Segment three	Wet	Ice	1	Wet	1
Segment four	Wet	Wet	1	Wet	1
Segment five	Frost	Wet	5	Frost	2
Segment six	Wet	Wet	1	Frost	1
Segment seven	Wet	Wet	1	Wet	1
Segment eight	Snow	Clear to Ice	4	Clear to Ice	4
Segment nine	Packed snow	Ice	4	Snow	2
	Average SL	1.58		1.36	
Cost-reduction	# at 5 or lower	693		201	
ratio: 3.63	Average cost per day	$1,999		$1,369	

The information presented at the bottom of the figure includes the average service level (SL) computed over all segments and iterations. Type I errors, those producing a service level of "5" (poor), are counted. Note the Type I error at segment five. The "media" supposition anticipated "wet," but frost occurred. In this scenario, using the RWIS reduced the Type I errors by 71% (693 to 201), and the service level improved by 14% (1.58 to 1.36).

The average costs per day shown in the figure are computed based on the costs of weather information and snow and ice control activity. It is assumed that the information used to form a supposition ("media weather") is free. The reduced costs of snow and ice control, offset by the costs of sensors and tailored forecasts, show a cost advantage for RWIS use of $1,369 per day compared to $1,999 without the RWIS.

The display indicates that 822 iterations were required to provide 95% confidence that the cost-reduction ratio is within 5% accuracy. Since 1,016 iterations were accomplished, one can be 95% confident that the cost-reduction ratio of 3.63 is within 5% accuracy. Another 4,125 iterations, or 5,141 total, would be required for 2% accuracy based on the calculation at the 1,000th iteration.

Results

In all cases, model runs result in significantly reduced costs when decisions are made using only tailored forecast support. Given typical costs of tailored forecast services, even a slight improvement in decision making will produce significant cost savings. Forecasting costs are somewhat depressed due to competition and frequent low-bid contracting by agencies. The consequence of lower cost may be suboptimal meteorological support in both the quality and quantity of information provided to decision makers.

The value of prediction, in general, comes from acting on knowledge of the future rather than reacting to a phenomenon as it happens. This value includes not taking acting because the future knowledge indicates something will not happen and action is not warranted.

Taking no action is perhaps the most cost-effective reason for using forecast information. There is no cost involved in doing nothing, if in fact, the future knowledge is accurate. The model includes nonaction explicitly by having the decision maker take action only when a forecast (right or wrong) indicates the occurrence of a road condition that requires treatment. Model runs based on comparing sensors and forecasts (prediction) to sensors alone (detection) gave the results presented in Table 2-13.

When comparing the costs of snow and ice control using sensors and forecasts (for prediction of conditions) with sensors alone (detection of conditions), the model produced cost reduction ratios of 51, 25, and 11, for Washington, Minnesota, and Colorado respectively. The differences in the ratios result from the increased investment in sensor technology.

These results indicate that the use of forecasts increases can result in significantly decreased snow and ice control costs. This is partially true because the forecasts are inexpensive in comparison to the cost of snow and ice control activities. There is additional benefit because sensors provide information, heretofore unavailable, on which forecasts can be based, and have better forecasts.

Table 2-14 provides calculations of both the service level and the numbers of Type I errors obtained when sensors are added to assist forecast capabilities. There is a small increase in the service level, but there is a dramatic 80% reduction in the number of Type I errors. The reduction is attributed to a marked increase in the ability to predict pavement condition based on the forecast of pavement temperature. Reliable and accurate knowledge of coming weather events will also substantially reduce erroneous decisions due to nonoccurrence of forecast bad weather (Type II errors).

These calculations were performed using the Denver, Colorado scenario. Similar results were obtained using the Seattle and Minneapolis scenarios.

There is an optimal number of sensors to install, however. Too many sensors can drive up the cost of an RWIS to a point where it offsets the savings obtained through their use. Figure 2-24 shows the relationship between sensor cost and snow and ice control cost-reduction ratio in the three field test areas.

Table 2-14. Model output showing the benefit of including sensors in RWISs

Service Level with forecasts only	1.47
Service Level with forecasts and sensors	1.42
Type I Errors with forecasts only	887
Type I Errors with forecasts and sensors	176

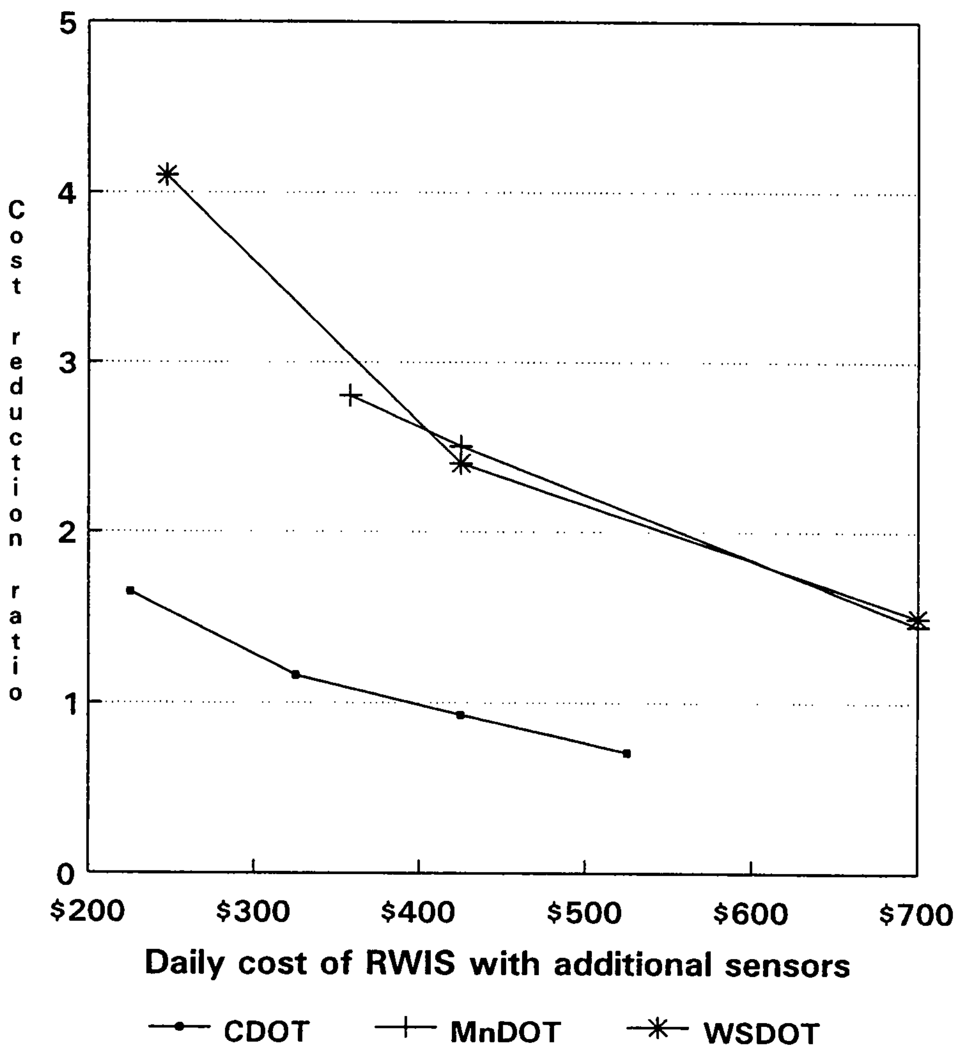

Figure 2-24. Cost reduction as a function of investment in sensors

An area supported by a \$500-per-day RWIS might justify elimination of two or three night patrols costing \$600 to \$900 per day. This suggests a net cost reduction of \$100 to \$400 per day just for ending unnecessary patrols. Unnecessary callout (Type II errors) of a five-person crew costs 1.3 times the daily estimated cost of an RWIS (\$54 bonus + \$27 travel time + \$54 two-hour minimum = \$135, × 5 persons = \$675). The elimination of night shifts suggests savings of 1.4 to 3.0 times the cost of the RWIS (\$720 ÷ \$500; \$1,480 ÷ \$500). Each of these figures is one part of a number of costs which are reduced under various scenarios in the model. The savings from eliminating night shifts or night patrols probably pays for the cost of an RWIS.

The field tests in the three different states indicated that for fourteen of the seventy-five winter weather situations, action was triggered by DOT patrols. This indicates significant potential for realizing the cost savings from reduced patrolling through use of an RWIS.

To determine the effects of regional climates on opportunities for reducing the costs of snow and ice control, the model was run using the climatologies of four different regions of the country. The climatology of each region was represented by that of a particular state and city in the region, since climatic data are available by city. The regions and the cities/states representing them are shown in Table 2-15.

The costs associated with three states' snow and ice control scenarios were also applied to the four regional climatologies to see what effect local RWIS configurations and snow and ice control procedures had on cost-reduction opportunities. It was found that regional climatology has little influence on the cost-reduction ratios calculated by the model. Local RWIS configurations and snow and ice control procedures exert considerably more influence. The results of these model runs, shown in Figure 2-25, underscore the relative importance of the costs associated with snow and ice control activities and with obtaining weather information.

Table 2-15. Climatic regions and states representing them

Climatic Region	Representing City/State
West Coast	Seattle, WA
Rocky Mtns.	Denver, CO
Midwest	Minneapolis, MN
East Coast	Newark, NJ

For example, the cost-reduction ratios obtained using Washington State cost data are higher because the Washington practice in the model is to use road patrols when no tailored weather forecasts are available, and to drop them when that information is available. The cost reduction ratios obtained using Colorado cost data are lower because the large number of RPU stations in the Denver area increases the cost of weather information there.

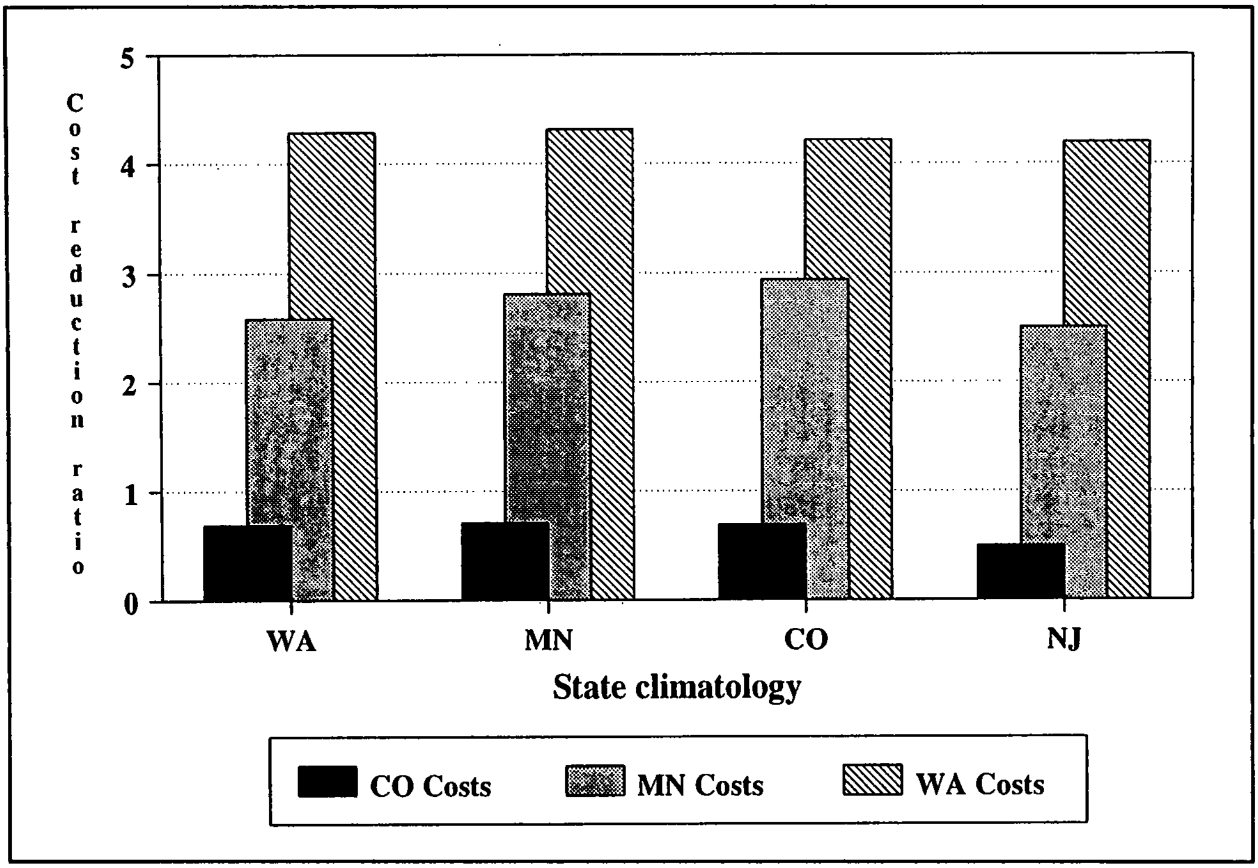

Figure 2-25. Comparison of cost reductions with various climatologies

Conclusions

The model developed for the cost analysis supports the conclusion that using road weather information system technologies can significantly reduce the costs of snow and ice control. The model results indicate that weather and pavement condition forecasts save the most money by allowing maintenance managers to mobilize resources before snow and ice problems accumulate, and to avoid unnecessary mobilization or patrols. Similarly, the model results confirm that deploying resources in a timely and efficient manner and at the right locations also improves the service level provided to road users.

For analysis purposes, the greatest cost reductions are produced by using weather and pavement condition forecasts. Large savings result from the low cost of such forecast services when compared to the cost of snow and ice control activities. Because the model always makes the appropriate maintenance decision based on the weather information, the savings may be somewhat inflated. However, the model indicates that a tenfold increase in the cost of tailored weather forecasts would still provide a positive return on investment. It also confirms that using routine winter safety patrols is costly. Reliable forecasts can reduce the costs of snow and ice control by eliminating or reducing the need for patrols. With an RWIS, patrols should not be necessary for snow, ice, or when the forecast is for high wind or heavy precipitation.

Cost reductions for sensor systems and road thermal analysis used by themselves are significantly lower than those for tailored weather and pavement condition forecasts. In fact, the cost of using one of these technologies alone (without forecast support) may exceed the financial savings produced. Using a single technology can improve the service level, however.

Sensitivity analysis performed with the model indicated that the amount of cost reduction achievable varies inversely with the frequency of adverse weather. Little cost reduction is likely in severe climates which have frequent or continuous snow and ice conditions. When this is the case, there are fewer decisions to be made. The same reasoning argues that road weather information systems are less likely to provide significant savings when maintenance managers are located in an environment where snow and ice control resources must be deployed throughout the winter in multiple shifts. Significant savings can be achieved, however, in the spring and fall transition seasons when resources are deployed less frequently.

Although the model is capable of the calculations, indirect costs of snow and ice on highways were not considered. If the technologies described improve the service level as suggested by model runs, it can be assumed that they will also reduce the societal costs of traffic problems caused by snow and ice. One example supporting this conclusion is contained in a draft report from Finland for the COST 309 study. This study included indirect benefits and costs, and it computed a benefit-cost ratio of five for an RWIS based on calculations for one maintenance district. The analysis considered indirect (societal) savings due to reduced numbers of accidents, savings in time costs for vehicle operators due to increased road speeds, and savings in vehicle costs due to decreased fuel consumption (EUCO-COST 309 1990).

Winter Index

Purpose

The variability of annual and year-to-year weather conditions makes it difficult to assess the effectiveness of snow and ice control based on cost data alone. For example, lower expenditure cannot always be attributed to higher efficiency but may be due to a warmer winter. Also, higher expenditure can be due to lower efficiency, a colder winter, or both. A generally applicable index which measures winter severity is thus required for assessment of efficiency of snow and ice control.

Various weather indices have been derived to compare the weather of different seasons at different places and for different years (e.g., Cutler 1973; Hulme 1982). A few attempts have been directed at developing and applying winter indexes which engineers can use to assess how effectively an ice prediction system is being used in practice (Thornes 1989; Voldborg and Knudsen 1988).

Thornes used the Hulme winter index in his assessment of the British ice prediction system (Thornes 1988). The index was constructed using mean daily maximum temperature, number of days with snow on the ground at 9:00 a.m., and number of night ground frosts (grass minimum temperature below 32°F (0°C)). This index was derived from British weather and is thus restricted to the climate in Britain. There are two main shortcomings of the Hulme winter index. The first is that atmospheric humidity, which is one of the prerequisites of frost formation on highways, is neglected in the formula. The second is the generality of the snow parameter; i.e., it does not give the quantity of snowfall. To overcome these shortcomings, and for the specialized application in the winter maintenance of highways, a new winter index has been developed.

Methodology

It is clear that winter severity is related to air temperature, amount of snowfall, and frequency of ground frost. A new winter index is expected to be an objective indication of winter severity and reflect the importance of winter maintenance, and to have general application in many countries, i.e., only a few general or common parameters are to be employed.

Thus, the new winter index is based on the following parameters for the period from November 1st to March 31st, which includes 151 days or 152 days in leap years (longer winters are found in colder areas):

- **Temperature index (TI)**: TI = 0 if the minimum air temperature is above 32°F (0°C); TI = 1 if the maximum air temperature is above 32°F (0°C) while the minimum air temperature is at or below 32°F (0°C); and TI = 2 if the maximum air temperature is at or below 32°F (0°C). The averaged daily value is used.

- **Snowfall (S)**: mean daily values in millimeters (the number of days with snowfall was also considered but did not improve the index).

- **Number of air frosts (N)**: mean daily values of number of days with minimum air temperature at or below 32°F (0°C) ($0 \leq N \leq 1$);

- **Temperature range (R)**: the value of mean monthly maximum air temperature minus mean monthly minimum air temperature in °C.

These four parameters are summed from daily records available from the National Weather Service and then averaged for each month to eliminate the influence of month length (number of days). These parameters, of all those available, proved to be the most significant indicators of winter weather and frost and ice formation. The new winter index is thus expressed as:

$$WI = a\sqrt{TI} + b\ln\left(\frac{S}{10}+1\right) + c\sqrt{\left(\frac{N}{R+10}\right)} + d \qquad (1)$$

In Equation (1), the temperature index (TI) and snowfall (S) terms make the greatest contribution to winter severity (WI). Temperature range (R) has a similar but inverse distribution to relative humidity in the United States. Here it is used as an effective indication of atmospheric humidity. Therefore, the third term in Equation (1) is considered as an expression of frost likelihood (F).

There are different ways to determine the coefficients of a winter index formula (here, a, b, c, and d). The most common and easiest way is to assign appropriate weights to each term. This has been done as follows:

Term	**Weight**
Temperature Index (TI)	35%
Snowfall (S)	35%
Frost (F)	30%

The nonequal weight on the third term means that it is considered of slightly less significance to maintenance costs.

With reference to the U.S. climate data, and considering potential application of the index in cost analysis, the coefficients of Equation (1) are derived by taking into account the critically significant level of each parameter to winter maintenance cost (1.87 for TI, 16.5 for S, and 1 for N), and solving a set of simple equations. The resulting coefficients are:

$$a = -25.58$$
$$b = -35.68$$
$$c = -99.5$$
$$d = 50.0$$

To examine the derivation of these coefficients, take TI, which has a 35% contribution on winter index, as an example, and assume the other parameters are constant. If a winter is warm enough to have TI = 0 (i.e., no frost at all in the winter), TI has no "negative" contribution on WI, and WI should be +50 (or some other value, depending on other parameters). If the winter is at another extreme, the most severe, TI has a fully "negative" contribution on WI, which means that:

$$a\sqrt{TI} = -35 \qquad (2)$$

A critical value of 1.872 (about 28 days with maximum air temperature below 0°C per month) for the TI is used (not 2, because 2 is thought to be too strict). Substituting 1.872 into Equation (2), yields a = -25.58.

Other critical values for S, N, and R are 16.5 mm, 1, and 1°C, respectively. As demonstrated above, their coefficients can be easily derived as -35.68, and -99.5.

Equation (1) is then written as

$$WI = -25.58\sqrt{TI} - 35.68\ln\left(\frac{S}{10}+1\right) - 99.5\sqrt{\left(\frac{N}{R+10}\right)} + 50 \tag{3}$$

The absolute contribution of each term to WI is minimal when the temperature index, snowfall, and frost are of minimum value, i.e., WI is maximized when TI, S, and N are zero. The absolute contribution of each term to WI is greatest when the temperature index, snowfall, and frost reach their maximum; i.e., WI reaches its greatest negative value when TI, S, and N are maximized.

Thus, WI has a value ranging from -50 (most severe and maximum level of snow and ice control) through 0 (not too severe and mean level of snow and ice control) to +50 (warm and no need of snow and ice control). An example for the calculation of the winter index is given in Appendix B.

Winter Index Performance

The winter index developed above was examined spatially (geographically) and temporally (across time) to note ways it varies across these variables. Its correlation to snow and ice control costs was also examined to determine its usefulness in managing these costs.

Spatial Variation of Winter Index

The winter index developed above has been used to show the spatial variation of winter severity across the United States using data from 188 weather stations (at least one in each state except Hawaii) for the period 1950/51-1988/89 (see Table 1 in Appendix B). The results of the calculation are shown in Figure 1 of Appendix C. The spatial distribution of the winter index shows the following characteristics:

- The winter index increases from the north to the south, as one might expect. The lowest WI areas appear around the Great Lakes and at the northeastern corner of the country.

- At higher latitudes, the eastern part of the United States shows a significantly lower WI value than that of the western part. At middle latitudes, the winter index in the Great Plains is notably lower than those in the eastern and western coastal areas.

- In mountain areas, the winter index is much lower than in the adjacent lower areas.

Three latitude lines (45°N, 40°N, and 35°N) were chosen to express longitudinal variation of the index (Figures 2 through 4 in Appendix C). The details of the selected stations along these latitudes are given in Table 2 of Appendix B. The results shown in these figures and tables reflect the characteristics mentioned above and the sensitivity of the national winter index distribution.

Temporal Variation of Winter Index

To see the temporal variation of the winter index from the winter of 1950/51 to the winter of 1988/89, nine stations along the reference latitudes were selected to examine the year-to-year variability of the winter index, mean minimum temperature, snowfall, and the number of frosts (Figures 5 through 31 in Appendix B). How well the winter index correlates to minimum temperature, snowfall, and frost are shown in these figures by the correlation coefficients (r).

The results obtained from the nine stations can be summarized as follows:

- The winter index varies from year to year, but neither a cold nor a warm trend is seen from the 39-year series.

- In the northern areas, the variation of the winter index is greater than that in the southern areas.

- The winter index varies with snowfall, minimum temperature, and the number of frosts, but it is most strongly correlated with snowfall.

Correlation of Winter Index to Snow and Ice Control Costs

The most important use of the winter index is to estimate the cost and potential savings of snow and ice control. In the United States, where data on average annual snow and ice control costs and centerline miles of roads are available (from the forty states responding to the survey), the cost per centerline mile ($/mile) can be plotted against the winter index for each state (Figure 32 of Appendix C). Here, the winter index is an average of all available sites in each state.

This figure shows that a lower winter index (WI) is associated with a higher cost (C), and vice versa. A strong logarithmic-linear relationship exists. The scatter of points in the figure is attributed to differences in maintenance policy, maintenance methods, economic activities (reflected by traffic volume), topography, definitions of terms, and many other factors. A surrogate variable to account for some of these factors is population density. This variable serves this purpose because the roads in densely populated areas have a heavier traffic flow and are usually given more priority for winter maintenance than those in sparsely populated areas. Taking the population density of each state (P = persons/km^2) into account (see Table 3 in Appendix B), the following equation is obtained by stepwise regression analysis:

$$C - 632.3 + 7.3\,P^{(-0.09WI)} - \left(\frac{0.19\,WI^3}{1+P}\right) \qquad (4)$$

The variables in the equation were selected at a significance level of 0.99, and the equation explains 84% of the variation in snow and ice control costs. It thus provides us with a useful tool for cost-reduction analysis.

The winter index can also be used at a smaller scale. In Washington State, there are six road maintenance districts. Fifty-six weather stations (See Table 4 in Appendix B) were chosen for calculating district averages of winter index considering both data availability and site spatial distribution. The weather data were taken from 1969 to 1989. For historical analysis, the yearly values of winter index of the sites in each district were averaged to obtain a district value (See Table 5 in Appendix B). The cost data (in $1,000s) in the table were adjusted back to the standard of the earliest year (1983/84) from which cost data were available, according to the annual inflation rate in the United States.

For each district, the relationship between winter index (WI) and snow and ice control cost (in $1,000s) was analyzed by the regression method. As population and lane-miles data were not available, a linear regression was taken. The regression results are shown below, where s is an estimation of the standard deviation of cost (in $1,000s) about the regression line, and r^2 is the coefficient of determination or the fraction of the variation in cost that is explained by the winter index. It is obvious that the lower the winter index, the higher the expenditure, and vice versa.

District 1: Cost = 3,081.4 - 61.12WI
s=173.9 r^2=92.4%

District 2: Cost = 2,751.4 - 36.28WI
s=157.9 r^2=75.9%

District 3: Cost = 2,353.6 - 53.37WI
s=150.3 r^2=88.9%

District 4: Cost = 2,408.6 - 31.91WI
s=186.0 r^2=66.3%

District 5: Cost = 3,747.6 - 54.16WI
s=318.6 r^2=48.4%

District 6: $\text{Cost} = 2{,}497.6 - 44.34\text{WI}$
$s=221.8 \quad r^2=69.0\%$

Bellingham and Olympia are the two Washington State sites for which cost data are available, and for which the maintenance location is collocated with a climate station. Regression analysis shows:

Bellingham: $\text{Cost} = 662.78 - 13.785\text{WI}$
$s=19.55 \quad r^2=96.9\%$

Olympia: $\text{Cost} = 604.41 - 15.122\text{WI}$
$s=28.25 \quad r^2=96.1\%$

A highly-correlated inverse relation is seen at both sites, where climate data and maintenance costs are taken over a small area. It is likely that higher correlations for all stations are possible when using smaller-area costs rather than state averages.

In Minnesota near Duluth, annual expenditure of sand and salt was examined on six routes (numbers 301-306) for the 1986/87 and 1988/89 winters. The expenditure data was divided by lane-miles for each route. Because of the few years' worth of data available, a proper statistical analysis was not possible, but nevertheless, an analysis was attempted to give an indication of the relationships. Routes 302 and 303, which are close in location and defined as "Urban Commuter," were combined into an independent sample (see Table 6 in Appendix B). The winter index was calculated from the nearby Duluth Airport. A relationship was found between sand and salt consumption (in tons/mile) and the winter index. The results are as follows:

$$\text{Sand} = 571.66 + 12.247\text{WI} - 0.347(\text{WI}+50)^2$$
$$s=2.750 \qquad r^2=97.7\%$$

$$\text{Salt} = 83.15 + 1.245\text{WI} - 0.054(\text{WI}+50)^2$$
$$s=1.927 \qquad r^2=96.0\%$$

Both sand and salt consumption appear to be closely related to the winter index.

A study in England has shown that using RWISs can reduce snow and ice control costs (Ponting 1988). Computations of the winter index for years prior to using RWIS information showed a linear relationship between WI and salt usage (Figure 2-26, white bars). Prior to the 1988/89 winter, RWIS sensors were installed. The effect that using RWIS information had is clear (black bars). The linear relationship between WI and salt usage still appears, but salt usage for a given WI is lower than before RWIS information was used. The 1990/91 data were particularly significant in that the three previous winters were mild. Since the 1990/91 winter had more occurrences of winter weather, it provided additional evidence that the use of RWIS information will reduce costs. Note that its costs were lower than those for the two years bracketing it (1984/85 and 1986/87), neither of which used RWIS information.

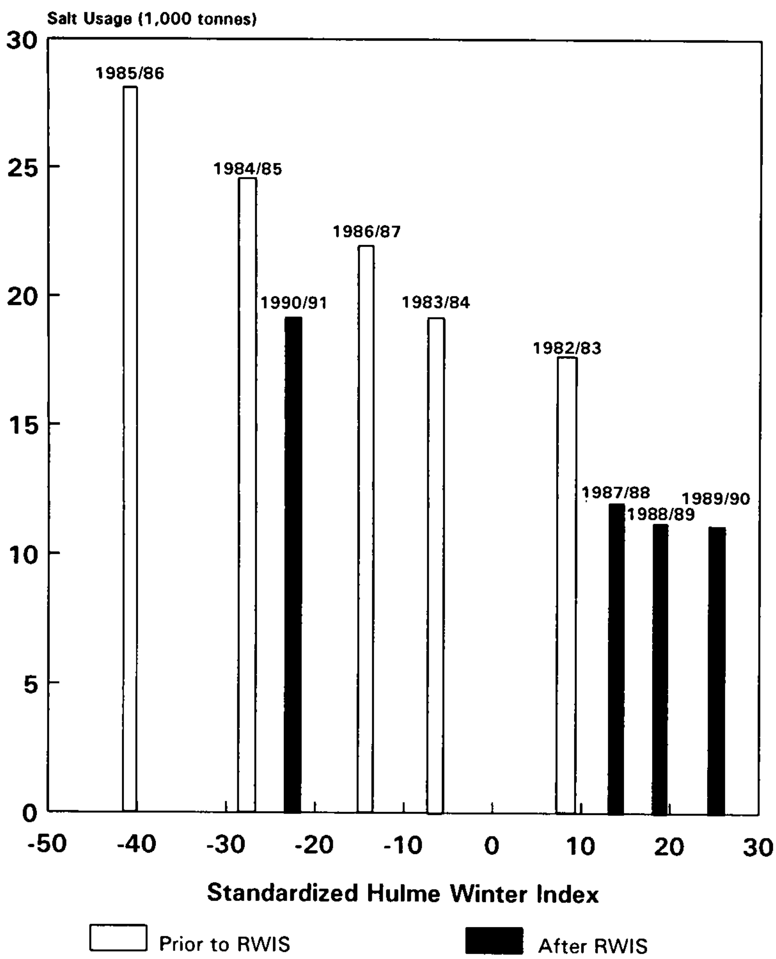

Figure 2-26. Reduction in salt usage with an RWIS

The other aspect of snow and ice control cost is the practices themselves. It is also possible to use the winter index to assess the efficiency of the practices, which include the application technology as well as policy. An index was developed to measure the efficiency of these practices:

$$E_i = \frac{1}{A}\left[\frac{A-D_i}{\Delta C_i}\right] \tag{5}$$

where A is a constant, D_i is the difference in winter index between year "*i*" and a base year (BY), i.e., $D_i = WI_i - WI_{BY}$; and ΔC_i is the ratio of costs for year "*i*" and that of the base year, i.e., $\Delta C_i = C_i/C_{BY}$.

If the winter index and costs for the *i*th year are equal to the base-year figures, then the efficiency is unity:

$$E_i = \frac{1}{A}\left[\frac{A - (WI_i - WI_{BY})}{C_i/C_{BY}}\right] = \frac{1}{A}\left[\frac{A - (0)}{1}\right] = \frac{A}{A} = 1 \tag{6}$$

If the winter index increases, in order for the efficiency to remain unity, costs would have to decrease, and vice versa. For the purposes of this study, the value of A was set at 50. This means that a decrease of 5 in the winter index has to be compensated by a 10% increase in cost.

Figure 2-27 shows examples of calculations of efficiency computed at four locations in Washington State. A base year of winter 1983/1984 was used. These computations are for years prior to RWIS use. Additional study is necessary to determine the effect of RWIS use on efficiency. Such study may also provide a more realistic value for the constant A. Small-scale studies, such as comparing costs in areas where different practices are conducted, may offer an even better opportunity for describing the efficiency of different practices (e.g., anti-icing, deicing, use of alternative deicers) and the utility of RWIS information for making snow and ice control decisions.

Conclusions

The winter index developed during this project represents to a great extent the main characteristics of the climate in the United States. Taking air temperature, snowfall, frost likelihood into account, it gives a quantitative expression of winter severity and shows the necessity of snow and ice control. The results of the cost analysis show that the winter index is a good indicator for snow and ice control expenditure. With a set of historical cost and weather data, the index is expected to be able to help evaluate the efficiency of snow and ice control at any scale, be it district, county, state, or national.

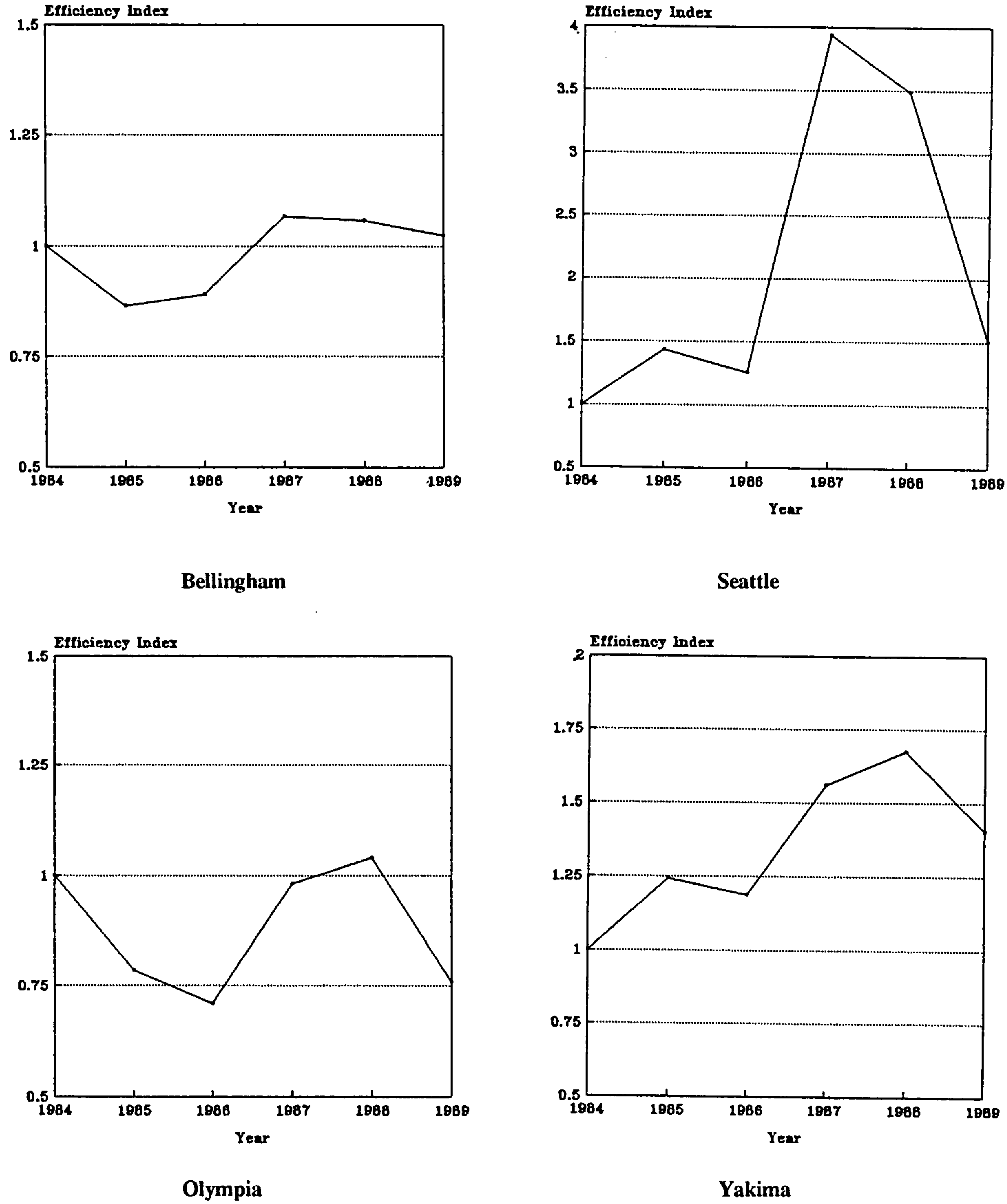

Figure 2-27. Examples of efficiencies calculated at four locations in Washington State

3

RWIS Implementation

The interviews conducted with snow and ice control managers and supervisors, and the discussions pursuant to the acquisition and analysis of field data, documented factors relating to the use or nonuse of RWIS information. These factors are extremely important in considering the use of RWISs for snow and ice control.

Summary of Current Snow and Ice Control Practices

In order to describe the potential benefits of the use of RWISs in support of snow and ice control, the range of snow and ice control practices must be described. By describing these practices, decision points for implementing them can be determined, and appropriate weather-related thresholds identified.

Survey questionnaires and interviews of state highway agency snow and ice control managers showed that there is a wide variety of practices as well as methods to initiate them. These practices include patrolling, deicing, plowing, and removal. In some areas, efforts are also being undertaken to test or implement anti-icing or pretreatment.

In most organizations, the decision to initiate one or more of the snow and ice control activities listed above is based on a reaction to current conditions, or at best, a forecast of wintery weather obtained from the media. Forces are mobilized, perhaps first by instituting patrolling to check road conditions, or by changing shift schedules. More frequently than not, a supervisor will be notified that roads have become icy, or snow has begun to accumulate. The supervisor calls out the forces to attack the problems as they occur. People stay on the job until the problems have subsided. This reactive response can be costly in both time and materials.

Preventing the bonding of ice to pavement requires less deicing material than that required to break the bond of ice to pavement. Some state highway agencies apply deicing chemicals as snow begins to fall to assist with plowing. If pavement temperatures are too cold, snow may bond to pavement before chemicals can be applied. If salt is used, pavement temperatures may be too cold for the salt to work properly. If pavement temperatures are forecasted to rise, chemicals may not be needed at all.

Labor in most states is the most costly component of snow and ice control. Personnel rules and/or union contracts provide the framework for decisions for scheduling shifts. Callouts typically incur costs, such as a guaranteed two or four hours of overtime pay. An unwarranted callout can quickly run up labor costs. Keeping people on the job beyond when they are needed also incurs needless costs.

Many equipment operators believe, and perhaps rightly so, that the winter work they perform is the most meaningful and beneficial work they can do. They have done it for a long time and believe they are doing it right. It is also a source of considerable additional compensation for some. It is therefore with some reluctance that a few snow and ice control workers approach the concept of using information for activity decisions that can reduce labor costs.

A typical state highway agency equipment fleet is sized to meet the perceived needs for snow and ice control based on reactive ways of doing business. There is a tendency to keep the plows permanently mounted and deicing materials (salt, abrasives, and other chemicals) loaded. This causes unnecessary wear and tear to these vehicles. In addition, fleets may be larger than those needed if RWIS information were available.

Reactive dispatching of resources precludes timely, customized material application for known or forecast road conditions. It poses problems for efforts to reduce mis- or over-applications. Reduced amounts of salt and other deicing chemicals provide both cost savings and environmental mitigation. Reductions in amounts of abrasives are especially desirable in some air-quality nonattainment areas. Many of these problems can be mitigated significantly through the use of road condition and weather information.

Strategies for Using RWIS Information

Opportunities exist for using weather and road condition information to change certain snow and ice control practices. Reductions in costs of labor, equipment, and materials are possible for nearly all practices and weather scenarios.

Patrolling

The use of winter patrols is a common practice for monitoring or detecting conditions of roads for snow and ice control. Daily patrols are normally used. Night patrols supplement daytime observations. Patrols are also used in some areas to monitor other effects of winter storms such as downed trees, flooding, plugged drainage facilities, and drifting snow from earlier storms. RWIS information can make patrolling unnecessary in normal snow and ice conditions. RWIS forecasts could provide warning about high wind and heavy rain which cause hazardous roadway conditions.

Detailed forecasts of weather and road conditions, combined with data from RWIS sensors, provide information decision makers need for implementing efficient snow and ice control. In addition, sensors become the eyes and ears of supervisors. Forecasts and sensors, used in conjunction with road temperature profiles, tell supervisors when and where maintenance will be required. With good weather information, the only weather-related reason for patrols would be to check for downed trees or power lines, or to conduct other damage assessment activities. If a supervisor is very conservative, then forecasts of impending weather might trigger patrolling, but patrols would not be needed every day.

Deicing

Chemical deicing for snow and ice control is a practice which has grown significantly over the last few decades to ensure motorists safer passage during freezing weather. The amount of deicing chemicals used in some states exceeds 500,000 tons annually. Typical application rates average 300 pounds (136 kilograms) per lane-mile. Rock salt (sodium chloride) is the predominant chemical used due to its effective action in melting ice and snow and its relatively low cost. However, salt becomes less effective as the temperature drops below about 25°F (-4°C). Below this temperature, salt can be mixed with other dry chemicals, such as calcium chloride, or wetted with liquid calcium chloride or magnesium chloride. Some state highway agencies also mix salt with abrasives (50-50 mixes are common, as is a 5-to-1 sand-to-salt mixture to keep sand piles from freezing). Others may use only an alternative deicing chemical (not a chloride), such as calcium magnesium acetate (CMA) or urea, or a chloride with a corrosion inhibitor added.

All of these chemicals or mixes have temperature thresholds or limits of effectiveness. Supervisors who direct mix selection or application have heretofore based their decisions on presumed current conditions. A key piece of information for deicing chemical effectiveness is pavement temperature, now available from pavement temperature sensors. For proper decision making, though, pavement temperature *forecasts* are crucial. Decisions need to be based on what the temperature is going to be. For example, if the pavement temperature is forecast to rise above freezing soon, little or no action is warranted.

In addition to revealing pavement temperature, pavement sensors provide information on the extent of deicing chemical already on the road surface. Typically, a parameter called chemical factor is used to indicate the presence of deicing chemical. If the chemical factor, which has a range of 0-100, is high, e.g., greater than 50, perhaps no additional treatment is needed. On the other hand, a low chemical factor indicates that action may be required. The chemical factor is a relative term which needs to be calibrated by each highway agency for the chemical in use. The chemical factor is based on the conductance of the surface. Ionic compounds, such as chlorides, produce relatively higher chemical factor readings than substances such as CMA or urea.

With RWIS data, supervisors can make more informed decisions about what chemicals to put on the roads, how much to put down, and when and where to put them. Snow and ice control managers indicate that some of the most cost-effective decisions can be to do nothing because the pavement temperature forecast showed that the surfaces would stay above freezing. With many agencies facing severe budget problems, avoiding spending money unnecessarily for snow and ice control helps the financial situation significantly.

Plowing

Most decisions whether to plow are based on how much snow has accumulated. If plows are not mounted permanently for the winter season, related decisions include when to mount or dismount plows, what to mount (ice blades or snow blades), where to plow, and what to mobilize (plows, motor graders, snow blowers). For highway agencies that use contractors to help with plowing or snow removal, the decision regarding when to mobilize the contract force is also important. Calling out contractors too soon can be a large expense. Calling them out too late may require more plowing effort, another large expense.

RWIS information can be used in each of these decisions. Many weather scenarios occur, and these may range from moderate snow falling with pavement temperatures above freezing (where one might not need to mobilize plowing resources because the snow will not stick) to snow falling with pavement temperatures below freezing or expected to fall below freezing (where plowing resources may be necessary depending on the amount of snow expected to accumulate).

In either case, the amount of snow expected to accumulate and the expected pavement temperature are important for making a decision

Anti-Icing

Anti-icing prevents ice from bonding to pavement through the application of chemicals before snow and ice accumulate on the surface. Effective anti-icing means that snowplows can remove accumulations with less work, can cover greater areas, and can clear pavements more effectively. Anti-icing is a recommended practice in the United Kingdom (Department of Transport 1987). Road weather information systems are considered essential for effective prosecution of anti-icing (termed "precautionary salting" by the British), and the country is blanketed with over 350 RWIS sensors. The Meteorological Office provides on "Open Road" weather forecast service for the National Motorway and the Trunk Road networks, and for local roads. Private forecasting services also operate in the country. Anti-icing is facilitated by the National Ice Prediction Network which establishes standards for a national RWIS and outlines procedures for County CPUs to communicate directly with shared RPUs (Department of Transport 1991). Guidance is also given for siting and inspecting pavement ice detectors (Department of Transport 1990).

Deciding to Acquire an RWIS

At least four possible reasons exist for agencies to consider acquiring RWIS technologies, and any of these reasons may be sufficient for a manager to decide on the course to follow. First, a snow and ice control manager may decide to install sensors and use forecasts knowing that an RWIS provides *information on weather conditions in a particular area.* Inordinate amounts of resources may be expended in treating snow and ice control problems in a specific area or along a particular stretch or road. These problems may require patrolling and reaction to problems. RWIS information can allow managers to be at the right place at the right time with the right resources.

Second, a manager may decide to acquire and use RWIS technologies because of their *cost-effectiveness.* It is difficult to argue for NOT doing something that saves close to five times as much as it costs; highway agencies frequently face decisions to do or not do something where the savings-to-cost ratio is close to one.

Third, a state may mandate a *reduction in the use of chlorides.* RWIS information has the potential to help in this reduction. Pavement sensors provide an indication of the residual concentration of chemicals on a road surface. When sufficient chemicals remain, more are not required; and if a pavement temperature forecast indicates that the surface will remain above freezing, no deicing chemicals may be needed in any case. Chemical use can be reduced with RWIS information.

Finally, administrators and managers may just believe that acquiring an RWIS is the correct thing to do. Using RWIS information for decision making may make more sense than continually reacting to situations. It also allows for *better planning* of maintenance activities other than snow and ice control, *revisions to archaic or difficult labor agreements*, providing *better information to the public*, and *better snow and ice control service* on the roads.

The following outline describes a process agencies can follow in analyzing whether to acquire and implement RWIS technologies. It should be noted that the following discussion is not designed to be a list of sequential activities.

- Describe expectations. Decide what the purposes would be for using an RWIS.

- Establish system requirements. Based on the purposes specified above, define what the RWIS needs to do.

    - Designate an office of primary responsibility, someone in charge.

    - Analyze the agency's snow and ice control response methods.

    - Enumerate RWIS technologies to consider, e.g., sensors, forecast support, and road thermal analysis.

    - Consider obtaining the services of a weather advisor.

- Survey existing RWISs and other related systems. Inspect systems in or near the area or road of concern which can help satisfy requirements.

- Identify opportunities for mutual assistance. Identify other states, municipalities, airport authorities, or turnpike authorities who might participate, cooperate, or help fund.

- Determine how RWIS communications are to be established (e.g., statewide network, leased lines, microwave, radio links).

- Conduct a preliminary siting analysis. Involve the weather advisor and snow and ice control supervisors.

- Design the system. Determine what kind of sensors are needed, how many are needed, and where they should go.

- Determine contractual parameters.

  - Determine who will install the equipment.

  - Decide who will maintain the system (e.g., agency forces or contractor).

  - Determine training requirements.

- Implement the RWIS acquisition process.

  - Specify the lead procurement agency.

  - Determine the source(s) of funds.

  - Prepare a request for proposals.

  - Negotiate with qualified proposers, and let a contract.

- Install the system based on the decision above for contract, vendor, or self-installation.

- Integrate the RWIS into snow and ice control operations in order to fully utilize its capabilities.

  - Determine the structure for information flow from RWIS to decision makers.

  - With the weather advisor, develop and conduct training for snow and ice control decision makers.

  - Develop a maintenance plan to ensure that the RWIS performs as required.

- Develop the system evaluation process.
  - Decide who will perform the evaluation: the highway agency, an independent agency, or consultant.
  - Specify what components of an RWIS are to be evaluated.
  - Identify evaluation parameters.
  - Specify how the evaluation is to be conducted.
  - Establish the evaluative criteria.
  - Conduct periodic evaluations.
- Define the management indicators that will be used for deciding whether to expand, improve, or enhance the system.

The process described above is not all-inclusive. It should serve as a reminder that implementing an RWIS into an agency's snow and ice control activities involves more than installing sensors, getting weather forecasts, and setting up computers. The process is a management initiative which requires planning, participation, and training in order for the implementation to be effective. The following sections examine some aspects of the process in more detail.

Contracting for Meteorological Services

Problems can occur in the acquisition of weather and road condition forecasting services. These problems center on the tendency of agencies to acquire these services based on lowest-cost bids. This creates two problems for agencies.

First, agencies are not getting the quality of service from VAMS that they could. This results from the necessity of some VAMS to cut back on their levels of service to compete with VAMS who submit low bids. Some state highway agencies pay less than $300 per month for forecasting services, or about $10 per day. Ten dollars cannot buy much of a meteorologist's time, and certainly does not buy a detailed look at weather or road conditions. At that price, it is hardly worthwhile for VAMS to even compete for the job.

Second, although anecdotal information is not necessarily reflective of the general situation, one state highway agency told of problems encountered during a significant winter event. About thirty-six hours into a storm, the agency lost contact with its VAMS. Upon calling, the agency was informed by the meteorologist's mother that the meteorologist had fallen asleep from sheer exhaustion. This VAMS had only a single staff member. Therein lies the other problem with lowest-cost bidding: those that do respond to requests for proposals may be unable to provide the level of service needed.

The cost analysis conducted for this project used an average of $500 per month for tailored weather services for a metropolitan area. As pointed out earlier, the cost reduction calculated for forecasting services indicated that a tenfold increase in the costs of such services is still cost-effective at the service level currently being provided. It should not be a surprise if the service level provided by VAMS would increase as a result of being able to pay more attention to the needs of clients.

Agencies should consider meteorological services in the same way they consider other professional services. A two-step process is used to obtain these services. First, responders are evaluated based on technical criteria, then cost is negotiated.

Evaluating Meteorological Services

A corollary to this approach is that procedures should be established in each agency to evaluate the services provided by VAMS. Most of the time, supervisors can only provide a subjective evaluation of these services.. Arrangements should be made for documenting forecast accuracy, including percentages of hits and misses of weather events, timing of the onset and duration of events, and quantities of precipitation. The evaluation should also include the VAMS communication in discussing forecasts before and during events. Post-event analyses of both problem areas and good support is an important part of evaluation.

Evaluating the VAMS's performance has two purposes. First, it allows for dialogue between the VAMS and the agency so that problems in obtaining and using the information can be corrected, whether they are within the VAMS or the agency. Second, it documents the vendor's capabilities, and these can be used for comparison with other support or for contract review.

Evaluation requirements and procedures should be clearly detailed in RFPs. A suggested RFP format is provided in the *Road Weather Information Systems Vol. 2 Implementation Guide.*

Even though it is suggested that agencies contract for meteorological services first on the basis of technical qualifications rather than cost, the cost of meteorological services also needs to be considered. However, there is an unfortunate perception that adequate forecast support should be available for a small increase in fee over that the NWS charges, i.e., nothing. Detailed, site-specific forecasts tailored to the needs of a highway agency require the investment of hours, not minutes, of professional meteorologist's time. These forecasts should be available 24 hours per day, seven days per week, during the snow and ice season.

To derive a reasonable cost range for weather services, consider the option of having a full-time meteorological staff available. A minimum of three professionals would be required to provide a continuous rotation of twelve-hour shifts, with a six-day-on, two-day-off schedule, without vacation or sick leave considerations. A cost of even $2,000 per month for forecast services pales in comparison to the salary and benefit requirements of a staff of professionals. Two thousand dollars per month is also a small investment compared to the costs of snow and ice control.

An agency issuing an RFP for forecasting services should state its requirements in as detailed a fashion as possible and expect to pay market prices for professional services, rather than discounted prices for reduced services.

Contracting for RWIS Hardware

Until recently, most state highway agencies acquiring RWISs have been doing so in a research or test mode. This has meant that usual procurement practices have not been followed. State highway agencies, in essence, have said that they want to test a certain technology and have procured that technology from a vendor. Or, they've received a presentation from a vendor and have prepared a request for bids to acquire what the vendor sells, in some instances, even stating the particular system's operational specifications. State highway agencies then find themselves in the position of having to specify the same thing again if they want to expand or add capabilities.

The procurement process becomes unnecessarily complicated when time has to be spent figuring out how to acquire a specific piece of equipment. What highway agencies need is the ability to issue uncomplicated RFPs which state that a certain number of RWIS installations are required to support the snow and ice control program, and that they should meet certain minimum criteria.

Minimum performance standards have at least two benefits. First, they ease the burden of agencies in preparing RFPs by stating that any hardware has to meet certain performance standards without having to enumerate those standards in the RFP. Second, vendors must ensure that their hardware is "up to standard." Queries of sensor vendors and manufacturers indicated that they are not opposed to having standards established as long as the standards do not restrict technological development and ingenuity of the manufacturers.

RWIS Maintenance

During the project's field tests, it was difficult to determine why pavement sensor temperature readings sometimes did not match pavement temperature readings obtained by other means. Discrepancies can arise for four reasons: the pavement sensors may not be functioning properly, may not be calibrated properly, may not be the same temperature as the pavement, or the other measuring instrument may not be functioning or be used properly.

The problems associated with thermal budget differences between pavement and pavement sensors were discussed earlier in this report: sensors may indicate temperatures too warm when the sky is clear, and especially when the sun is shining. On the other hand, each agency has make sure that its system is calibrated and functioning properly. Once sensors are installed, an agency should not expect that they will continue indefinitely to report accurately. Continuation of accurate reporting can be assisted by in-house resources or by contracting for maintenance.

Establishing an RWIS Maintenance Program

Each agency with RWIS hardware in place, or acquiring an RWIS, should establish a maintenance program which includes preventive and recurring maintenance requirements, and at a minimum, a requirement for annual calibration of meteorological and pavement sensors. The frequency of and procedures for this maintenance and calibration should be based on manufacturers' recommendations, which should be requested by agencies in RFPs for the hardware.

Barriers to RWIS Implementation

From interviews conducted with snow and ice control people at every level from state maintenance engineers to equipment operators, and from a review of the field tests of the 1990 winter, a number of recurring themes emerged. First, barriers exist to using RWIS information for decision making for snow and ice control. Second, in general, snow and ice control managers do not always know how to effectively use weather information. This is true whether the information is from media forecasts or VAMS.

Barriers to RWIS implementation are psychological, philosophical, and institutional. Each type of barrier will be discussed briefly:

- In some instances, decision makers at lower levels perceive the implementation of new strategies as a *downward-directed*, upper-management decision. That can bring typical management/labor problems. Part of the problem may be that at the lower decision-making levels, particularly well-seasoned foremen and supervisors have come up through the ranks. They identify with the operators and tend to be skeptical of management initiatives on general principles.

- The "*not-invented-here*" syndrome is particularly evident when personnel changes take place. A new person in a job with RWIS information available refuses or is reluctant to use technology new to him/her. In both this case and the case above, there is no acceptance of the technology at the decision-maker level.

- Many of the people involved in snow and ice control have been doing it for years. They believe that the public thinks they're doing a good job. They ask why they should change what they're doing. "*We've always done it this way!*"

- Equipment operators are a dedicated, professional group. They enjoy operating their plows and spreaders. It is meaningful and appreciated work. Plus, it brings in a lot of extra overtime money during the winter. "Why should I want to *cut back my overtime paycheck?*"

- There is an occasional feeling at nearly all levels that this weather thing with fancy computers is a "*technological toy*" that certainly can't help in dealing with snow and ice on the roads. A similar attitude exists with operators who continually rely on the view out the rear-view mirror as the best indication of the chemical or abrasive application rate on the road rather than calibrated rates based on dials, knobs, and ground speed controllers. In other instances, supervisors may pay attention to the RWIS computer screen for a while, but when the pressures of other work increase, the computer is often left alone.

- Management removes some of the decision-making capability at the appropriate lower levels by a belief that the portable computers necessary to access RWIS data when at home or on the road are too costly. In this case, data are not placed in the hands of those that need them in a timely fashion.

- In some agencies, personnel rules or labor agreements stifle creativity and initiative in devising appropriate responses to snow or ice situations. Snow and ice control is viewed as normal activity, and overtime and callout penalties frequently make decision makers reluctant to institute timely and efficient resource allocation decisions.

Removing Barriers to Implementation

In order to fully integrate weather information into the snow and ice control decision process, proper training should be conducted for all involved staff levels.

In most cases, behavioral changes are required on the part of decision makers to move from widespread reactive decision processes to the anticipative decision processes necessary to take advantage of RWIS information. These changes can only come through adequate and properly designed training. The best practice is to educate affected personnel on a new system at their level, so using it becomes a logical thing to do. Then everyone agrees that part of the action is owned at that level.

General training packages can be developed that describe RWIS technologies and the use of weather information. However, each state has different weather, staffing procedures, and snow and ice control practices. In addition to general training materials, agency-specific materials need to be developed which are weather-scenario dependent and can be used in an interactive process including managers, supervisors, and line personnel.

Weather Advice

One of the problems frequently encountered by state highway agencies in attempting to implement RWIS technologies is that there really is no one to turn to for advice. State highway agency personnel may feel that RWIS vendors give nice presentations describing their systems' capabilities, meteorological services seem nebulous at best, and implementation seems remote or unlikely.

A model for solving these kinds of problems comes from the military, where the commander of a unit seldom makes an operational decision without conferring with or getting advice from the staff weather advisor, a meteorologist on hand to answer questions and provide advice, but not to make operational decisions.

Such a role can be valuable for a highway agency. Weather advice could be obtained from a part-time agency employee, a full-time employee shared with other agencies, a consultant meteorologist on contract with specific duties, or a VAMS. Typical functions could include assisting in the preparation of RFPs for weather services or other RWIS technologies, providing coordination among agencies who have weather-data capabilities or needs, providing coordination between a VAMS and an agency to ensure that the latter's needs are being met, assisting in developing siting plans for RWIS hardware, developing training programs to help integrate RWIS technologies into a snow and ice control program, performing local forecast studies to improve forecasting capabilities, and evaluating weather services. All of these services can probably be acquired for the price of one RWIS RPU, the cost of which might be saved through the weather advisor's assistance in RPU siting.

Highway agencies should consider obtaining such advice and services from professional meteorologists to assist in acquiring and using RWIS technologies effectively.

Liability and RWIS Technologies

Based on inputs from both RWIS vendors and state highway agencies, some liability issues have surfaced. These issues range from tort liability to product liability concerns. Agencies should be aware of these issues and should consult with their counsel about them. No attempt is made to provide even general guidance on these issues because the transportation counsel for each agency should do that based on the local statutes. Letters were sent to the attorneys general in each of the seven states participating in the field tests, but responses were received from only two, and these were sufficiently divergent that only the issues themselves are presented here. However, there are no known cases of claims against state highway agencies because of RWISs (Vance 1990; Tedesco 1983; and Thomas 1976). The following paragraphs provide examples of liability issues.

"Constructive knowledge" of road conditions requires that highway agencies take action to correct deficiencies such as snow or ice problems on roadways. Pavement surface sensors provide indications of existing road conditions. This might suggest that pavement sensors provide constructive knowledge. In like manner, it might be construed that forecasts of road conditions could provide constructive knowledge which would require action.

It is possible that the demonstrated capabilities of RWISs constitute the state of the art in snow and ice control technology. Such a view could make highway agencies liable for not acquiring the technology.

Many state highway agencies have installed and use RWIS technologies in a research mode, i.e., evaluating the technology. Once RWISs leave the research/testing mode and become operational, the public may have a right to the RWIS data. The issue concerning placing RWIS data in the public domain was discussed earlier. One RWIS vendor has expressed concern over the dissemination of these data and not having control over how the data are used. That vendor is concerned about being liable for any improper use of the data.

A similar issue exists regarding the use of standard communication protocols and data formats for RPU-CPU communication. An RWIS vendor has expressed a need for agencies to indemnify the vendor from liability for other vendors' equipment tied to an existing or future CPU. The concern is over another vendor's equipment not working properly in a system. In one instance, this vendor chose not to respond to an RFP because the state would not indemnify vendors.

Finally, there is always the issue of how much information, what kind of information, and in what form, should be provided to the traveling public. In Europe, in a less litigious environment, RWISs are directly connected to variable-message signs. The signs give indications of road conditions, such as slippery, windy, or foggy. At what level can or should this be accomplished in this country is a subject which can generate lively discussion.

4

Conclusions and Recommendations

Documentation in the field test data sheets and interviews with maintenance supervisors following the winter field tests point to different ways for saving money or performing snow and ice control more efficiently with RWISs available. Comments on data sheets indicated that:

> "Sensors show pavement temperature high enough to eliminate the need for chemical applications."
>
> Materials and labor were saved because "the forecast tells us that the storm will continue," and crews stayed on to stay ahead of work.
>
> Materials and labor were saved because the forecast and observations provided "advance notice for the next shift."
>
> "Temperature rising; no further material needed."
>
> Observations "showed that this was an isolated area needing treatment..."

Forecasts are not perfect. It should be pointed out that the one negative comment stated:

> "Productive time was wasted waiting for the big storm."

Interviews with supervisors also documented savings. One maintenance superintendent in a state highway agency with centralized direction for snow and ice control said he was able to successfully argue for not deploying forces in his area because the pavement sensors indicated that the surface temperatures were high enough that snow would not stick to the pavement.

A maintenance foreman in one location where calcium magnesium acetate (CMA) is the only deicing chemical used on a bridge has been able to cut his CMA use by 50%. He tries to apply the CMA after pavement sensors show the surface is wet. This allows the moisture to help the CMA stay on the bridge surface.

In another state, where conditions are usually borderline between winter and non-winter weather, the foreman successfully used pavement sensor temperature output and pavement temperature forecasts to avoid chemical applications. The surface would be too warm for ice to form. This was in an area devastated by severe ice storms just a month prior to the RWIS being operational. The decision maker had faith in the system.

In December 1991, a tremendous snowstorm hit one area usually unprepared for winter weather. The state highway agency received a forecast of heavy snow and was "armed and ready" when the first flakes fell. (Unfortunately, the populace was not.) The state highway agency was able to keep traffic moving at least two hours longer than if it had not been prepared.

A final example occurred in Colorado. At the time of a Strategic Highway Research Program-American Society of Civil Engineers conference in Denver during April 1991, snow was forecast to arrive in the Denver area in the early morning hours. Members of the research team for this project, attending the conference, were conducting temperature measurements that morning at one RWIS sensor site. Cars inbound to Denver were covered with three to four inches of snow, and at least that much snow covered the ground, but the pavement was bare. The team members contacted the DOT to find out what action they had taken to ensure the bare pavement. The answer was "none." The rationale for taking no action was that the forecast indicated that the pavement temperature was going to be too high (40°F (5°C) or more), and "we knew that the snow would not stick on the pavement."

The following is a recap of the conclusions and recommendations from the project research. In general, because of the potential for reducing costs and improving service, every agency that regularly engages in snow and ice control should consider acquiring some form of road weather information system technology. At a minimum, forecast services should be used.

Sensor Siting

Siting Pavement Sensors

Pavement sensors provide pavement condition (wet, dry, icy) and chemical-factor data, which may affect their placement. The placement of sensors in the roadway should be related to the intended use of the data. As is the case with meteorological data, pavement sensor data can be related to *predicting, detecting,* and *monitoring* pavement temperature. Sensors placed for *prediction* purposes should be located using these criteria:

- Pavement sensors should be placed where surface temperatures are representative of general conditions and where specific problems can be detected. Sensors should never be placed where they will be in the shadow of structures or trees.

- Sensors should be placed where the temperature is coldest and traffic is the lightest. In general, this is the inside (passing) lanes of a multilane roadway. In large urban areas with a commuter environment, each lane may be heavily traveled. Since the coldest pavement temperatures and the most frequent formations of ice occur in morning hours, sensors should be placed in the wheel track in the inside (passing) lane of the outbound traffic direction, or adjacent to either inside lane in rural areas.

- If the site under consideration is a bridge, the same rules apply, except it is recommended that sensors be installed on the deck in the second span from the abutment where the flow of air affects the deck temperature, and in the approach roadway far enough back from the abutment so that the frost penetration does not affect the sensor. In addition, the roadway and bridge deck can frequently have significantly different temperatures and conditions.

- Subsurface sensors can be located below surface sensors for economy of installation and maintenance. Care should be taken that the subsurface conditions at sensor locations are representative of subgrades in the area. This would include presence or absence of water, and pockets of unusual materials, such as clay or peat. Subsurface sensors are placed about 16-20 in. (0.4-0.5 m) below the pavement surface to determine subgrade temperature. This measurement is important to ascertain whether heat will flow toward or away from the pavement surface, and it has a direct and determining affect on pavement temperature forecasts.

Pavement sensors placed for *detection* and *monitoring* purposes should be located using the following criteria:

- If a highway agency decides to install only one sensor, it should be placed in a wheel track of a passing lane about 18-20 in. (0.4-0.5 m) from the center of the track. If the highway is a commuter route, then the sensor should be placed in the passing lane on the outbound side so it will be least influenced by traffic in the morning when the lowest temperatures are most likely.

- At least two sensors should be placed. On commuter routes, they should be located in the wheel tracks of the passing lane and the outside lane of the outbound side. An alternative could be an outside lane in both directions.

- Sensor location within wheel tracks should also be considered. The center of the track, where most vehicles run, will show the first presence of water ponding. The combination of crown, depth of rut, grade, the expected rate of rainfall or thawing, and tire splash will determine whether there will be standing water in a wheel track. Sensor placement on the side of wheel tracks is recommended to avoid standing water.

- Care should be taken to ensure that the slope of the road at any location is such that there is no drainage onto a sensor from the shoulder or the median. Sensors should not be placed in the roadway on curves.

- Since vehicle heat does influence pavement temperature, placing a sensor in the center of a lane is not recommended.

- Pavement sensors should be implanted flush with the pavement surface. This will help ensure that moisture does not collect on them (installed too low). It will also prevent them from being scrubbed off at a rate greater than the surrounding pavement (installed too high). Care must be exercised in installing sensors in grooved pavement. They should be flush with the top of grooves, not the bottom.

Since the cost of a pavement sensor is only about 10% of the cost of installing an RPU, adding pavement sensors for multiple purposes is cost-effective. More than one pavement sensor can be placed at or near each RPU for detection and monitoring pavement temperature or roadway conditions. Comparing data from alternate sensors is also an appropriate way to determine whether an RPU is working properly. The specific location of pavement sensors with respect to their RPU should be consistent among RPUs so people who monitor the real-time data will not have to remember where each sensor is.

Siting RPUs and Weather Sensors

The purpose of using weather sensors in an RWIS is to gather weather information related to the road environment in order to assist with the *prediction, detection,* and *monitoring* of weather and road conditions. RPUs should be located carefully to address agency data needs.

- For *prediction*, the sites selected should be representative of a general area.

- For *detection*, RPUs may be placed at locations maintenance personnel know are particularly troublesome during winter weather. These can include bridges, elevated roadways, shadowed roads, or frost hollows. Accurate and reliable forecasts compiled using data from these sensors will predict slick conditions before they occur. This allows responsible parties to make decisions before the fact instead of waiting and reacting once snow and ice occur.

- For *monitoring*, RPUs should be placed to detect changes in weather or road conditions that will provide lead time for decision makers. A typical location would be the western edge of an area where the weather frequently comes from the west. This monitoring function also provides near-term information (depending on the speed of a storm) to fine-tune long-term forecasts.

Ideally, one can find locations where RPUs can be installed to satisfy more than one of these needs.

The location of roadside RPUs should be based on the following:

- Meteorological considerations. The better the meteorological information, the better the forecasts will be.
- Equipment limitation. Manufacturers of atmospheric sensors specify a distance limit between sensors and their RPU.
- An RPU should be installed as close to the road as possible without being influenced by passing vehicles. If placed too close, during winter road conditions, vehicles can propel slush and deicing chemicals onto the RPU electronics, atmospheric sensors, and tower.
- A site should be as safe as possible to prevent vehicles from striking the system. On-ramp gores are usually low-impact areas. Along a highway, the area on the right-of-way outside of the roadway prism is also a preferred location if the elevation of the area is within a few feet of the roadway and the area is relatively open and not lined with trees. Trees, cuts, and fills preclude gathering representative data.
- Proximity to power and communications should not be primary considerations. It is better to install an RPU 500 ft (150 m) away from power and pay for cabling than it is to install it in an area not representative of general conditions. Also, solar power cells can be used at an RWIS if no commercial power is available. Solar power cells for an RPU cost about the same as 500 ft of trenching.

Ideal RPU locations in a typical urban area would include, at a minimum:

- one in a low spot where temperatures tend to be cold when skies are clear.
- one at a higher elevation where temperatures tend to be cold when skies are cloudy.
- sufficient additional RPUs, but not less than two, at representative predictive locations.

It should be noted that the RPUs near the border of one area can also serve an adjacent area, so that two adjacent areas might need only six total RPUs based on the need for four per area.

RPUs should be sited to provide data to forecasting services as well as to provide detection and monitoring information to agency snow and ice control managers.

RPUs and their sensors should be sited with the assistance of meteorological analysis, input from maintenance supervisors for operational considerations, and road thermal analysis.

In order for the meteorological information collected by RWIS sensors to be representative, standard meteorological instrument siting criteria should be followed to the extent practicable. Different meteorological parameters have different instrument siting criteria.

Within the highway right-of-way, being able to locate *wind speed and direction* sensors (anemometers) sufficiently far from an object may be impossible. However, the siting should first be determined based on the prevailing wind direction and/or the direction from which most winter storms come.

- Install anemometers in as open an area as possible, avoiding cuts and nearby obstructions to flow.

- Install anemometers upstream in the prevailing flow from highway obstructions. If the prevailing winds are from the west, do not install an anemometer just east of a bridge, for instance.

The ground also influences wind flow. The closer anemometers are to the ground, the greater the influence of the ground. Standard meteorological wind instrument height has been established at 33 ft (10 m). Standard meteorological towers are available for placing anemometers at that height.

- The standard 33-ft anemometer height should be used whenever possible, though lower heights down to 10 ft (3 m) may be used where this would more closely represent the wind field at the road surface.

- A tower should be sited using the guidance offered above for siting RPU stations. An RPU will normally be mounted on such a tower.

- If a standard tower cannot be used because of insufficient area in the right-of-way outside the clear zone, anemometers can be installed on light standards or utility poles. Anemometers should be placed on top of poles to negate their flow-disturbing effects.

- If no pole or tower is available, anemometers can be installed on sign bridges. Care must be taken, however, to ensure that they are installed to minimize disturbances from the signs and sign bridges themselves.

In the roadway environment, sensors for *temperature* and *relative humidity* should be located with standard instrument siting criteria as prime considerations.

- The instruments should be located as close as possible to 5-6 ft (1.5-1.8 m) above the surface, or 6 ft above average maximum snow depth.

- The instruments should be placed over grassy areas, with a second choice of bare ground rather than pavement.

- Temperature and relative humidity should NOT be measured from the top of light standards or sign bridges. The heights of these installations preclude obtaining representative values.

The primary consideration for the siting of *precipitation* measuring devices is exposure. As is the case with wind, precipitation patterns are heavily influenced by obstructions. An instrument should be located in as open an area as possible. The anemometer-siting criteria can be used to determine suitable locations. However, the tower itself can influence the flow through a precipitation detector, and hence, the determination of the occurrence and amount of precipitation. The detector should be installed as high as possible on the tower without obstructing the anemometer, and should be located on the side upwind of the prevailing winds.

RWIS Information

RWISs should be programmed so that data are acquired from every RPU and sensor at least once per hour to ensure the system is working properly, and to assist in the building of a database which can be used for development of forecast studies or analyses.

All agencies should consider using value-added meteorological services in their snow and ice control resource allocation decisions.

Contractual arrangements between agencies and VAMS should make clear the need for a consultant-client relationship to foster communication and mutual understanding of each other's needs and capabilities, and to provide feedback on forecast accuracy.

Agencies with RWIS sensors in place should ensure that forecasts of pavement temperature are available to decision makers.

Road Thermal Analysis

An agency considering the installation of a network of RWIS sensors, whether along a road or in an area, should also consider having road thermal analysis conducted to assist in the siting of these sensors.

Thermal analysis can also help an agency to improve the efficiency of snowplow deployment by, for example, ensuring that the coldest roads are plowed first.

If the climate shows sufficient variability and labor rules will allow it, an agency should consider using road thermal analysis to establish a staged response to snow and ice control.

RWIS Communications

Agencies should weigh the options of proprietary (closed) and nonproprietary (open) systems when developing RFPs for implementing RWISs.

In order to improve data exchange and allow for interoperability, a CPU-to-CPU standard communication protocol and standard data format should be established and used by agencies.

State highway agencies should consider using existing or developing statewide communication systems for the dissemination of RWIS data.

RWIS sensor data should be considered to be in the public domain in order to facilitate their widest distribution and use. An agency should include in RFPs for RWISs the statement that any data produced by its RWIS will be considered to be in the public domain.

Contracting for RWIS Technologies

In order to obtain the proper service level from a meteorological provider, agencies should contract for meteorological services with the same procedures used for obtaining professional engineering services, and evaluate responders based on technical criteria first, then cost.

Formal evaluation procedures should be implemented by agencies acquiring forecasting services to ensure the quality of services received and to foster understanding between the meteorological and highway maintenance communities.

Minimum performance standards for RWIS sensor systems should be adopted in order to facilitate the acquisition of RWISs. Example standards include the Federal Aviation Administration Advisory Circulars AC 150/5220-16 for meteorological instrumentation (U.S. Department of Transportation 1986), and AC 150/5220-13B for pavement sensors (U.S. Department of Transportation 1991). National Weather Service Automated Surface Observing System standards should be considered for meteorological sensors.

Implementing RWIS Technologies

Each agency with RWIS hardware in place, or acquiring an RWIS, should establish a maintenance program which includes preventive and recurring maintenance requirements, and at a minimum, a requirement for annual sensor calibration for both meteorological and pavement sensors. The frequency of preventive and recurring maintenance and sensor calibration should be based on manufacturers' recommendations.

In order to fully integrate weather information into the snow and ice control decision process, proper training should be conducted for all involved staff levels.

Agencies should consider obtaining advice from professional meteorologists to assist in acquiring and using RWIS technologies.

The winter index developed in this project should be used by agencies as part of their evaluation of the cost-effectiveness of their RWISs, and to maximize the efficiency of their maintenance by monitoring the costs of their snow and ice control activities as compared to the climate.

Interagency Cooperation

In order to foster the exchange of information and technology, state highway agencies might consider forming an "RWIS users' group," an interstate group of people who are interested in establishing and advancing road weather information systems. This group could be patterned after the Highway Engineers Exchange Program (HEEP), which, during the 1960s and 1970s, provided a useful mechanism for advancing the use and development of computer programs for highway engineering. In HEEP, individuals from highway agencies and public works organizations throughout the United States met periodically to share programs, transfer technology, solve problems, and develop a human network to draw on between meetings. A similar approach might be useful during the development, use, and evaluation of RWISs by highway agencies. Meeting activities could include:

- Sharing the goals, objectives, and needs of highway agencies;
- Reaching an initial understanding or agreement among participants for a coordination mechanism among highway agencies;
- Identifying critical issues and areas which need immediate attention, and establishing a mechanism to address and resolve the issues; and
- Standardizing documentation for road weather information systems, and establishing a mechanism for creating and maintaining such documentation.

It is also suggested that the highway community assess the need and methodology for surface transportation to participate actively in the meteorological community in order to better serve the highway community's needs for weather support.

Additional Research Needs

The following is a list of RWIS-related topics requiring research that is beyond the scope of the current project. The list is not prioritized.

- Determine avenues where interfacing and/or integrating RWIS information would be desirable as measured by criteria to be established. Possible criteria include, for example:
    - effect on highway agencies;
    - effect on transportation in general;

- to whom (and what kinds of) weather information is disseminated;
- advances in meteorology;
- elimination of federal redundancy in the field of meteorology; and
- highway agency, federal transportation, federal establishment, or international attitudes and perceptions with respect to dissemination of weather information.

Possible interfaces include Intelligent Vehicle Highway Systems and other motorist information systems, maintenance management systems, and both federal and nonfederal weather information systems.

- Determine requirements for establishing these interfaces.

- Determine the utility of expanding the current RWIS configuration to include new technologies such as radiometers and present-weather, visibility, and air quality sensors to increase the cost-effectiveness of RWIS installations with more detailed support throughout the year.

- Establish motorist needs for RWIS information through studying human factors and behavioral science, in order to provide information to effect behavioral change in drivers.

- Develop standard techniques for agencies to use for periodic pavement sensor calibration.

- Determine the ability of sensors on vehicles—such as infrared radiometers for pavement temperature, thermometers, and hygrometers—to acquire data that would enhance RWIS real-time information, assist in developing historical databases, and provide thermal profiles of pavement temperature.

- Evaluate the use of thermographic profiles in pavement temperature forecasting, and the utility of using road thermal analysis for snow and ice control resource staging or phasing, by conducting road thermal analysis in at least three different climates.

- Investigate the effects of training in the use of RWISs on different RWIS implementation styles, e.g., centralized versus decentralized decision making. Conduct tailored training for one year, then monitor the effectiveness of RWIS use over three winters after training.

- Determine the utility of integrating RWIS (or other) on-site measurements into existing or potential small-area, detailed forecasting models, perhaps as developed or in development through NOAA's Office of Atmospheric Research/Forecasting Support Laboratory, in order to improve decision support for transportation systems.

- Evaluate the benefits to the meteorological and transportation communities of archiving RWIS data for climatological purposes, either with state climatologists or the National Climatic Data Center.

- Determine the optimum role of the federal government in supporting surface transportation meteorological needs.

Appendix A

Acronyms and Abbreviations

AAA	American Automobile Association
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily traffic
ASOS	Automated Surface Observing System (NWS)
AWOS	Automated Weather Observing System (FAA)
BUFR	Binary Uniform Format for Data Representation
CDOT	Colorado Department of Transportation
COST	Cooperation in the Field of Scientific and Technical Research
CPU	Central processing unit
EUCO	European Community
FAA	Federal Aviation Administration
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FHWA	Federal Highway Administration
ICMSSR	Interdepartmental Committee for Meteorological Services and Supporting Research
IVHS	Intelligent Vehicle Highway System

Mn/DOT	Minnesota Department of Transportation
Mn/ROAD	Minnesota Road Research Facility
MUTCD	Manual of Uniform Traffic Control Devices
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorology
PIARC	Permanent International Assembly of Road Congresses
RFP	Request for proposals
RPU	Remote processing unit
RWIS	Road weather information system
SERWEC	Standing European Road Weather Commission
SIRWEC	Standing International Road Weather Commission
SSI	Surface Systems, Incorporated
TRAC	Washington Transportation Center, University of Washington
VAMS	Value-added meteorological services
WSDOT	Washington State Department of Transportation

Appendix B

Winter Index Tables

An example for the Calculation of Winter Index (Duluth Airport, December 1988). The data in the tables below are to be used in the calculations of the Winter Index. The formula is as shown on page 93 of the text. Data must be entered in metric.

Day	T_{max} (°C)	T_{min} (°C)	TI	Snowfall (mm)
1	-5.0	-17.8	2	0.0
2	2.8	-7.2	1	0.0
3	2.2	-7.2	1	0.0
4	-1.7	-9.4	2	0.0
5	6.7	-6.1	1	0.0
6	4.4	-2.8	1	0.0
7	-1.7	-12.2	2	0.0
8	-10.6	-16.7	2	10.2
9	-13.3	-13.9	2	0.0
10	-11.1	-17.2	2	0.0
11	-8.3	-13.3	2	0.0
12	-1.1	-17.2	2	40.6
13	-0.6	-8.3	2	55.9
14	-1.1	-17.8	2	134.6
15	-10.6	-17.8	2	0.0
16	-9.4	-13.9	2	25.4
17	-11.7	-15.6	2	0.0
18	-2.2	-12.8	2	12.7
19	-1.1	-8.3	2	0.0
20	-0.6	-12.8	2	5.1
21	-3.3	-12.8	2	0.0
22	1.1	-3.9	1	12.7
23	1.1	-6.7	1	30.5
24	-6.7	-17.2	2	5.1
25	-11.1	-15.0	2	0.0
26	-4.4	-16.7	2	111.8
27	-1.7	-15.6	2	50.8
28	-10.6	-15.6	2	0.0
29	-7.2	-12.8	2	10.2
30	-7.2	-12.8	2	2.5
31	-7.2	-17.2	2	17.8
Total	-131.2	-394.6	56	525.9
Mean	-4.2	-12.7	1.8	17.0

The above daily data show that the number of air frost days is 31. Thus N=31/31=1, and temperature range (R) is 8.5°C. Substituting TI = 1.806, S = 16.96, N = 1 and R = 8.5 into Equation (3), we have

$$WI = -25.58\sqrt{1.806} - 35.68\ \ln(2.696) - 99.5\sqrt{0.054} + 50 = -42.9$$

The winter index of December 1988 at Duluth Airport is -42.9.

Table 1. **Site list for the winter index calculation across the United States (188 stations, period of 1950/51-1988/89)**

State Code	Site Name	Latitude (N)	Longitude (W)	Elevation (in feet)	Winter Index
AK	YAKUTAT WSO AP	59°31'	139°40'	28	-42.2
AL	BIRMINGHAM FAA AP	33°34'	86°45'	620	21.3
AL	MOBILE WSO AP	30°41'	88°15'	211	34.9
AL	MONTGOMERY WSO AP	32°18'	86°24'	183	27.9
AR	FORT SMITH WSO AP	35°20'	94°22'	447	13.5
AR	LITTLE ROCK FAA AP	34°44'	92°14'	257	18.9
AZ	FLAGSTAFF WSO AP	35°08'	111°40'	7,006	-23.0
AZ	PHOENIX WSO AP	33°26'	112°01'	1,117	43.4
AZ	TUCSON WSO AP	32°07'	110°56'	2,584	37.0
CA	BOCA	39 23'	120°06'	5,580	-21.8
CA	BRIDGEPORT	30°15'	119°14'	6,470	-10.9
CA	CRESCENT CITY 1 N	41°46'	124°12'	40	40.7
CA	DONNER MEMORIAL ST PK	39°19'	120°14'	5,940	-32.4
CA	FRESNO WSO	36°46'	119°43'	328	36.0
CA	GRANT GROVE	36°44'	118°50'	6,600	-26.6
CA	HUNTINGTON LAKE	37°14'	119°13'	7,020	-29.2
CA	MODESTO	37°39'	121°00'	91	37.1
CA	WHITE MTN 2	37°25'	118°14'	12,470	-23.1
CO	BOULDER	40°00'	105°16'	5,445	-15.5
CO	COLORADO SPRINGS WSO AP	38°49'	104°43'	6,145	-10.1
CO	DENVER WSFO AP	39°45'	104°52'	5,283	-14.0
CO	GRAND JUNCTION WSO AP	39°07'	108°32'	4,855	-4.6
CT	BRIDGEPORT WSO AP	41°10'	73°08'	7	-1.8
CT	GROTON	41°21'	72°03'	39	-4.6
CT	HARTFORD WSO AP	41°56'	72°41'	169	-14.1
CT	NORFOLK 2 SW	41°58'	73°13'	1,340	-30.2
DE	WILMINGTON WSO AP	39°40'	75°36'	74	1.3
FL	JACKSONVILLE WSO AP	30°30'	81°49'	24	36.7
FL	MIAMI WSO AP	25°48'	80°16'	7	49.8
FL	ORLANDO WSO MCCOY AFB	28°26'	81°20'	9	45.7
FL	PENSACOLA FAA AP	30°28'	87°12'	112	37.3
FL	TALLAHASSEE WSO AP	30°23'	84°22'	55	31.3
FL	TAMPA WSO AP	27°58'	82°32'	19	46.3
GA	ALBANY 3 SE	31°32'	84°08'	180	27.5
GA	ATHENS WSO AP	33°57'	83°19'	802	21.6
GA	ATLANTA WSO AP	33°39'	84°26'	1,010	22.3
GA	MACON WSO AP	32°42'	83°39'	354	26.6
IA	CEDAR RAPIDS NO 1	42°02'	91°35'	818	-12.5
IA	DES MOINES WSO AP	41°32'	93°39'	938	-13.0
ID	BOISE WSO AP	43°34'	116°13'	2,838	-1.8
ID	IDAHO FALLS FAA AP	43°31'	12°04'	4,730	-15.9

WSO = Weather Service
WSFO = Weather Service Forecast Office
AP = Airport
FAA = Federal Aviation Administration

Continued

Table 1 (continued) **Site list for the winter index calculation across the United States (188 stations, period of 1950/51-1988/89)**

State Code	Site Name	Latitude (N)	Longitude (W)	Elevation (in feet)	Winter Index
ID	LEWISTON WSO AP	46°23'	117°01'	1,413	5.2
KS	WICHITA WSO AP	37°39'	97°26'	1,321	0.8
KY	LEXINGTON WSO AP	38°02'	84°36'	966	2.0
KY	LOUISVILLE WSFO	38°11'	85°44'	477	4.3
LA	BATON ROUGE WSO AP	30°32'	91°08'	64	34.5
LA	NEW ORLEANS WSCMO AP	29°59'	90°15'	4	38.0
LA	SHREVEPORT WSO AP	32°28'	93°49'	254	27.9
MA	AMHERST	42°23'	72°32'	150	-15.6
MA	BLUE HILL WSO AP	42°13'	71°07'	629	-16.7
MA	BORDEN BROOK RESV	42°08'	72°56'	1,110	-21.4
MA	BOSTON WSO	42°22'	71°02'	15	-6.3
MA	TULLY LAKE	42°38'	72°13'	690	-19.5
MA	WORCESTER WSO AP	42°16'	71°52'	986	-20.8
MD	BALTIMORE WSO AP	39°11'	76°40'	200	2.6
MD	HAGERSTOWN	39°39'	77°44'	660	-1.4
MD	OAKLAND 1 SE	39°24'	79°24'	2,420	-22.7
MD	SALISBURY FAA AP	38°20'	75°31'	800	8.0
ME	BANGOR FAA AP	44°48'	68°49'	160	-27.4
ME	CARIBOU WSO AP	46°52'	68°01'	624	-38.0
ME	PORTLAND WSO AP	43°39'	70°19'	43	-22.5
MI	DETROIT METROPOLITAN AP	42°14'	83°20'	633	-15.1
MI	FLINT WSO AP	42°58'	83°45'	770	-17.7
MI	GRAND RAPIDS WSO AP	42°53'	85°31'	784	-24.7
MI	SAULT STE MARIE WSO	46°28'	84°22'	721	-39.1
MN	DULUTH WSO AP	46°50'	92°11'	1,428	-31.3
MN	INT FALLS WSO AP	48°34'	93°23'	1,179	-27.4
MN	MINN-ST PAUL WSO AP	44°53'	93°13'	834	-22.3
MO	SAINT LOUIS WSCMO AP	38°45'	90°23'	535	1.1
MO	SPRINGFIELD WSO AP	37°14'	93°23'	1,268	3.1
MS	JACKSON WSO AP	32°19'	90°05'	31	23.7
MS	MERIDIAN WSO AP	32°20'	88°45'	290	23.5
MT	BILLINGS WSO AP	45°48'	108°32'	3,567	-15.7
MT	GREAT FALLS WSO AP	47°29'		3,662	-16.1
MT	MILES CITY FAA AP	46°26'	105°52'	2,628	-12.7
MT	MISSOULA WSO AP	46°55'	114°05'	3,190	-19.4
MT	WEST YELLOWSTONE	44°39'	111°06'	6,662	-45.6
NC	ASHEVILLE	35°36'	82°32'	2,242	7.7
NC	CAPE HATTERAS WSO	35°16'	75°33'	7	29.1
NC	CHARLOTTE WSO AP	35°13'	80°56'	735	16.4
NC	GREENSBORO WSO AP	36°05'	79°57'	897	10.6
NC	RALEIGH DURHAM WSFO AP	35°52'	78°47'	434	13.0
ND	BISMARCK WSO AP	46°46'	100°46'	1,647	-19.0
ND	FARGO WSO	46°54'	96°48'	896	-19.7

Table 1 (continued) **Site list for the winter index calculation across the United States (188 stations, period of 1950/51-1988/89)**

State Code	Site Name	Latitude (N)	Longitude (W)	Elevation	Winter Index
ND	GRAND FORKS FAA AP	47°57'	97°11'	839	-20.0
ND	MINOT FAA AP	48°16'	101°17'	1,713	-19.8
NE	GRAND ISLAND WSO AP	40°58'		841	-11.1
NE	NORTH PLATTE WSO AP	41°08'	100°41'	2,775	-10.4
NE	OMAHA NORTH OMAHA WSFO	41°22'	96°01'	1,323	-12.1
NH	CONCORD WSO AP	43°12'	71°30'	346	-21.3
NH	LEBANON FAA AIRPORT	43°38'	72°19'	562	-23.7
NJ	ATLANTIC CITY WSO AP	39°27'	74°34'	140	3.4
NJ	HIGH POINT PARK	41°18'	74°40'	1,410	-17.0
NJ	NEWARK WSO AP	40°42'	74°10'	11	1.2
NJ	WOODSTOWN	39°39'	75°19'	50	2.3
NM	ALBUQUERQUE WSO AP	35°03'	106°37'	5,311	5.4
NM	LOS ALAMOS	35°52'	106°19'	7,410	-13.3
NM	SANTA FE 2	35°39'	105°59'	6,720	-4.3
NV	LAS VEGAS WSO AP	36°05'	115°10'	2,162	0.4
NV	RENO WSO AP	39°30'	119°47'	4,404	-3.3
NV	WINNEMUCCA WSO AP	40°54'	117°48'	4,301	-3.2
NY	ALBANY WSO AP	42°45'	73°48'	275	-21.2
NY	BIRMINGHAM WB AP	42°13'	75°59'	1,590	-28.3
NY	BUFFALO WSO	42°56'	78°44'	705	-28.3
NY	NEW YORK CNTRL PK WSO	40°47'	73°58'	132	3.9
NY	RIVERHEAD RESEARCH FARM	40°58'	72°43'	100	-1.9
NY	ROCHESTER WB AP	43°07'	77°40'	547	-28.8
NY	SYRACUSE WB AP	43°07'	76°07'	410	-31.4
OH	AKRON-CANTON WSO AP	40°55'	81°26'	1,208	-15.8
OH	CLEVELAND WSO AP	41°25'	81°52'	777	-17.2
OH	COLUMBUS WSO AP	40°00'	82°53'	812	-6.7
OH	DAYTON WSCMO AP	39°54'	84°12'	1,002	-7.9
OH	TOLEDO EXPRESS WSO AP	41°35'	83°48'	669	-14.3
OK	OKLAHOMA CITY WSFO AP	35°24'	97°36'	1,285	10.8
OK	TULSA WSO AP	36°11'	95°54'	668	11.6
OR	ADEL	42°11'	119°54'	4,580	-1.2
OR	ASTORIA WSO AP	46°09'	123°53'	8	25.5
OR	BROTHERS	43°48'	120°36'	4,640	-6.6
OR	CRATER LAKE NPS HQ	42°54'	122°08'	6,480	-48.0
OR	EUGENE WSO AP	44°07'	123°13'	359	20.5
OR	PORTLAND WSO AP	45°36'	122°36'	21	23.1
OR	REDMOND FAA AP	44°16'	121°09'	3,075	-3.2
PA	ALLENTOWN WSO AP	40°39'	75°26'	387	-7.8
PA	ERIE WSO AP	42°05'	80°11'	732	-24.7
PA	HARRISBURG WSO AP	40°13'	76°51'	338	-6.3
PA	PHILADELPHIA WSCMO AP	39°53'	75°14'	5	1.6
PA	PITTSBURGH WSCMO2 AP	40°27'	80°00'	750	-5.1
PA	W-BARRE-SCRANT WSO AP	41°20'	75°44'	930	-14.3

Continued

Table 1 (continued) **Site list for the winter index calculation across the United States (188 stations, period of 1950/51-1988/89)**

State Code	Site Name	Latitude (N)	Longitude (W)	Elevation (in feet)	Winter Index
RI	NEWPORT	41°31'	71°19'	20	-2.8
RI	PROVIDENCE WSO AP	41°44'	71°26'	51	-7.3
SC	CHARLESTON WSO AP	32°54'	80°02'	41	28.5
SC	COLUMBIA WSFO AP	33°57'	81°07'	213	21.3
SC	GRNVLE-SPTNBG WSO AP	34°54'	82°13'	957	16.8
SD	ABERDEEN WSO AP	45°27'	98°26'	1,296	-19.0
SD	RAPID CITY WSO AP	44°03'	103°04'	3,162	-12.5
SD	SIOUX FALLS WSO AP	43°34'	96°44'	418	-17.4
TN	CHATTANOOGA WSO AP	35°02'	85°12'	665	15.2
TN	NASHVILLE WSO AP	36°07'	86°41'	590	11.1
TX	ABILENE WSO AP	32°25'	99°41'	1,762	21.0
TX	AMARILLO WSO AP	35°14'	101°42'	3,607	3.8
TX	AUSTIN WSO AP	30°18'	97°42'	597	35.1
TX	BROWNSVILLE WSO AP	25°54'	97°26'	19	47.7
TX	COLLEGE STATION FAA AP	30°35'	96°21'	314	34.4
TX	CORPUS CHRISTI WSO AP	27°46'	97°30'	41	43.4
TX	DALLAS FAA AP	32°51'	96°51'	481	27.6
TX	EL PASO WSO AP	31°48'	106°24'	3,918	19.7
TX	GALVESTON WSO CI	29°18'	94°48'	7	45.8
TX	HOUSTON FAA AP	29°39'	95°17'	50	40.0
TX	LUBBOCK WSFO AP	33°39'	101°49'	3,254	10.0
TX	SAN ANTONIO WSFO	29°32'	98°28'	788	33.8
TX	WICHITA FALLS WSO AP	33°58'	98°29'	994	17.0
UT	OGDEN SUGAR FACTORY	41°14'	112°02'	4,280	-6.5
UT	SALT LAKE CITY WSFO AP	40°47'	111°57'	4,222	-14.2
VA	LYNCHBURG WSO AP	37°20'	79°12'	916	5.5
VA	NORFOLK WSO AP	36°54'	76°12'	22	18.0
VA	RICHMOND WSO AP	37°30'	77°20'	164	8.3
VA	ROANOKE WSO AP	37°19'	79°58'	1,149	3.4
VA	WASH DULLES WSO AP	38°57'	77°27'	291	-0.4
VA	WASHINGTON NAT AP WSO	38°51'	77°02'	10	9.5
VT	BURLINGTON WSO AP	44°28'	73°09'	332	-28.2
VT	MONTPELIER FAA AP	44°12'	72°34'	1,126	-32.0
WA	BELLINGHAM FAA AP	48°48'	122°32'	150	12.6
WA	OLGA 2 SE	48°37'	122°48'	80	22.8
WA	OLYMPIA WSO AP	46°58'	122°54'	195	9.6
WA	QUILLAYUTE WSCMO AP	47°57'	124°33'	179	14.2
WA	SEATTLE-TACOMA WSCMO AP	47°27'	122°18'	400	22.6
WA	SPOKANE WSO AP	47°38'	117°32'	2,349	-15.8
WA	STAMPEDE PASS WSCMO AP	47°17'	121°20'	3,958	-50.0
WA	WALLA-WALLA FAA AP	46°06'	118°17'	1,170	8.5

Table 1 (continued) **Site list for the winter index calculation across the United States (188 stations, period of 1950/51-1988/89)**

State Code	Site Name	Latitude (N)	Longitude (W)	Elevation (in feet)	Winter Index
WA	WENATCHEE FAA AP	47°24'	120°12'	1,230	-8.2
WA	YAKIMA WSO AP	46°34'	120°32'	1,064	-5.9
WI	MADISON WSO AP	43°08'	89°20'	858	-17.7
WI	MILWAUKEE WSO AP	42°57'	87°54'	672	-19.4
WV	CHARLESTON WSO AP	38°22'	81°36'	939	-2.8
WV	HUNTINGTON WSO AP	38°22'	82°33'	827	-0.8
WV	MORGANTOWN FAA AP	39°39'	79°55'	1,240	-6.6
WY	CASPER WSO AP	42°55'	106°28'	5,338	-21.0
WY	CHEYENNE WSO	41°09'	104°49'	6,126	-12.6
WY	LARAMIE FAA AP	41°19'	105°41'	7,266	-15.1
WY	ROCK SPRINGS FAA AP	41°36'	109°04'	6,741	-16.0

Table 2. **National winter index distribution along different latitudes (averaged over 1950/51-1988/89)**

Winter index along 45N:

Station	State	Lat.(N)	Long.(W)	Elev.(ft)	WI
Olympia	WA	45°68'	122°48	80	10.2
Spokane	WA	47°38'	117°32	2,349	-15.8
Great Falls	MT	47°29'	111°22	3,662	-16.3
Bismark	ND	46°46'	100°46	1,647	-18.9
Duluth	MN	46°50'	92°11	1,482	-31.5
Sault St. Marie	MI	46°28'	84°22	721	-39.2
Syracuse	NY	43°07'	76°07	410	-31.4
Portland	ME	43°39'	70°19	43	-22.5

Winter index along 40N:

Station	State	Lat.(N)	Long.(W)	Elev.(ft)	WI
Crescent City	CA	41°46'	124°12'	40	40.6
Reno	NV	39°30'	119°47'	4,404	- 3.3
Salt Lake City	UT	40°47'	111°57'	4,222	-14.4
Denver	CO	39°45'	104°52'	5,283	-13.8
Salina	KS	38°48'	97°38'	1,260	- 1.8
St. Louis	MO	38°45'	90°23'	535	3.8
Lexington	KY	38°02'	84°36'	966	2.0
Baltimore	MD	39°17'	76°37'	14	2.6

Winter index along 35N:

Station	State	Lat.(N)	Long.(W)	Elev.(ft)	WI
Santa Barbara	CA	34°26'	119°50'	9	46.0
Flagstaff	AZ	35°28'	111°40'	7,006	-22.8
Albuquerque	NM	35°03'	106°37'	5,311	5.5
Amarillo	TX	35°14'	101°42'	3,607	4.1
Oklahoma City	OK	35°24'	97°36'	1,285	10.8
Little Rock	AR	34°44'	92°14'	257	18.8
Chattanooga	TN	35°02'	85°12'	665	15.2
Raleigh-Durham	NC	35°52'	78°47'	434	12.9

Table 3. **Winter maintenance cost, winter index, and population density for regression analysis**

State Code	Cost ($/ctrline-mi)	Winter Index	Population Density* (persons/mile²)
AK	11,527.38	-43.3	0.2
AL	18.18	28.0	11.8
AR	154.60	16.2	6.8
CA	4,166.67	- 3.4	24.7
CO	2,816.37	-10.7	4.7
CT	4,022.33	-12.7	94.5
GA	84.16	24.5	15.2
IA	1,526.57	-12.8	7.8
ID	1,159.60	- 4.3	1.9
IL	1,460.94	-10.1	30.8
IN	788.66	- 9.1	22.9
KS	510.20	- 1.3	4.5
KY	269.07	2.9	14.0
LA	36.60	33.4	13.9
MA	12,148.56	-11.7	105.5
MD	2,701.14	- 3.4	62.5
ME	4,628.71	-29.5	5.6
MI	2,628.50	-24.3	23.6
MN	2,120.31	-27.2	7.5
MO	576.12	1.4	10.9
MT	615.99	-22.0	0.9
NC	111.04	15.3	17.9
ND	306.87	-19.6	1.5
NE	550.52	-11.3	3.1
NH	4,332.52	-22.6	16.0
NJ	4,347.83	- 2.6	144.9
NV	568.56	7.8	1.3
NY	4,957.10	-19.6	54.0
OK	200.88	11.2	7.1
OR	1,745.25	3.8	4.2
PA	2,045.45	- 9.5	399.5
SC	84.03	22.2	16.3
SD	352.97	-16.4	1.4
TX	59.21	29.3	9.3
UT	1,294.44	-10.5	3.0
VA	596.42	7.4	21.1
VT	3,315.82	-30.3	8.3
WA	2,219.99	1.0	9.7
WV	629.79	- 3.5	12.1
WY	1,384.62	-16.1	0.8

Data provided by the University of Birmingham (U.K.)

Table 4. **Data for sites for Washington State winter index calculation**

Site Name	ID	District	Lat. (N)	Long. (W)	Elev. (ft)	Winter Index
Anacortes	176	1	48°31'	122°37'	30	25.0
Bellingham FAA AP	574	1	48°48'	122°32'	150	14.0
Coupeville 1 S	1783	1	48°12'	122°42'	50	20.2
Darrington	1992	1	48°15'	121°36'	550	-0.8
Everett	2675	1	47°59'	122°11'	60	21.0
Monroe	5525	1	47°51'	121°59'	120	17.5
Newhalem	5840	1	48°41'	121°15'	530	8.9
Palmer 3 ESE	6295	1	47°18'	121°51'	920	8.0
Seattle TAC WSCMO AP	7473	1	47°29'	122°18'	450	26.6
Sedro Woolley	7507	1	48°30'	122°14'	60	20.3
Snoqualmie Falls	7773	1	47°33'	121°51'	440	15.2
Startup 1 E	8034	1	47°52'	121°43'	170	16.8
Chelan	1350	2	47°50'	120°02'	1,120	-8.4
Ephrata FAA AP	2614	2	47°19'	119°31'	1,260	-3.0
Hartline	3529	2	47°41'	119°06'	1,910	-7.9
Mazama	5133	2	48°37'	120°27'	2,170	-30.2
Nespelem 2 S	5832	2	48°08'	118°59'	1,890	-7.1
Plain	6534	2	47°47'	120°39'	1,940	-32.3
Republic	6974	2	48°39'	118°44'	2,610	-17.9
Stehekin 4 NW	8059	2	48°21'	120°43'	1,270	-27.8
Waterville	9012	2	47°39'	120°04'	2,620	-18.1
Wenatchee	9074	2	47°25'	120°19'	640	-8.3
Winthrop 1 WSW	9376	2	48°28'	120°11'	1,760	-22.1
Aberdeen	8	3	46°50'	123°49'	10	25.8
Bremerton	872	3	47°34'	122°41'	110	23.3
Elma	2531	3	47°00'	123°24'	70	17.8
Forks 1 E	2914	3	47°57'	124°22'	350	15.8
Olympia WSO AP	6114	3	46°58'	122°54'	190	10.3
Port Angeles	6624	3	48°07'	123°24'	40	26.1
Shelton	7584	3	47°12'	123°06'	20	20.8
Battle Ground	482	4	45°46'	122°32'	280	16.7
Bickleton	668	4	46°00'	120°18'	3,000	-9.1
Centralia	1276	4	46°43'	122°57'	190	21.1
Cougar 6E	1760	4	46°04'	122°12'	660	17.0
Dallesport FAA AP	1968	4	45°37'	121°09'	240	9.2
Longview	4769	4	46°09'	122°55'	10	20.6
Toledo	8500	4	46°28'	122°51'	330	18.4
Vancouver 4 NNE	8773	4	45°41'	122°39'	210	15.9
Ellensburg	2505	5	46°58'	120°33'	1,480	-8.9
Prosser 4 NE	6768	5	46°15'	119°45'	900	3.5
Richland	7015	5	46°19'	119°16'	370	7.7
Sunnyside	8207	5	46°19'	120°00'	750	2.4
Walla Walla FAA AP	8928	5	46°06'	118°17'	1,170	9.0
Wapato	8959	5	46°26'	120°25'	840	1.4
Yakima WSO AP	9465	5	46°34'	120°32'	1,060	-4.9
Chewelah	1395	6	48°17'	117°43'	1,670	-12.6

Continued

Table 4 (continued) **Data for sites for Washington State winter index calculation**

Site Name	ID	Dist.	Lat. (N)	Long. (W)	Elev. (ft)	Winter Index
Colfax 1 NW	1586	6	46°53'	117°23'	1,960	-4.2
Davenport	2007	6	47°39'	118°08'	2,440	-14.6
La Crosse	4338	6	46°49'	117°53'	1,480	-0.1
Newport	5844	6	48°11'	117°03'	2,140	-20.8
Northport	5946	6	48°55'	117°47'	1,320	-17.4
Odessa	6039	6	47°20'	118°41'	1,540	-2.9
Pullman 2 NW	6789	6	46°46'	117°12'	2,550	-9.3
Ritzville 1 SSE	7059	6	47°07'	118°22'	1,830	-6.0
Rosalia	7180	6	47°14'	117°22'	2,400	-5.4
Spokane WSO AP	7938	6	47°38'	117°32'	2,360	-14.3
Wilbur	9238	6	47°45'	118°40'	2,230	-10.3

Table 5. **Winter index and cost (adjusted by inflation rate, in $1,000s) for the six highway maintenance districts in Washington State**

Year	1		2		3		4		5		6	
	WI	Cost	WI	Cost	WI	Cost	WI	Cost	WI	Cost	WI	Cost
83/84	24.9	1,701	-10.5	3,076	26.0	1,073	20.0	1,788	2.8	3,662	-5.5	2,559
84/85	4.4	2,704	-26.9	3,662	8.8	1,753	1.4	2,190	-8.2	4,428	-19.5	3,327
85/86	9.6	2,573	-23.5	3,803	11.5	1,917	5.7	2,523	-8.2	4,151	-15.0	3,413
86/87	25.8	1,467	-15.6	3,409	25.2	963	18.6	1,854	3.1	3,929	-3.5	2,899
87/88	23.2	1,428	-10.0	3,152	21.0	1,073	14.8	1,812	-0.1	3,314	-5.9	2,611
88/89	16.2	2,247	-20.0	3,270	16.1	1,547	12.5	1,955	-1.7	3,668	-15.7	3,063

Table 6. **Annual expenditure (tons/lane mile) of sand and salt on Routes 302 and 303, and winter index (WI) in the metropolitan area, Minnesota**

Year	Route 302			Route 303		
	Sand	Salt	Winter Index	Sand	Salt	Winter Index
86/87	23.23	10.54	-21.4	29.00	13.46	-21.4
87/88	44.85	17.15	-24.5	47.69	17.38	-24.5
88/89	57.38	26.15	-38.0	55.38	29.85	-38.0

Appendix C

Winter Index Figures

The following pages contain Figures 1-32 which support the section on Winter Index Development at the end of Chapter 2.

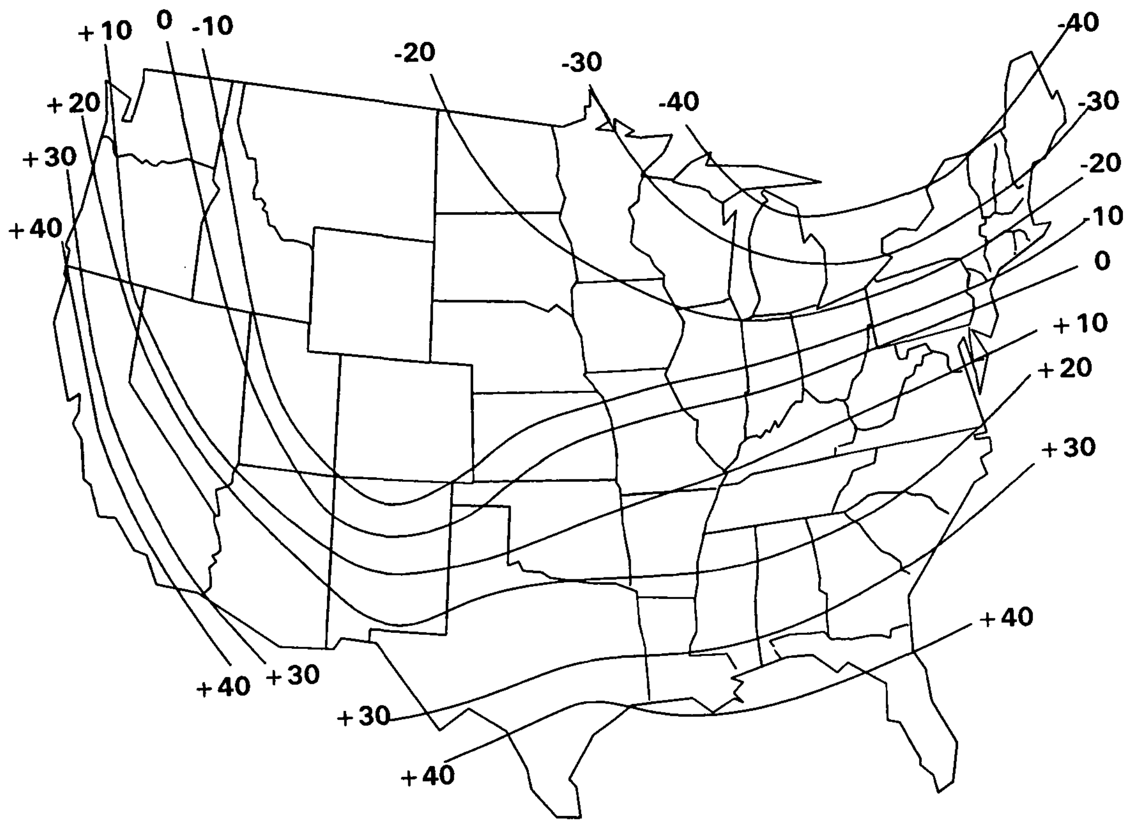

Figure 1. Distribution of the winter index across the United States, 1950 to 1986

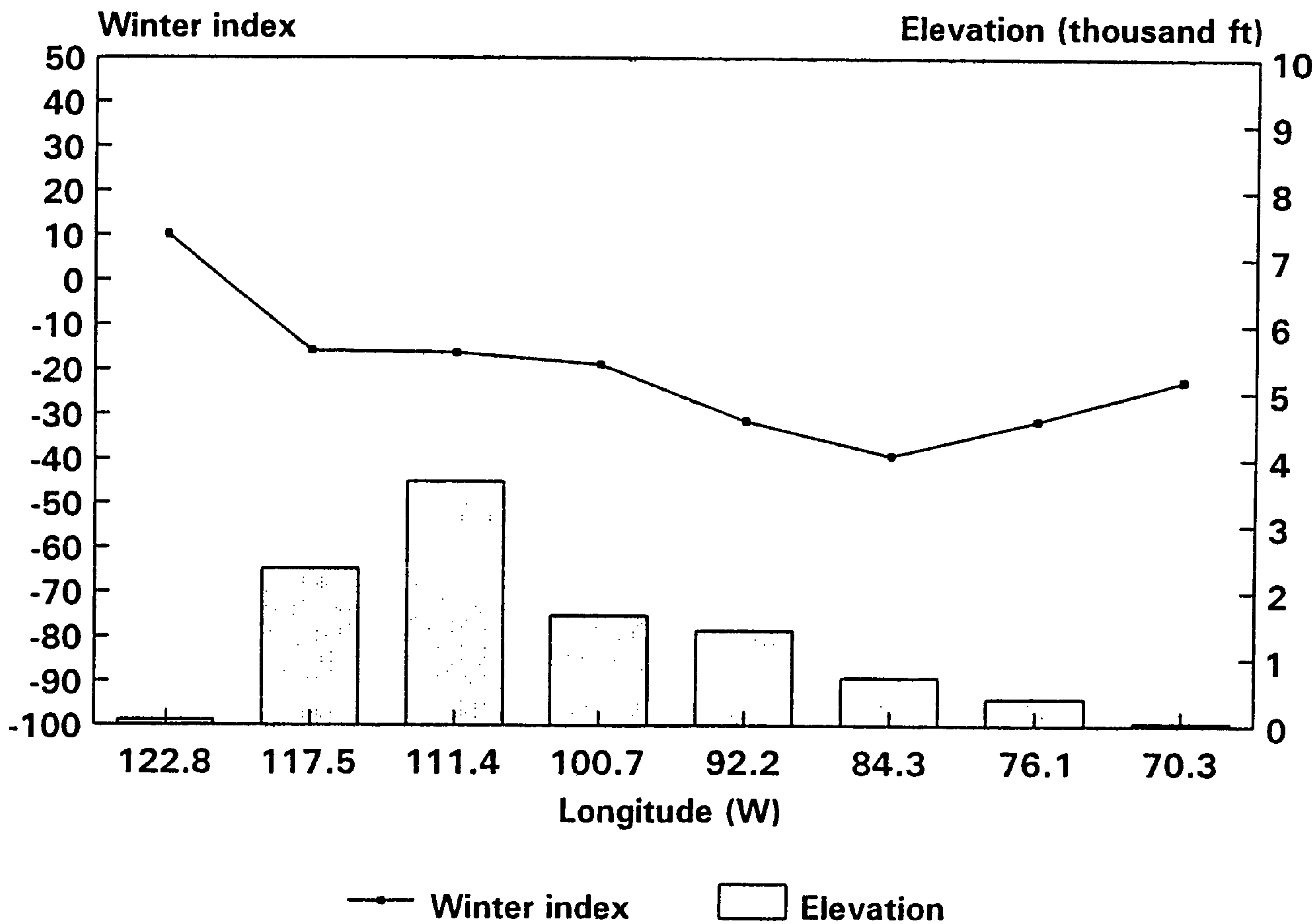

Figure 2. Winter index distribution along the latitude about 45°N (1950 to 1988)

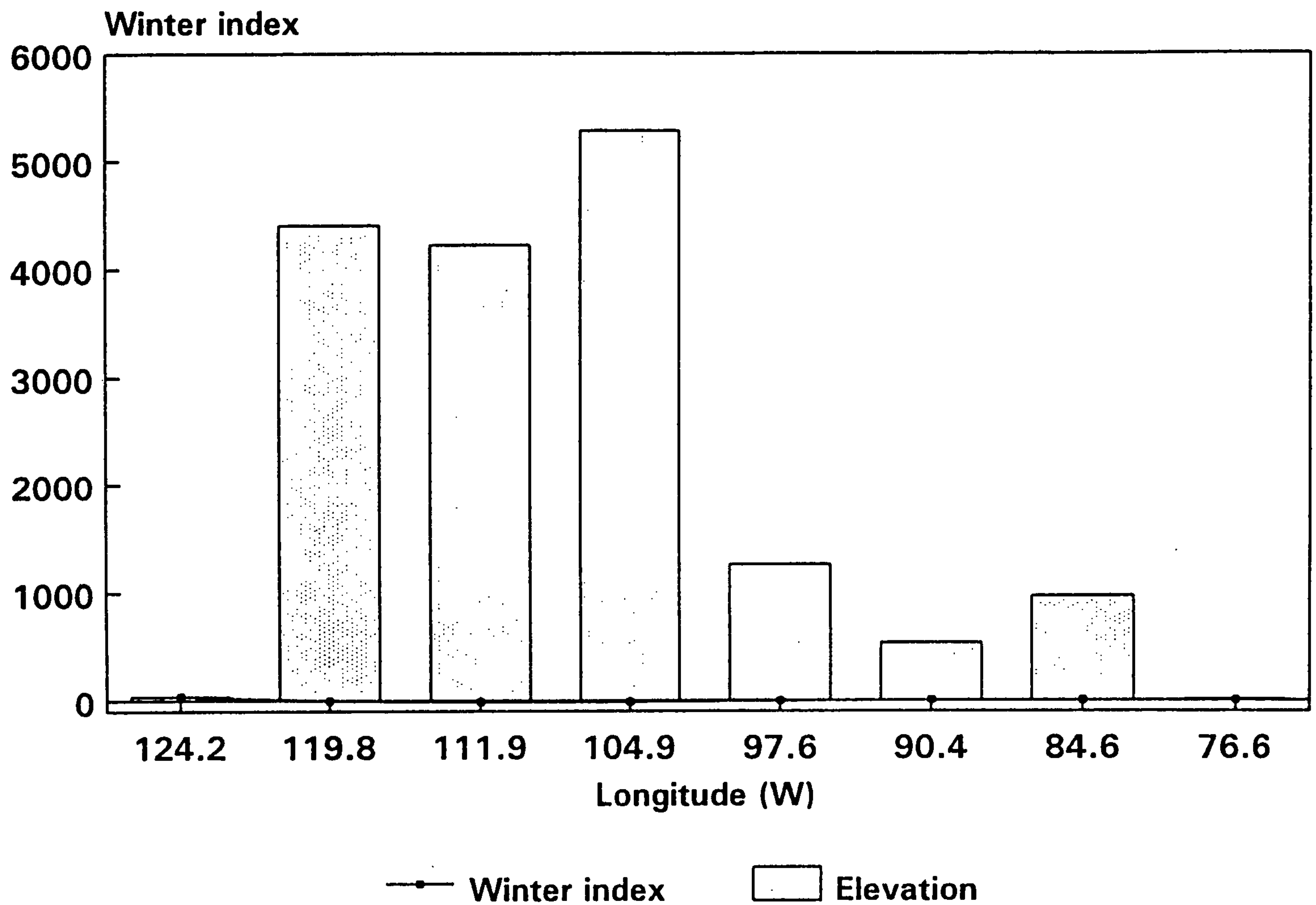

Figure 3. Winter index distribution along the latitude about 40°N (1950 to 1988)

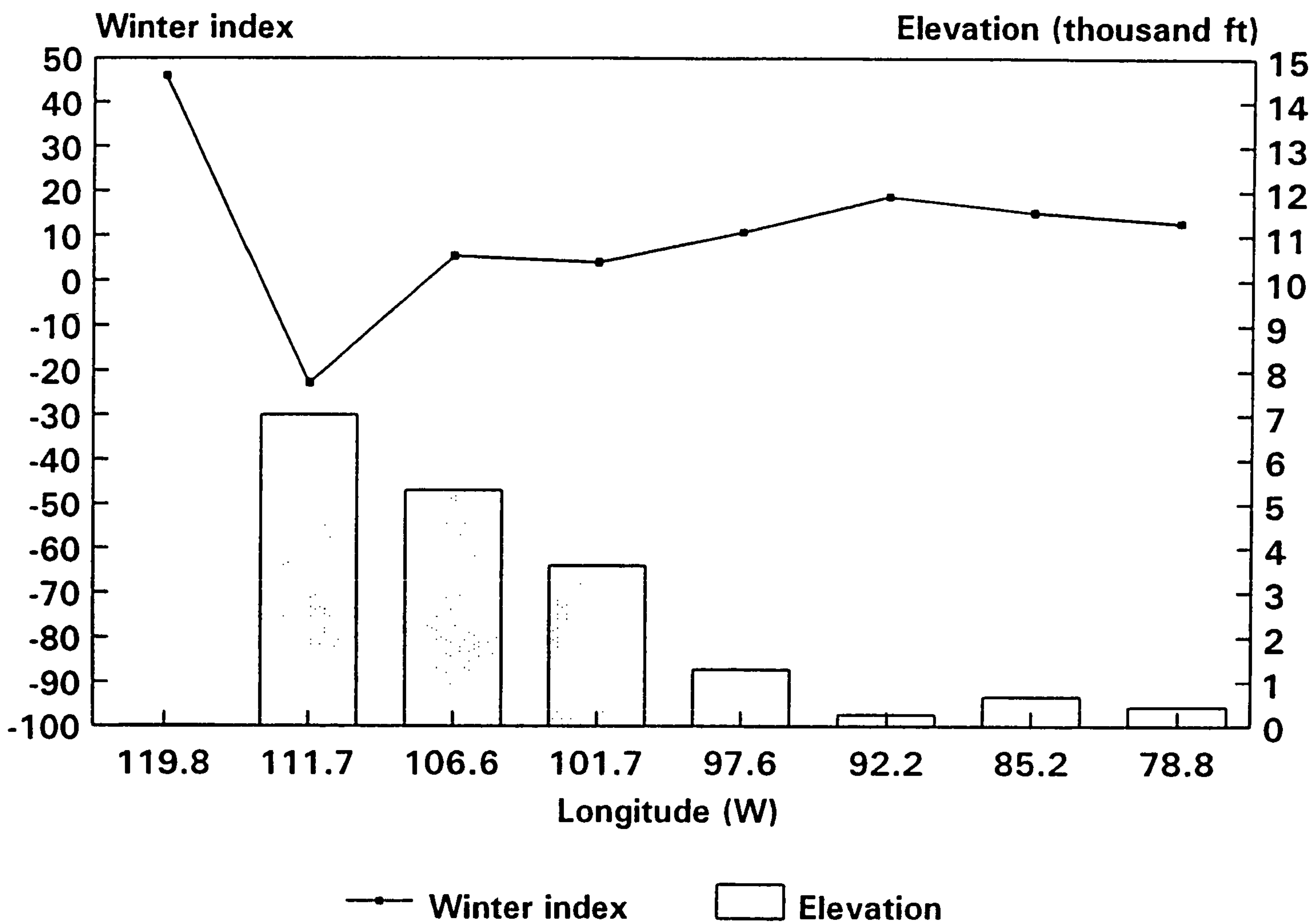

Figure 4. Winter index distribution along the latitude about 35°N (1950 to 1988)

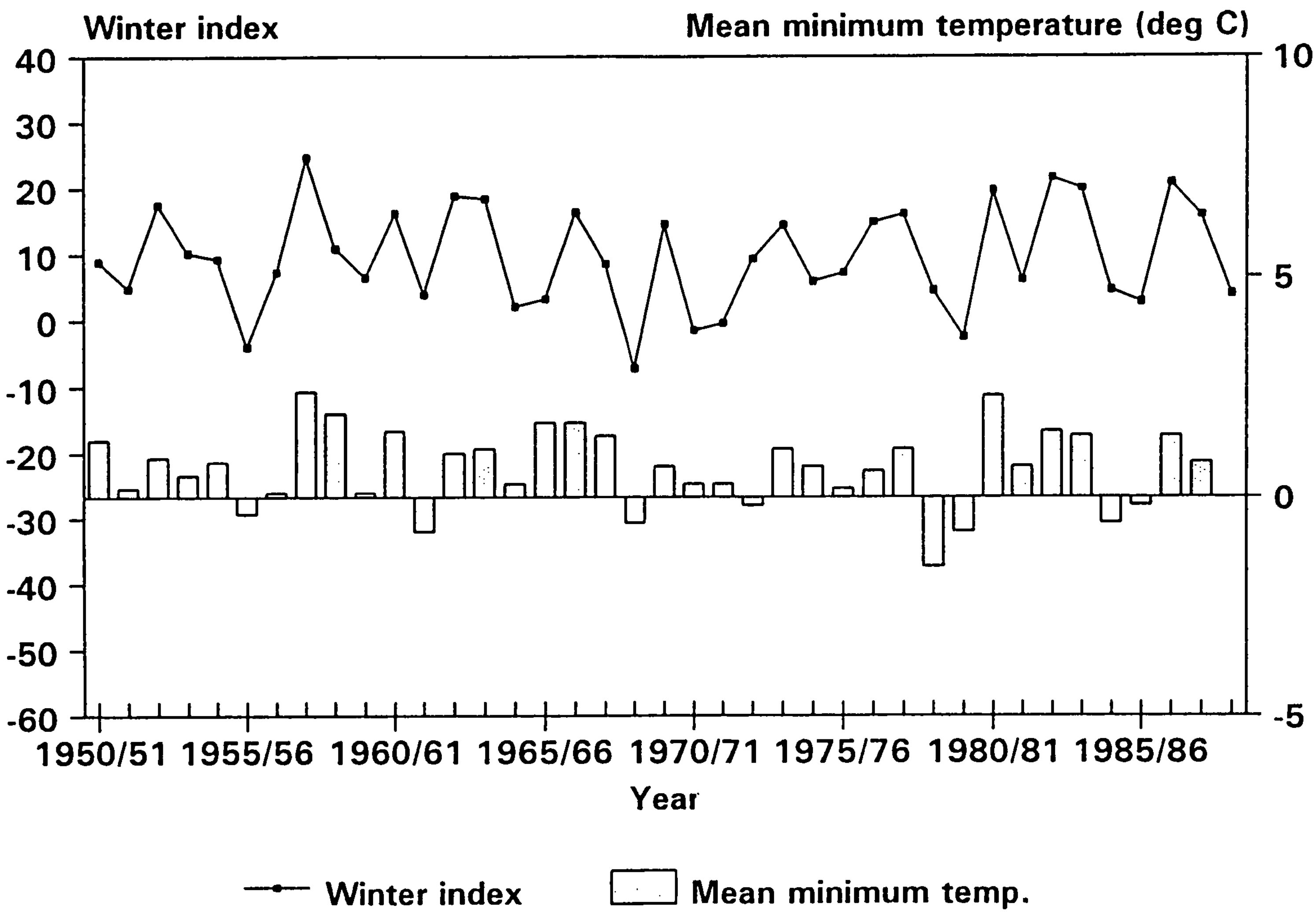

Figure 5. Winter index and mean minimum temperature (Olympia, WA) (r=0.72)

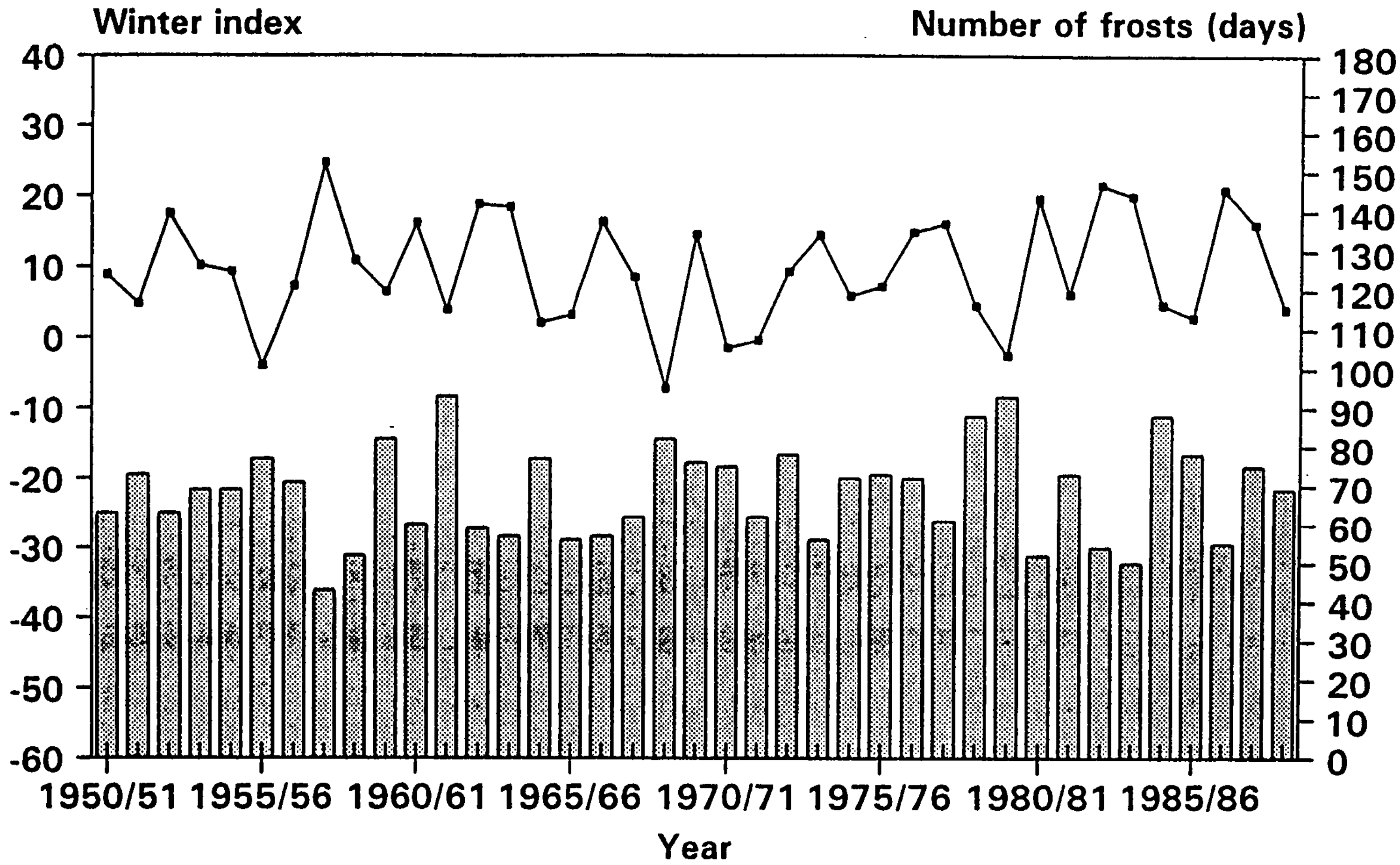

Figure 6. Winter index and number of air frosts (Olympia, WA
(r = -0.71)

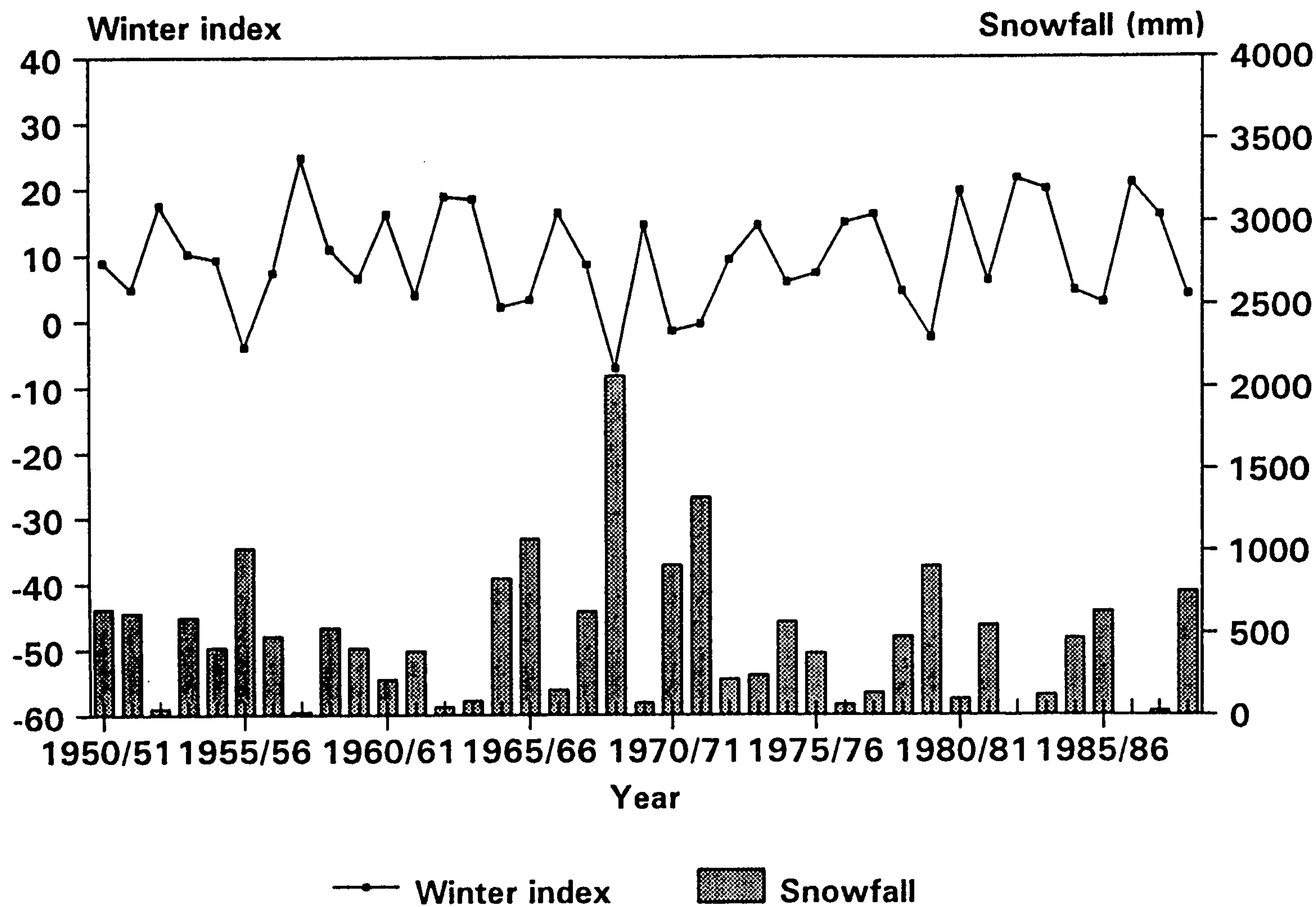

Figure 7. Winter index and snowfall (Olympia, WA) (r = -0.86)

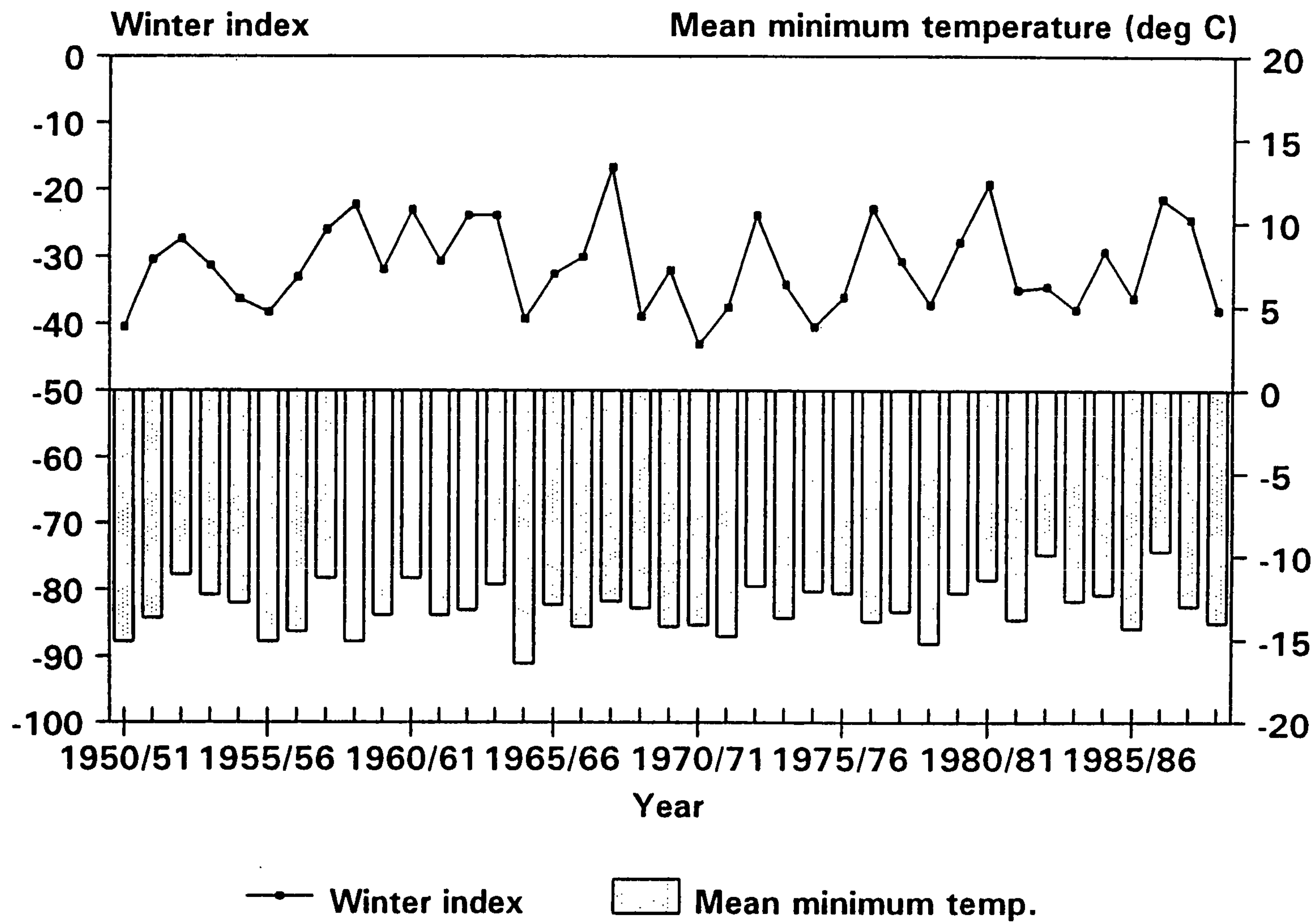

Figure 8. Winter index and mean minimum temperature (Duluth, MN) (r=0.41)

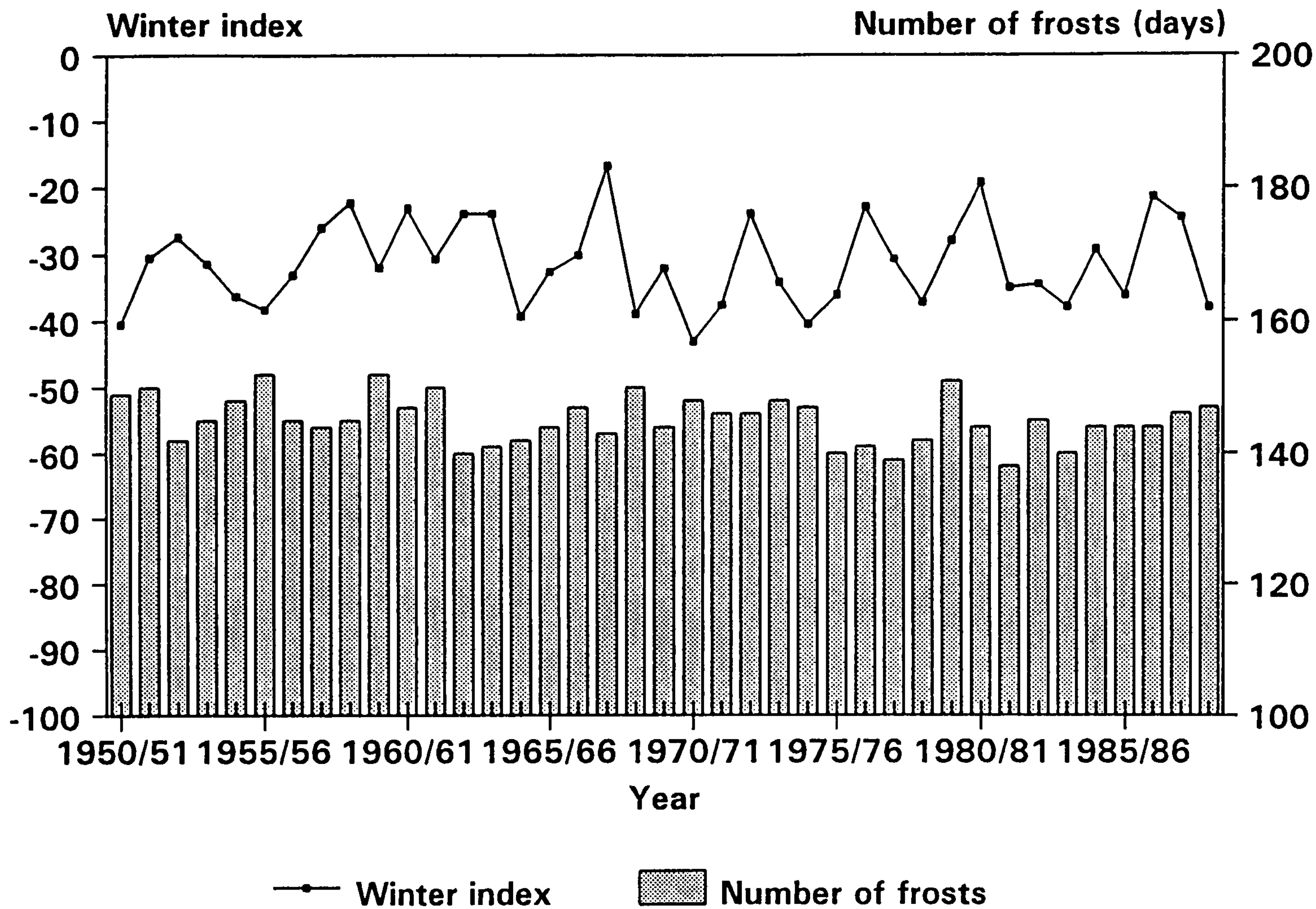

Figure 9. Winter index and number of air frosts (Duluth, MN) (r = -0.22)

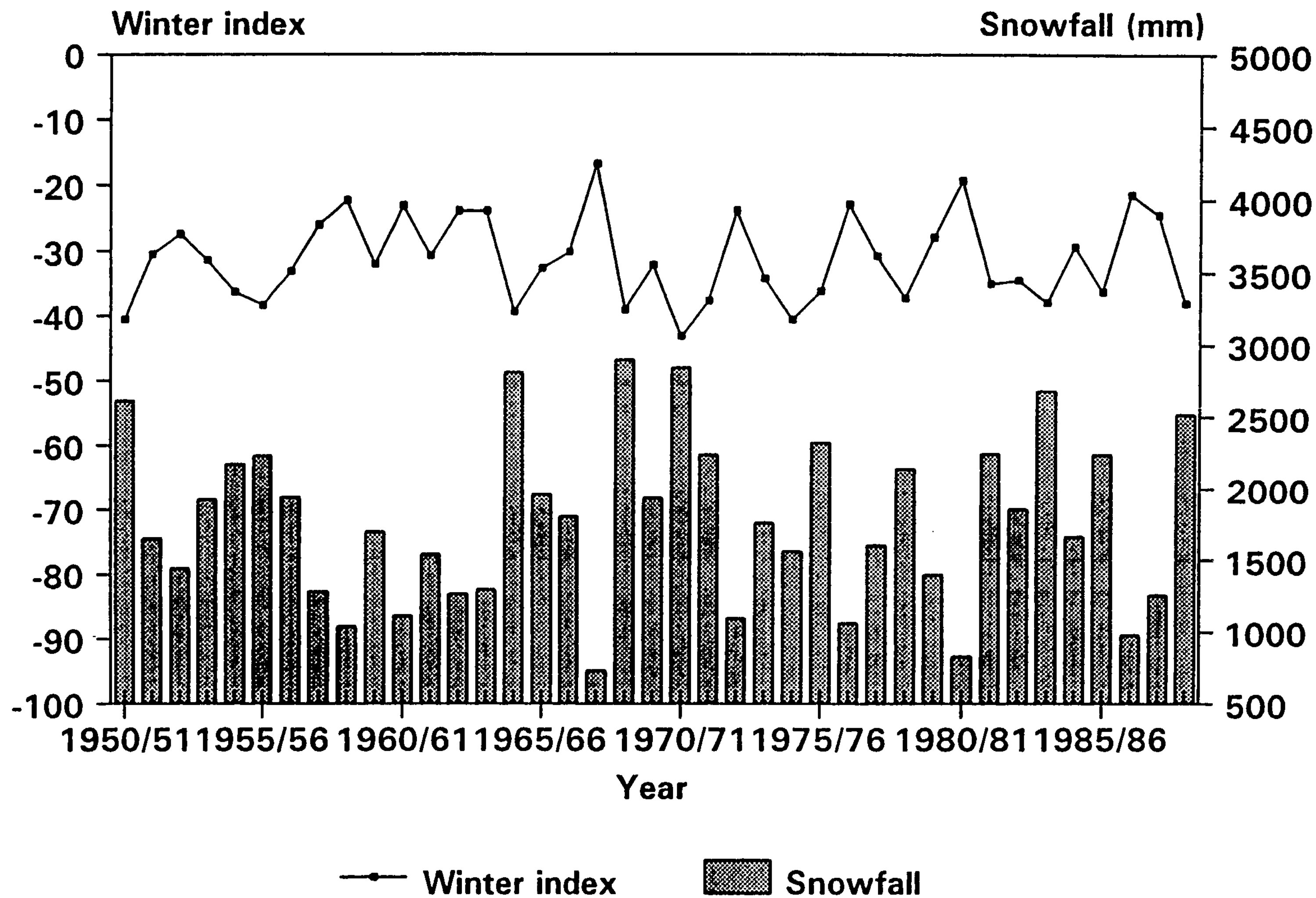

Figure 10. Winter index and snowfall (Duluth, MN) (r=-0.96)

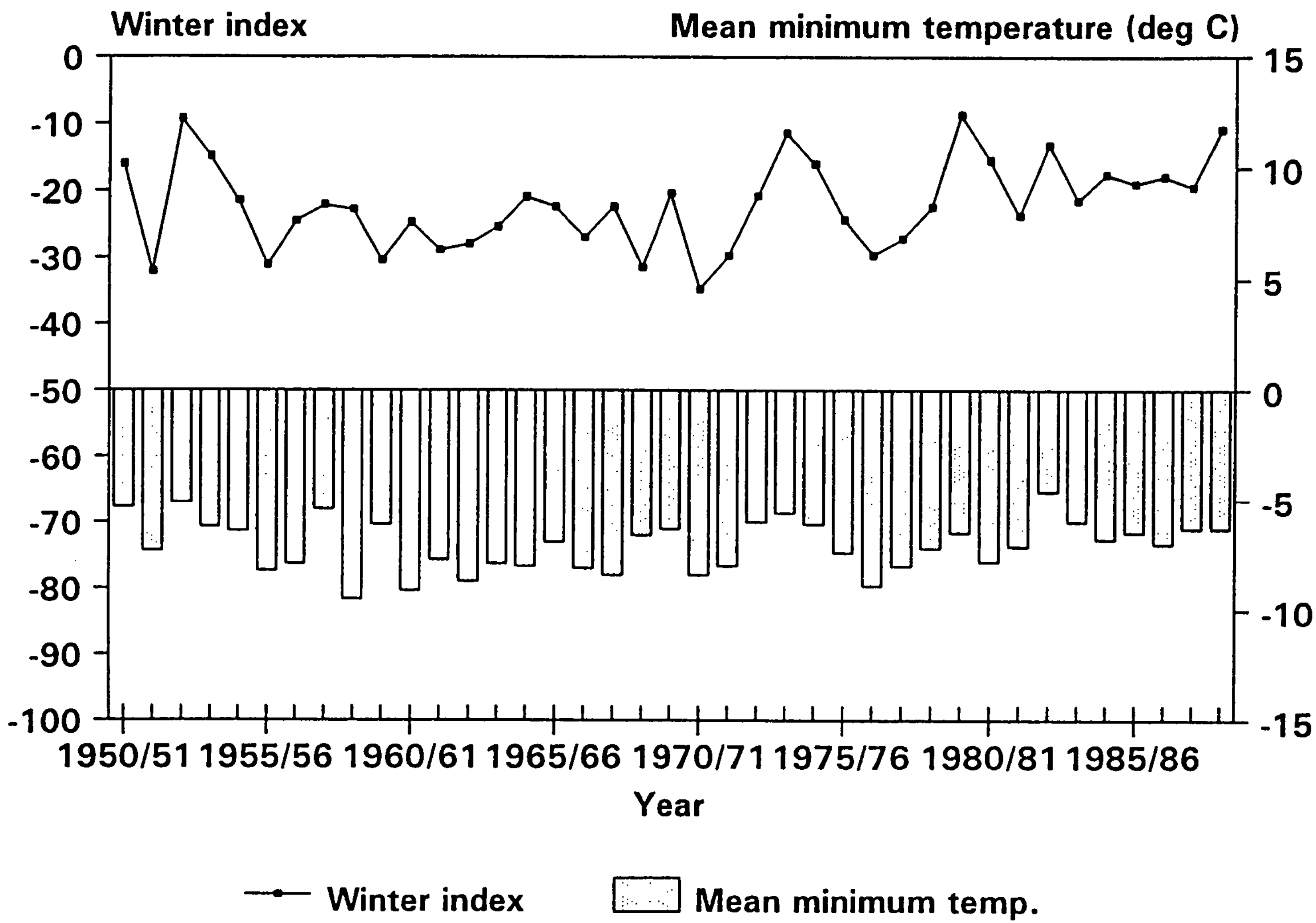

Figure 11. Winter index and mean minimum temperature (Portland, ME) (r = 0.60)

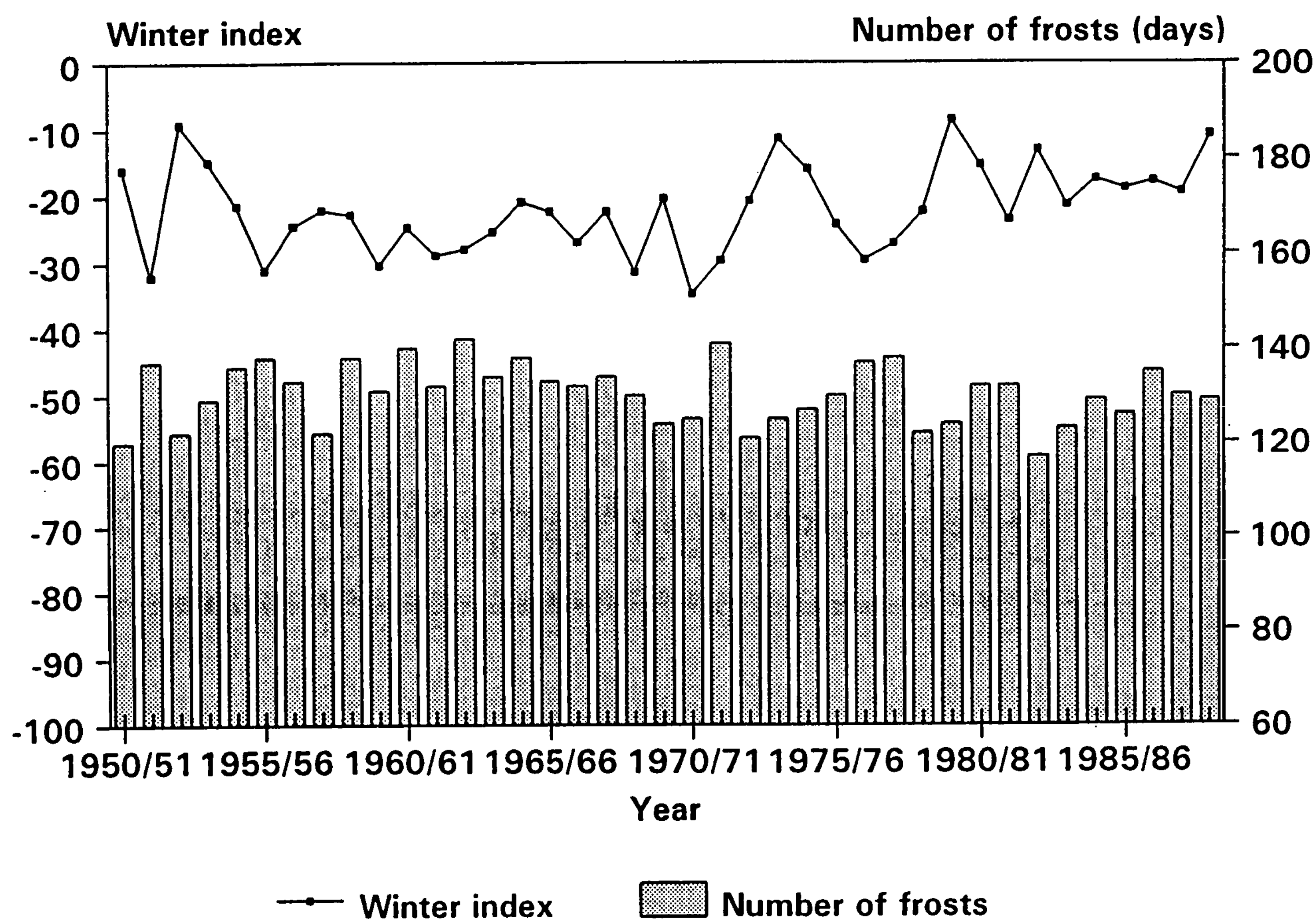

Figure 12. Winter index and number of air frosts (Portland, ME) (r = -0.56)

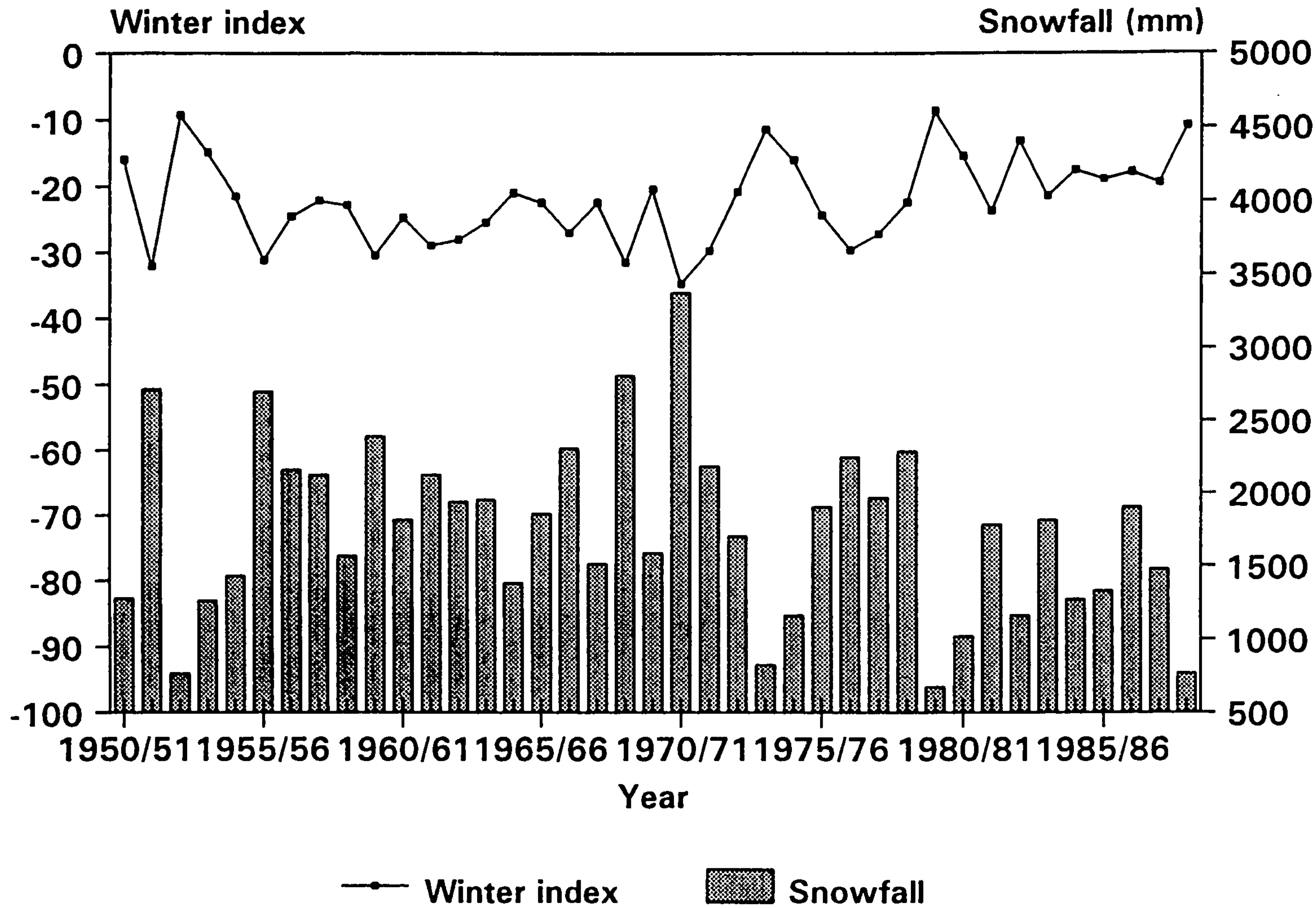

Figure 13. Winter index and snowfall (Portland, ME) (r=-0.94

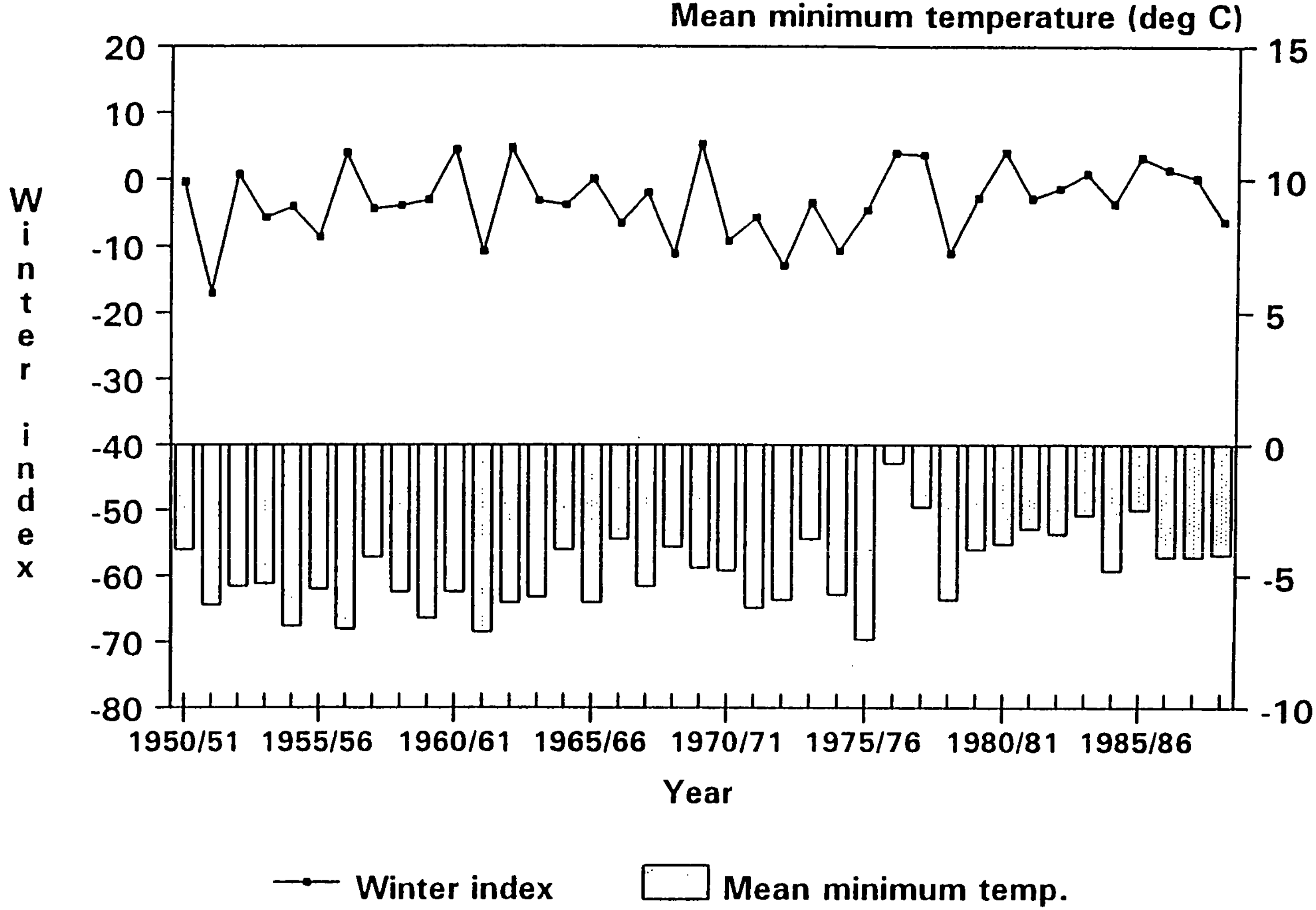

Figure 14. Winter index and mean minimum temperature (Reno, NV) (r=0.24)

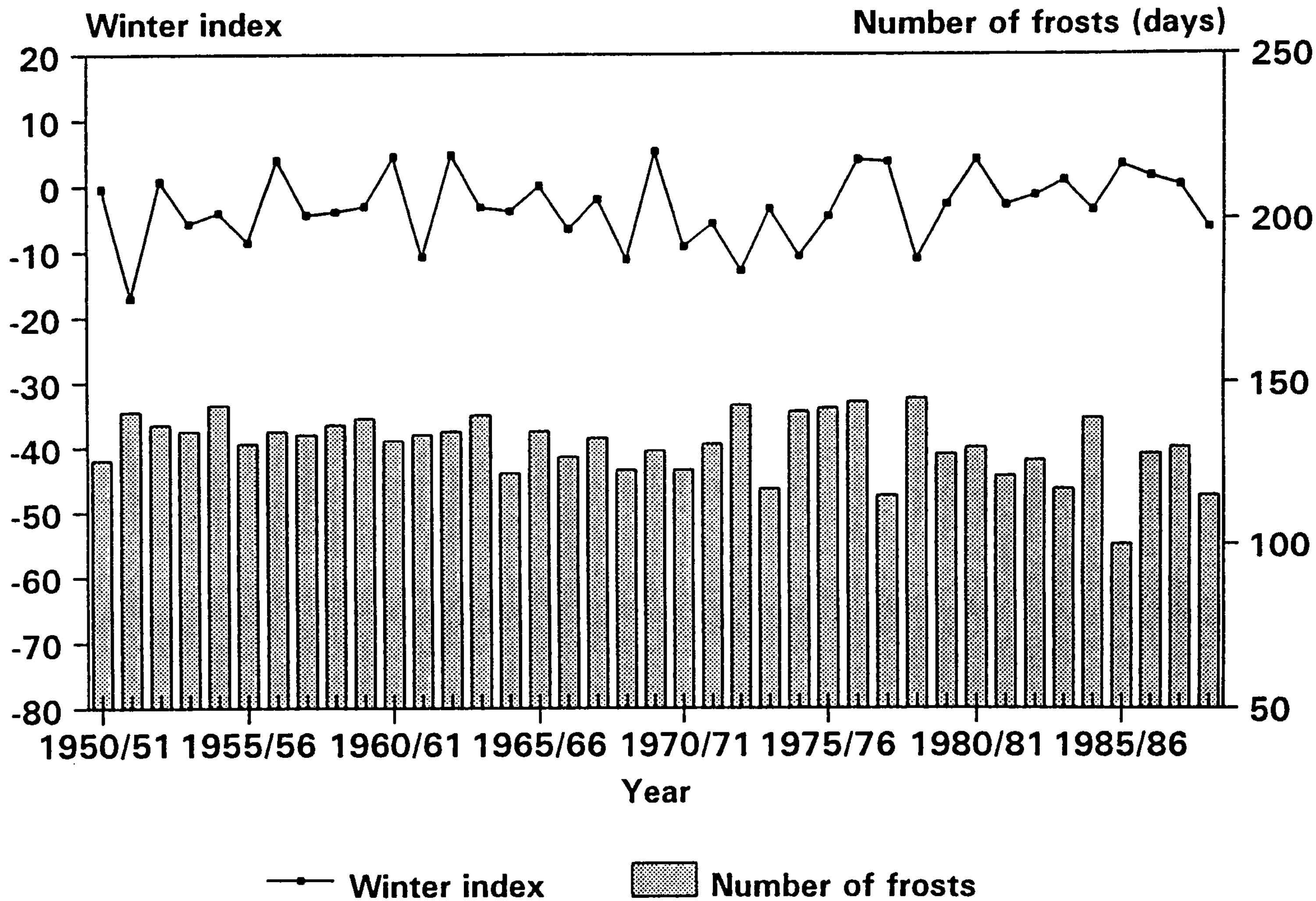

Figure 15. Winter index and number of air frosts (Reno, NV) (r=-0.31)

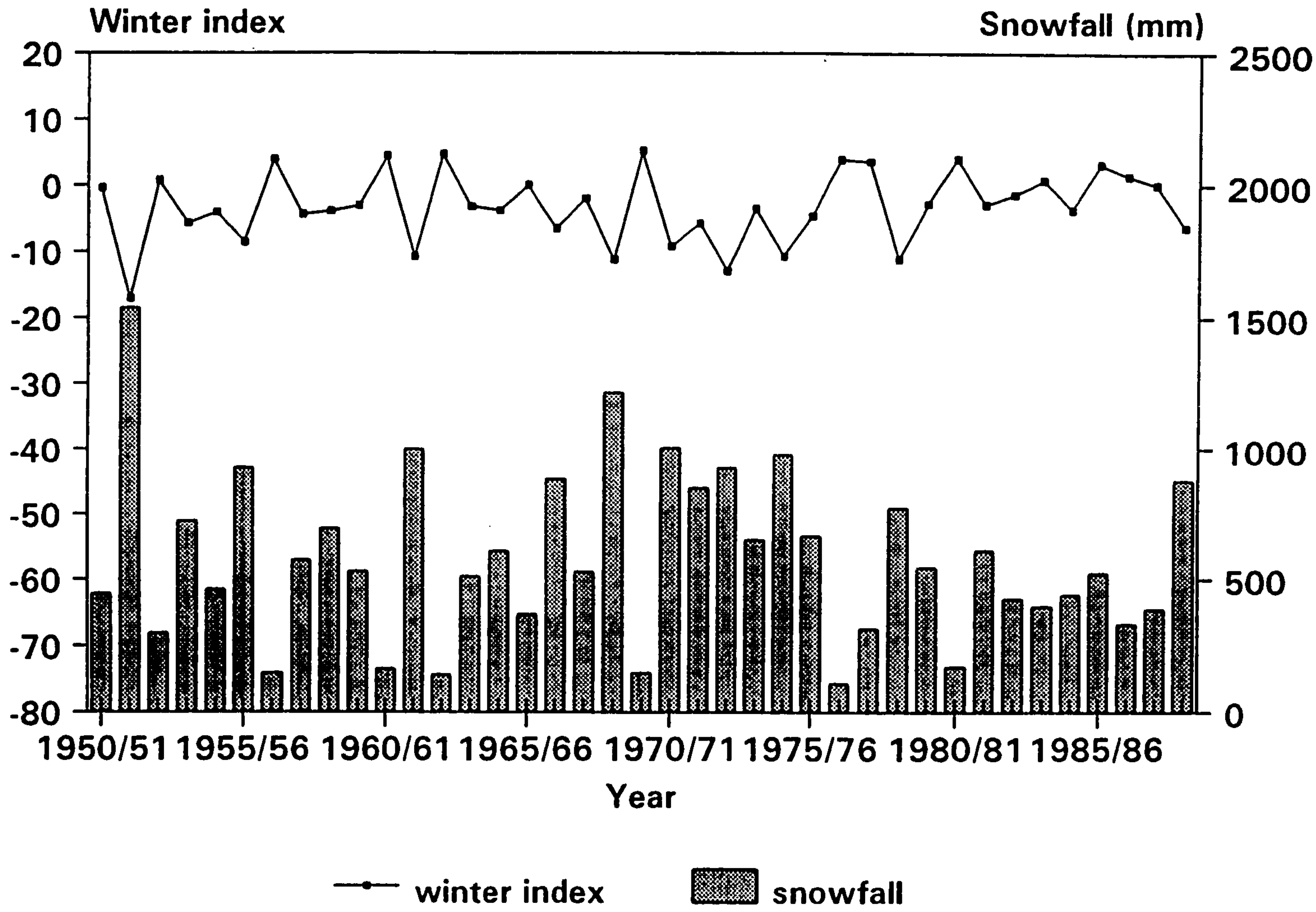

Figure 16. Winter index and snowfall (Reno, NV) (r=-0.94)

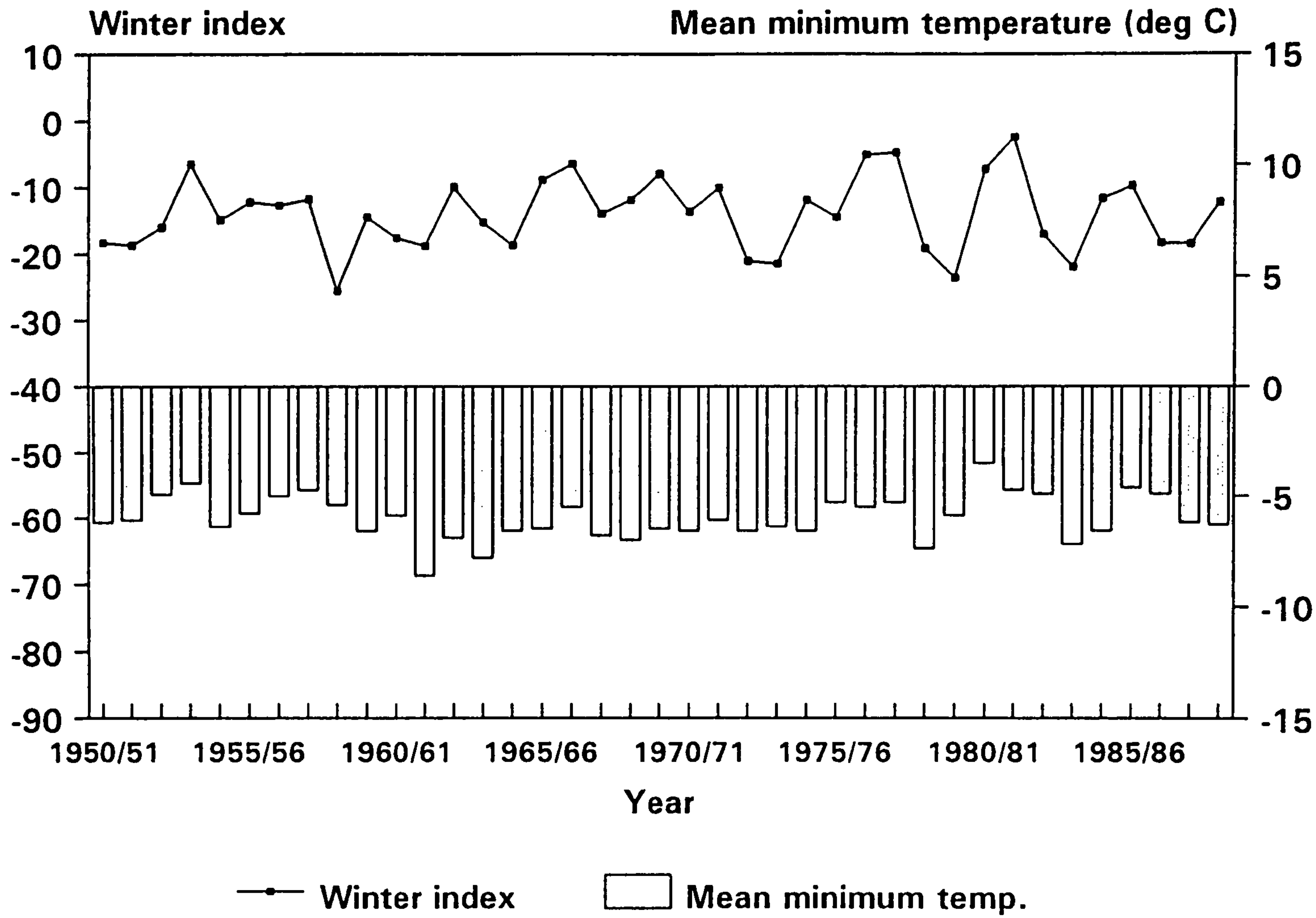

Figure 17. Winter index and mean minimum temperature (Denver, CO) (r=0.40)

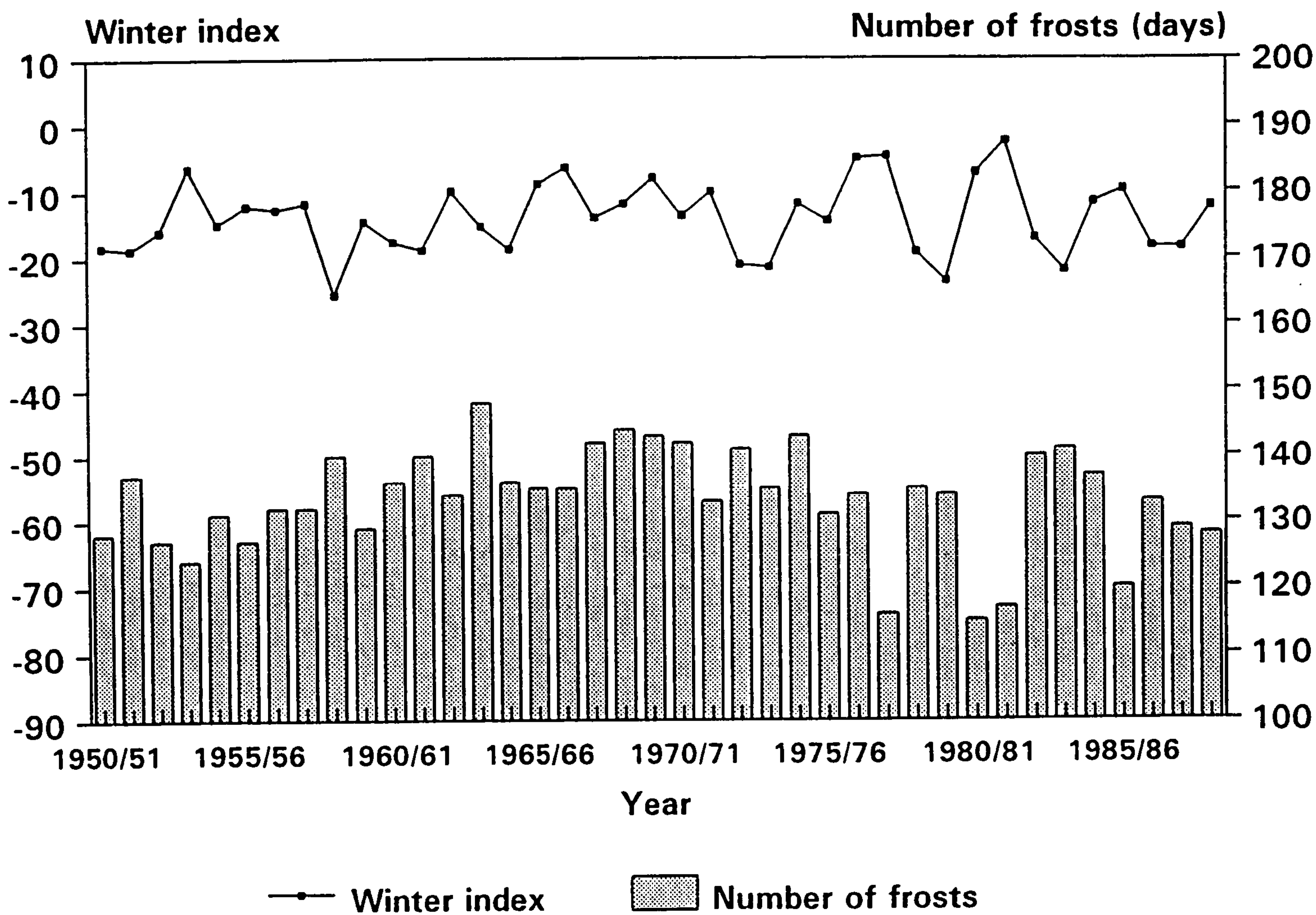

Figure 18. Winter index and number of air frosts (Denver, CO
(r = -0.48)

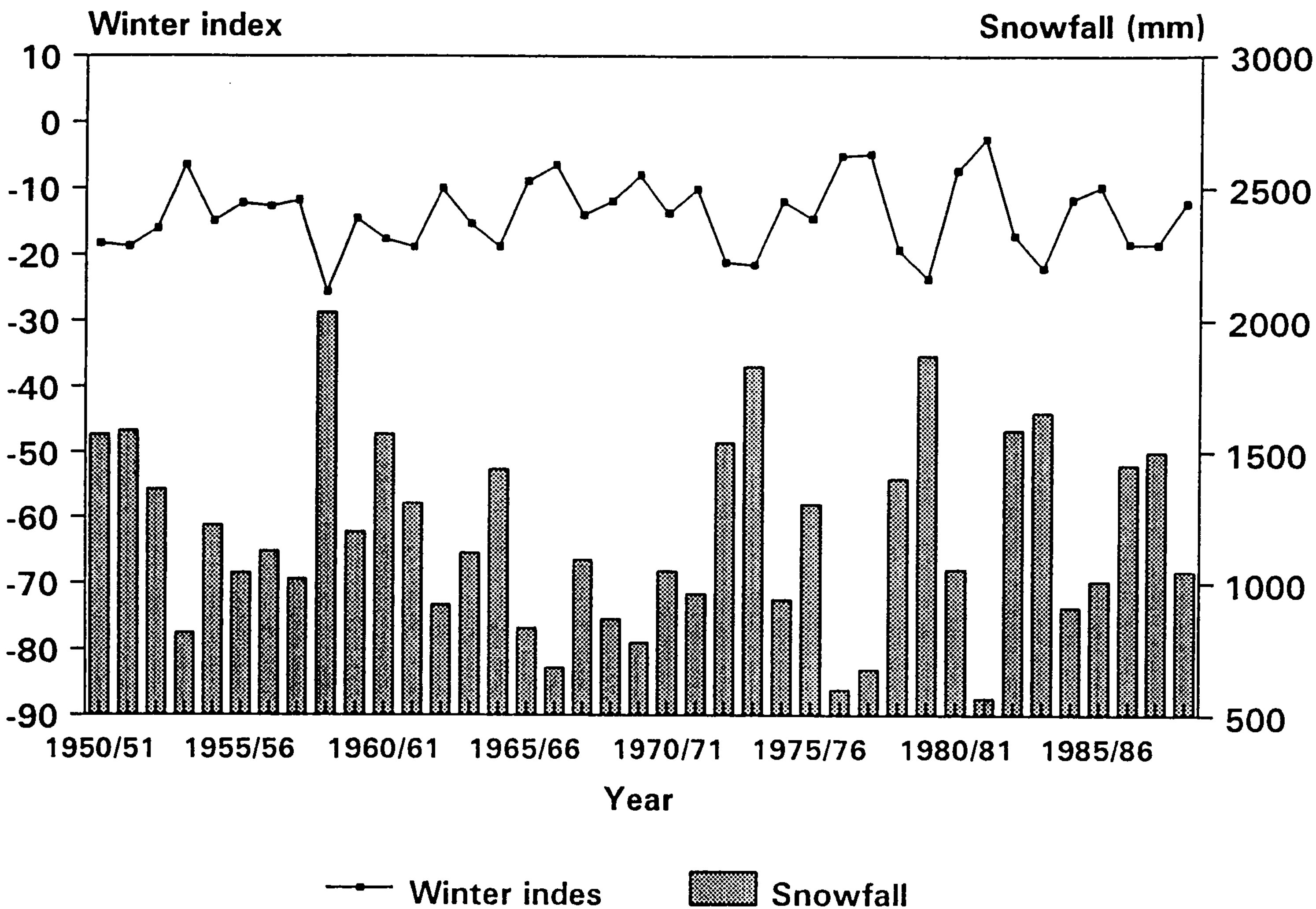

Figure 19. Winter index and snowfall (Denver, CO) (r = -0.95)

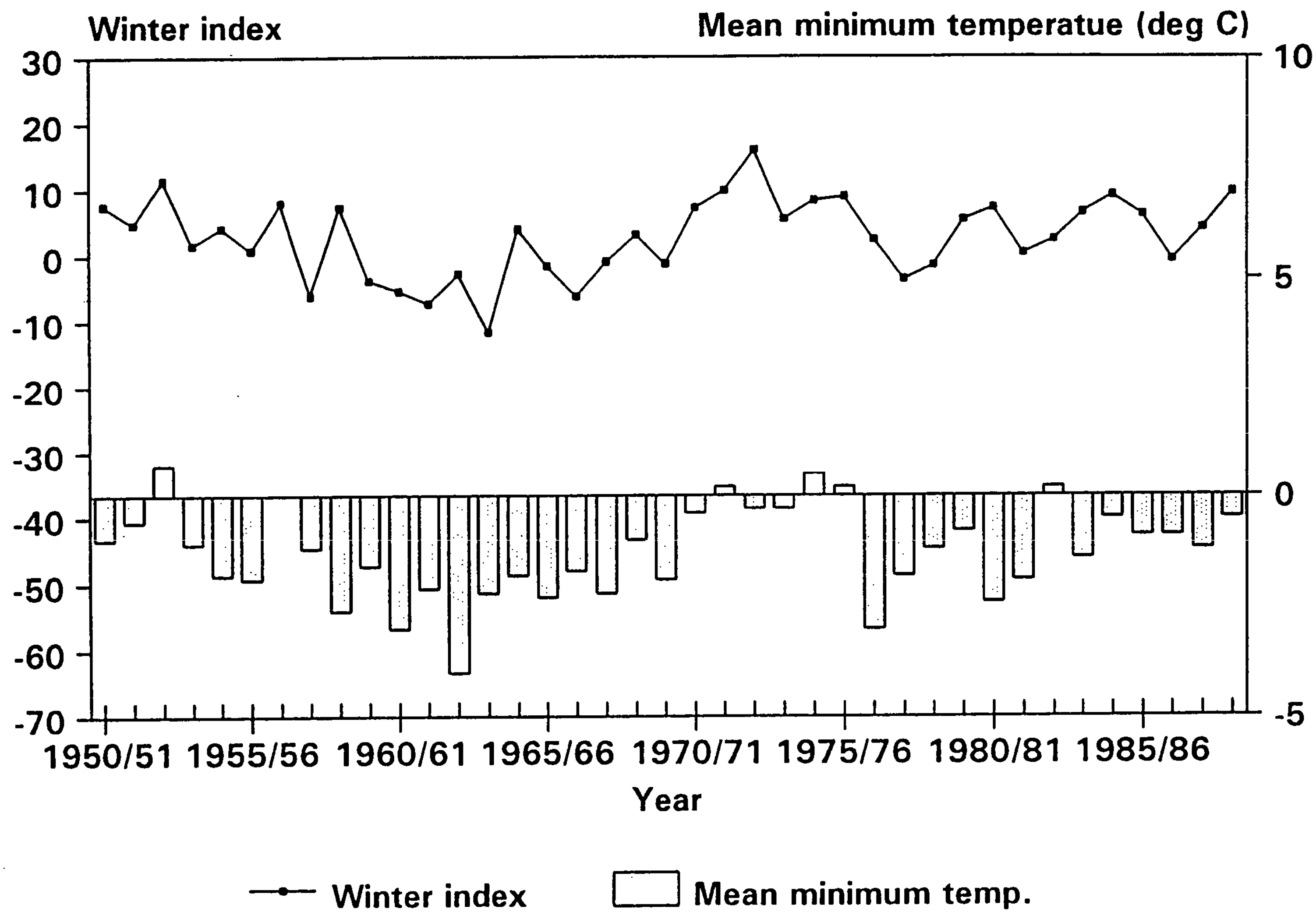

Figure 20. Winter index and mean minimum temperature (Baltimore, MD) (r=0.60)

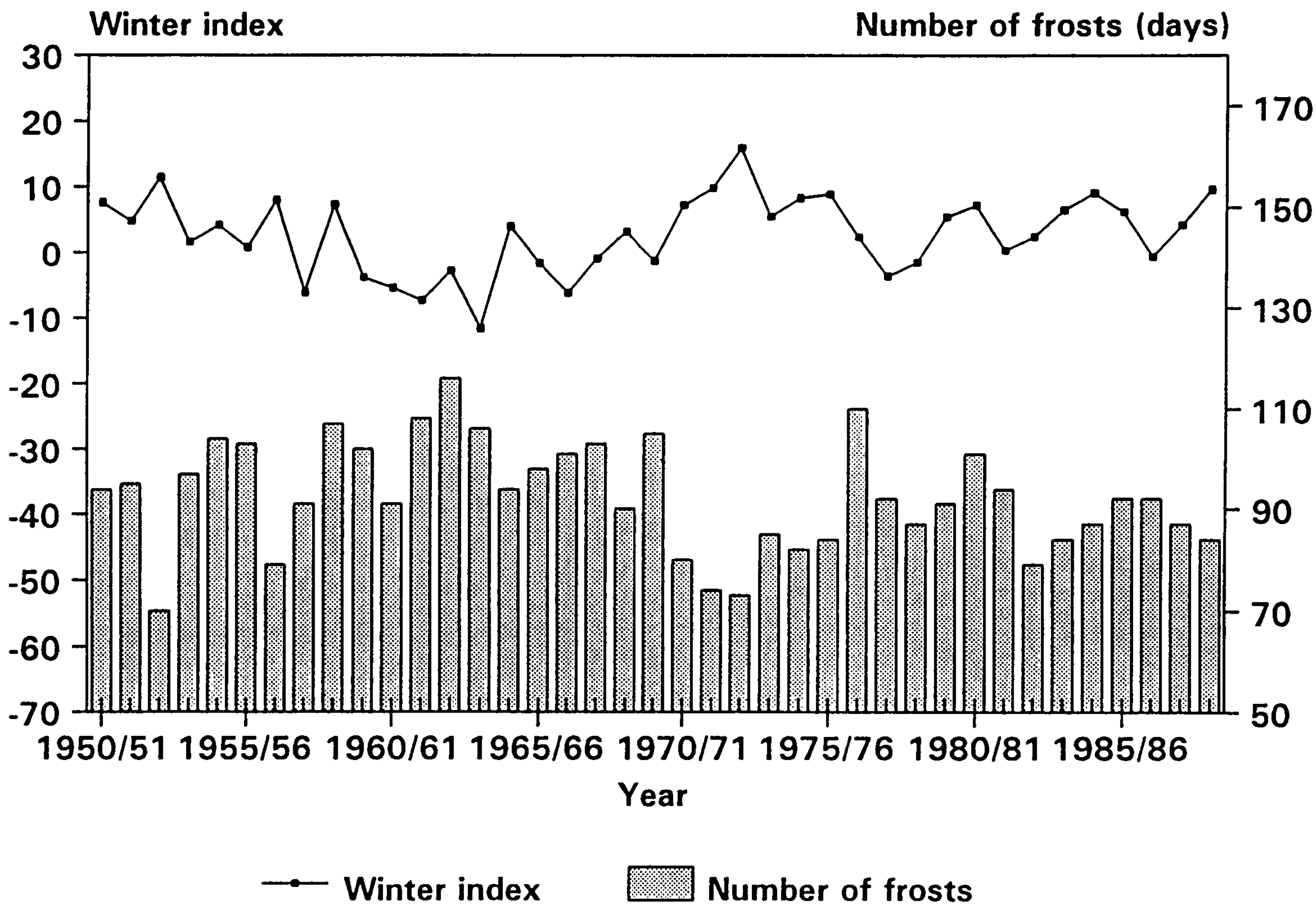

Figure 21. Winter index and number of air frosts (Baltimore, MD) (r = -0.62)

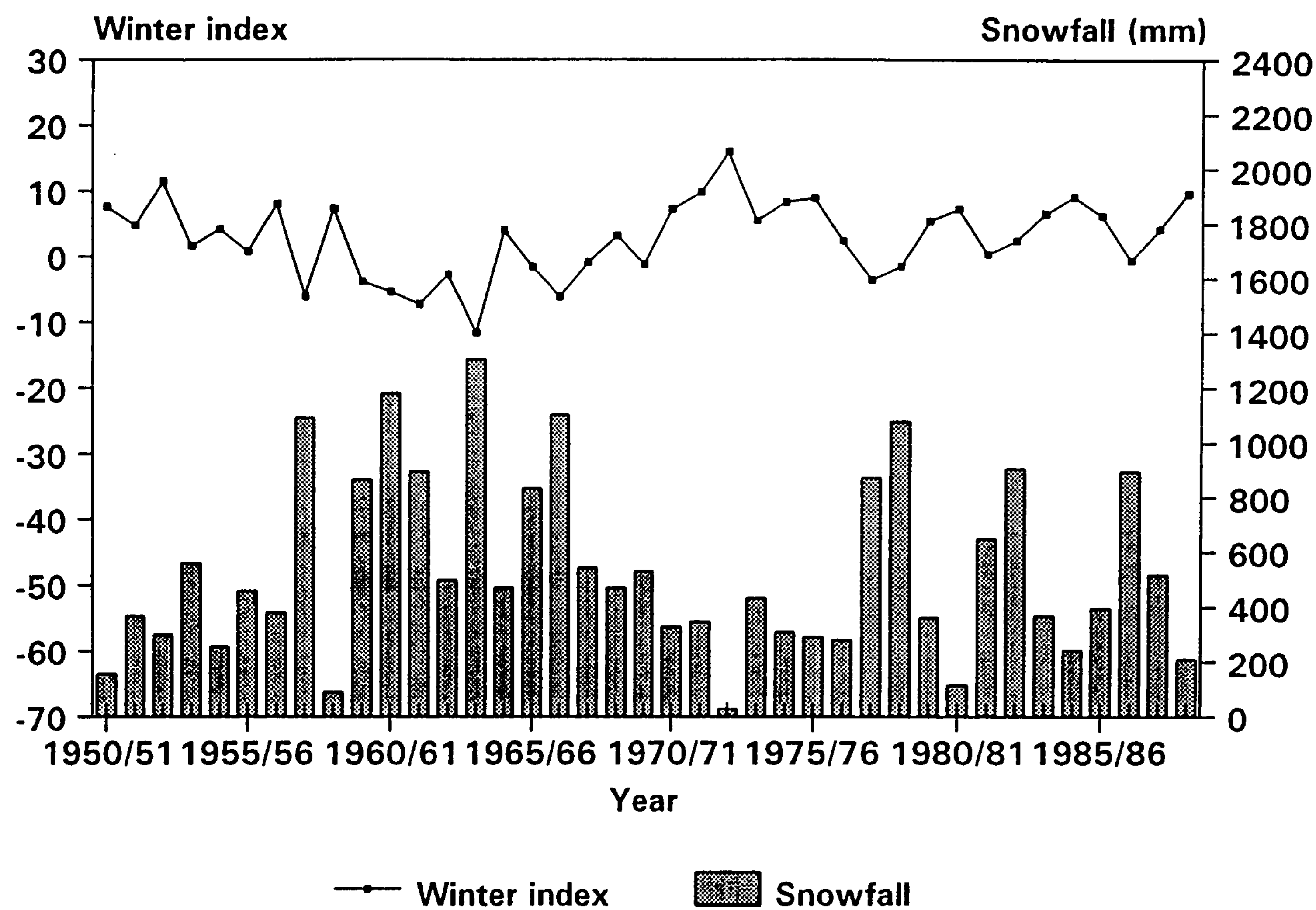

Figure 22. Winter index and snowfall (Baltimore, MD) (r = -0.88)

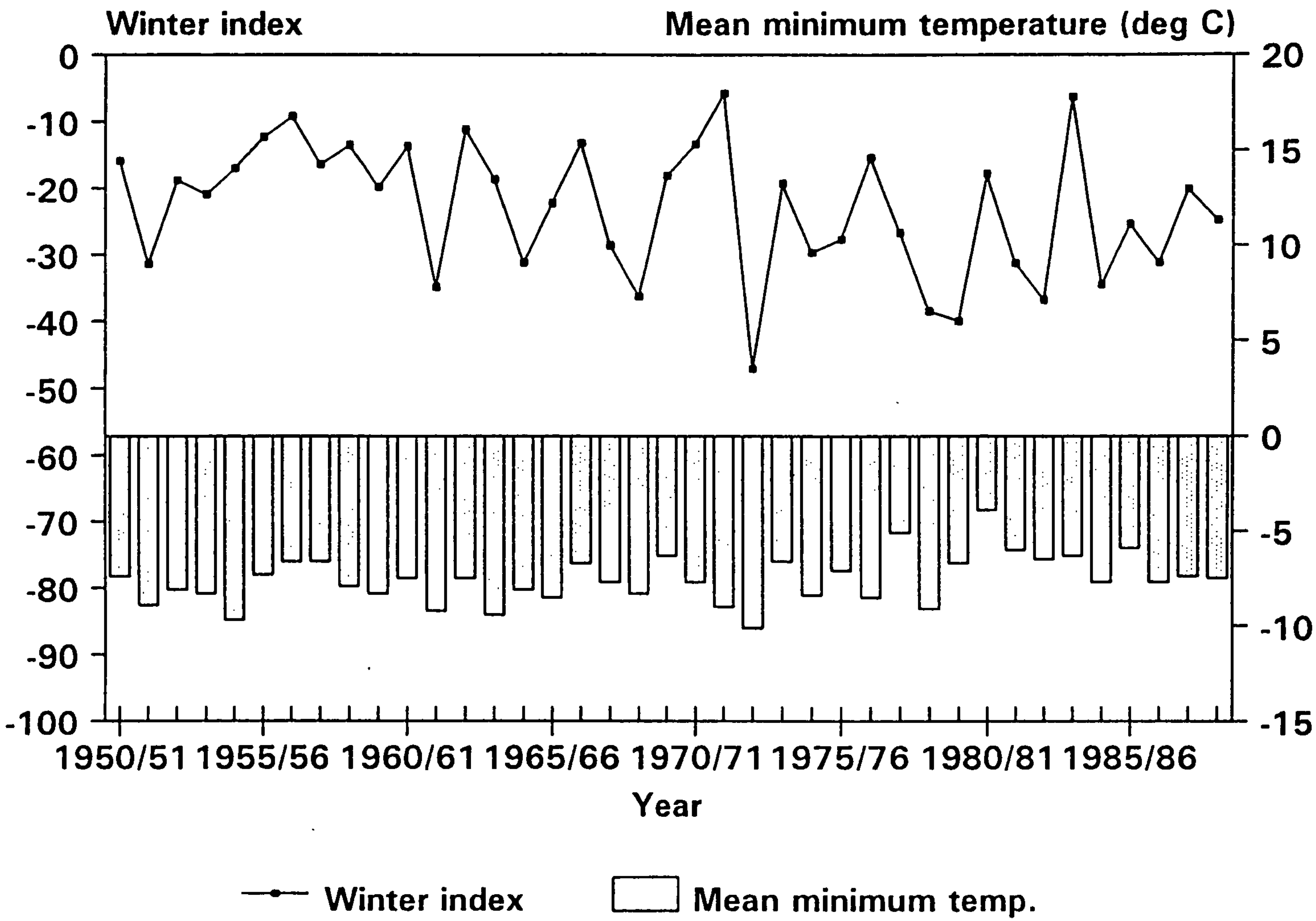

Figure 23. Winter index and mean minimum temperature (Flagstaff, AZ) (r=0.21)

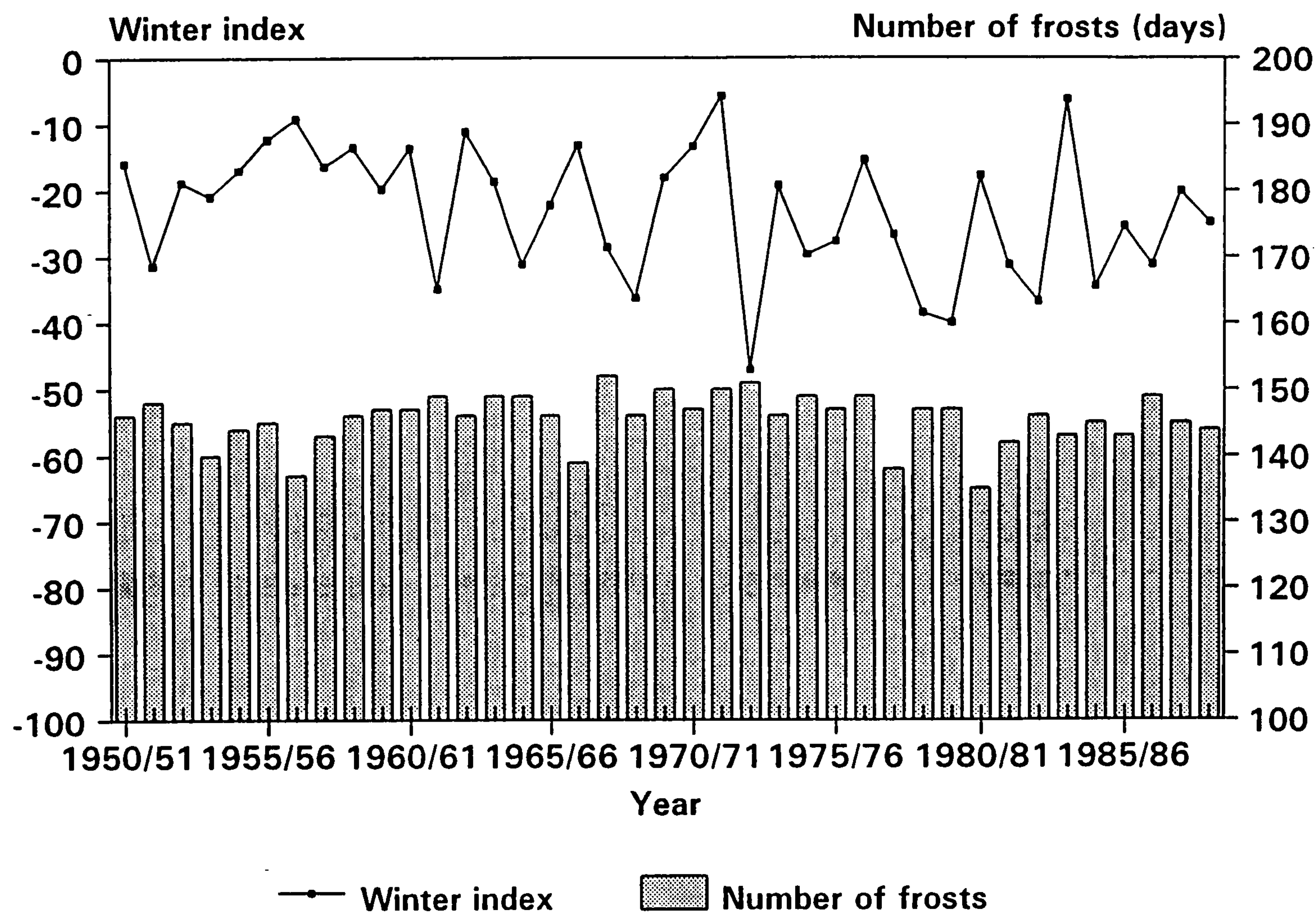

Figure 24. Winter index and number of air frosts (Flagstaff, AZ) (r = -0.29)

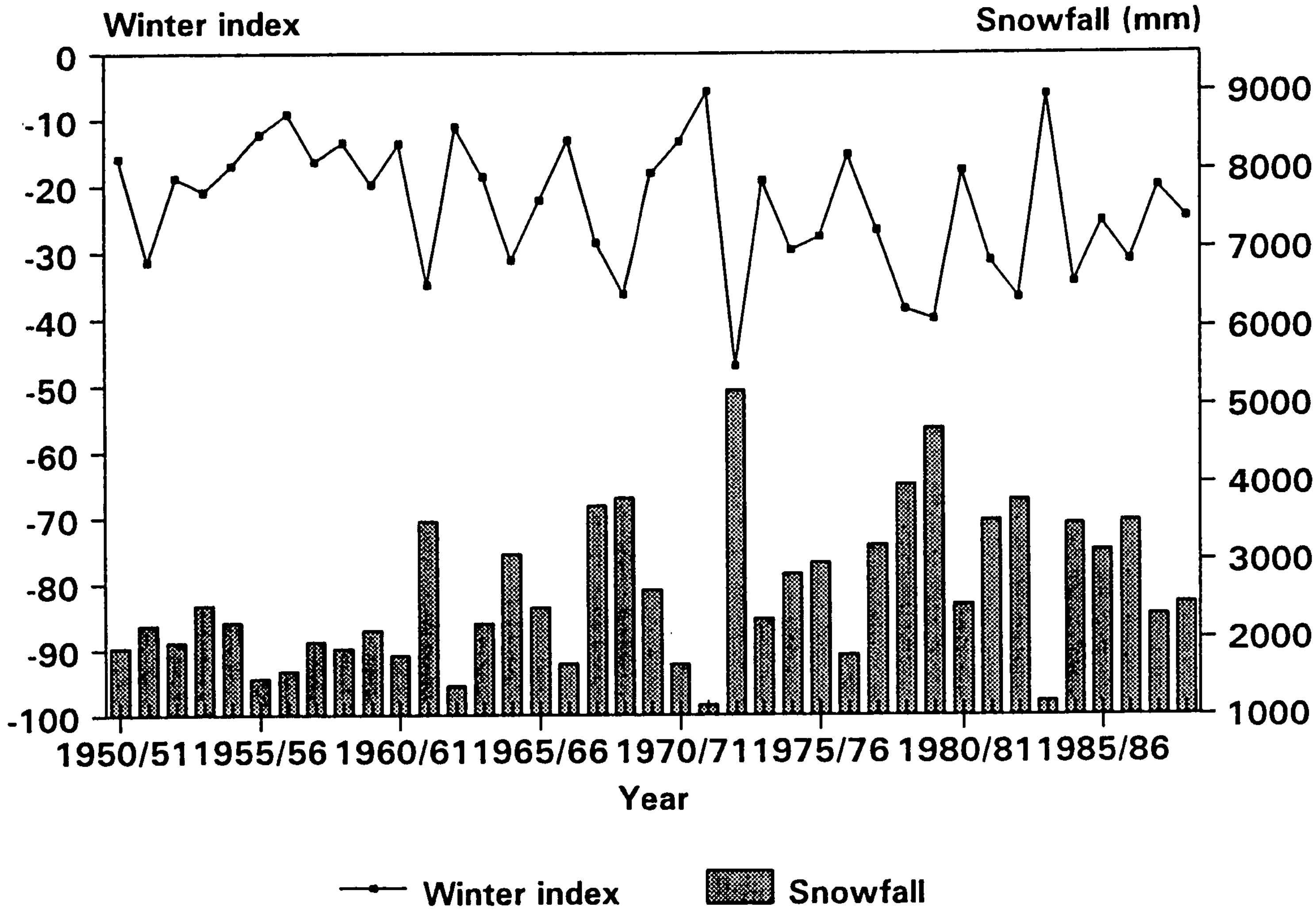

Figure 25. Winter index and snowfall (Flagstaff, AZ)
(r = -0.97)

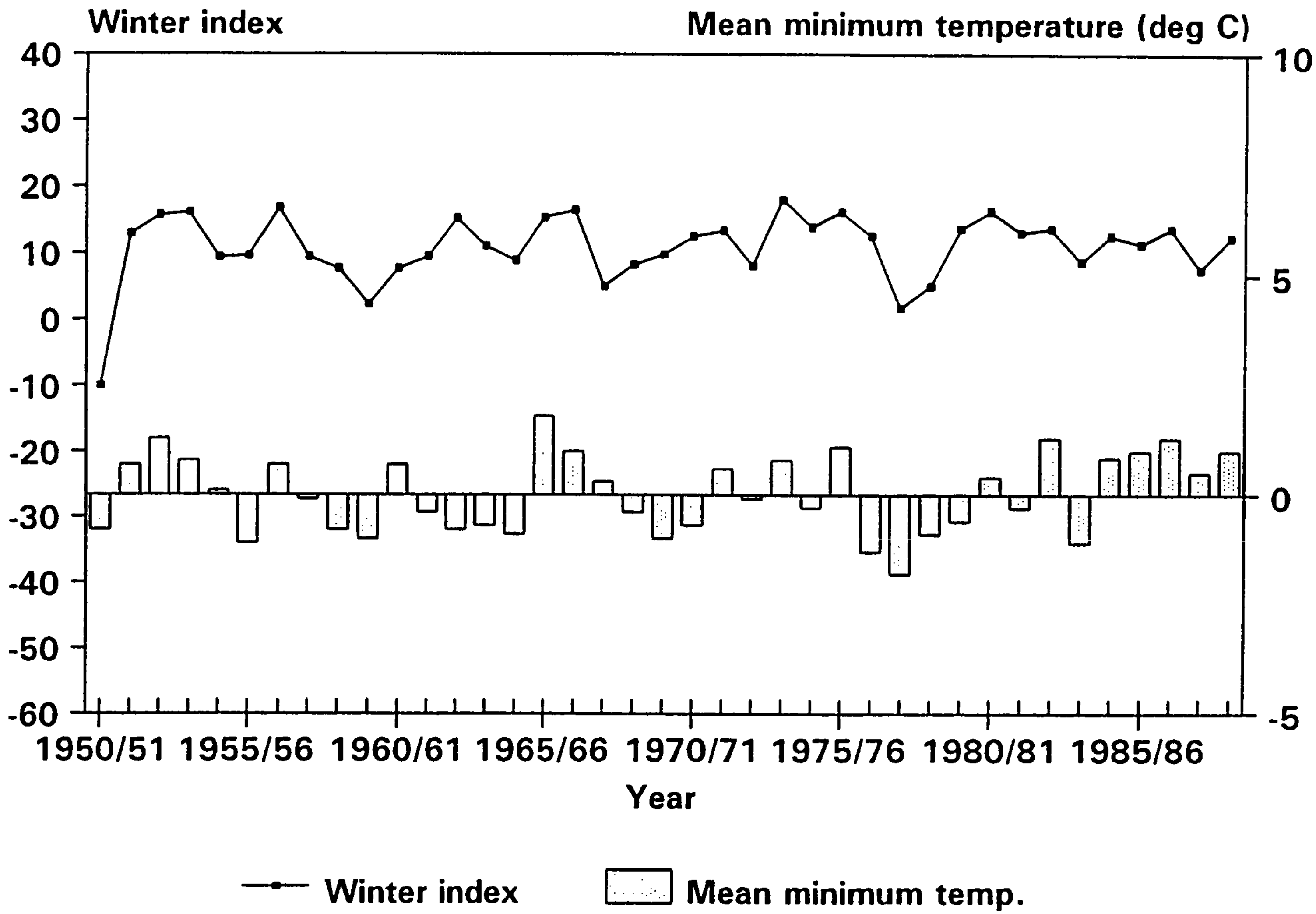

Figure 26. Winter index and mean minimum temperature (Oklahoma City, OK) (r=0.56)

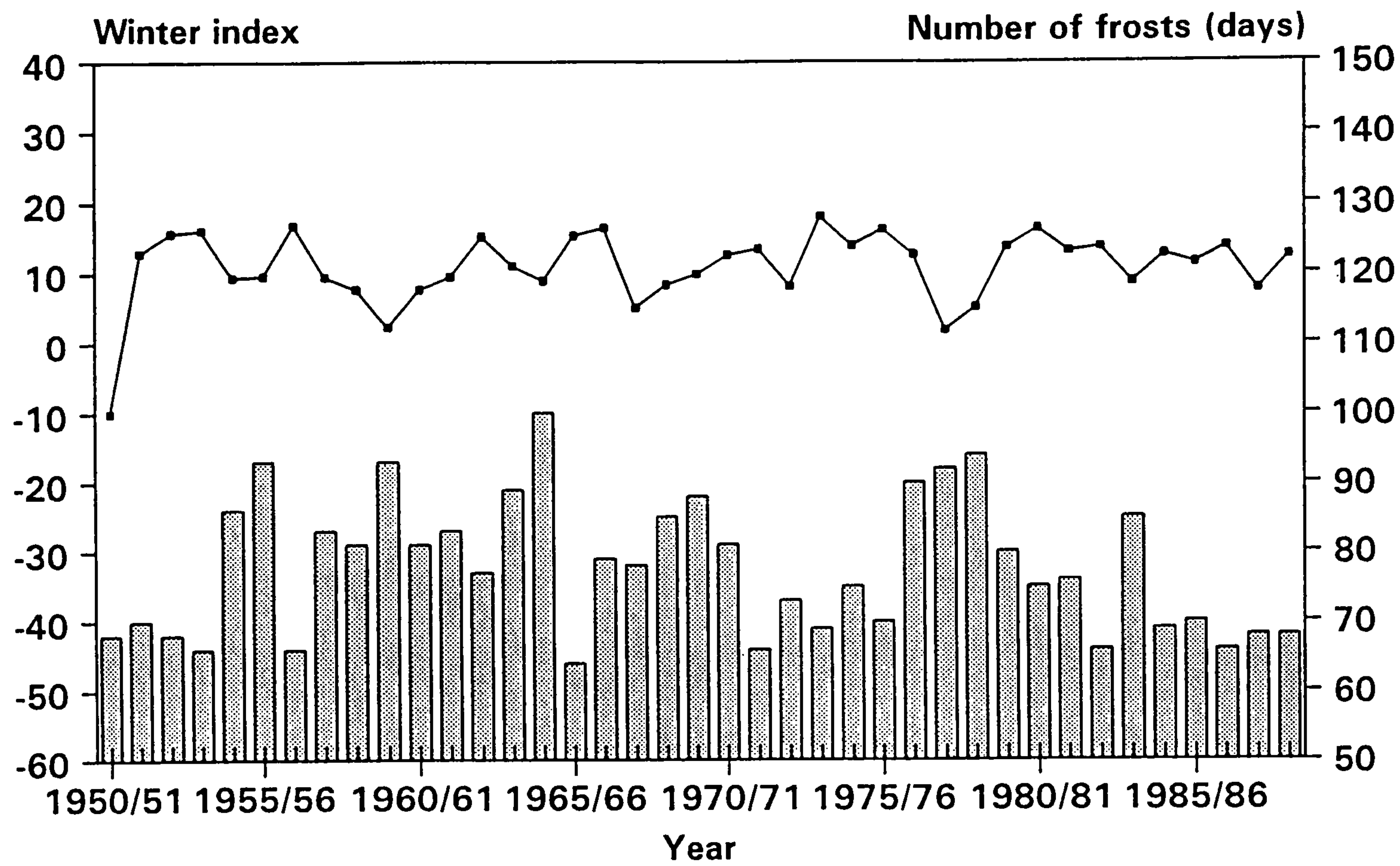

Figure 27. Winter index and number of air frosts (Oklahoma City, OK) (r = -0.39)

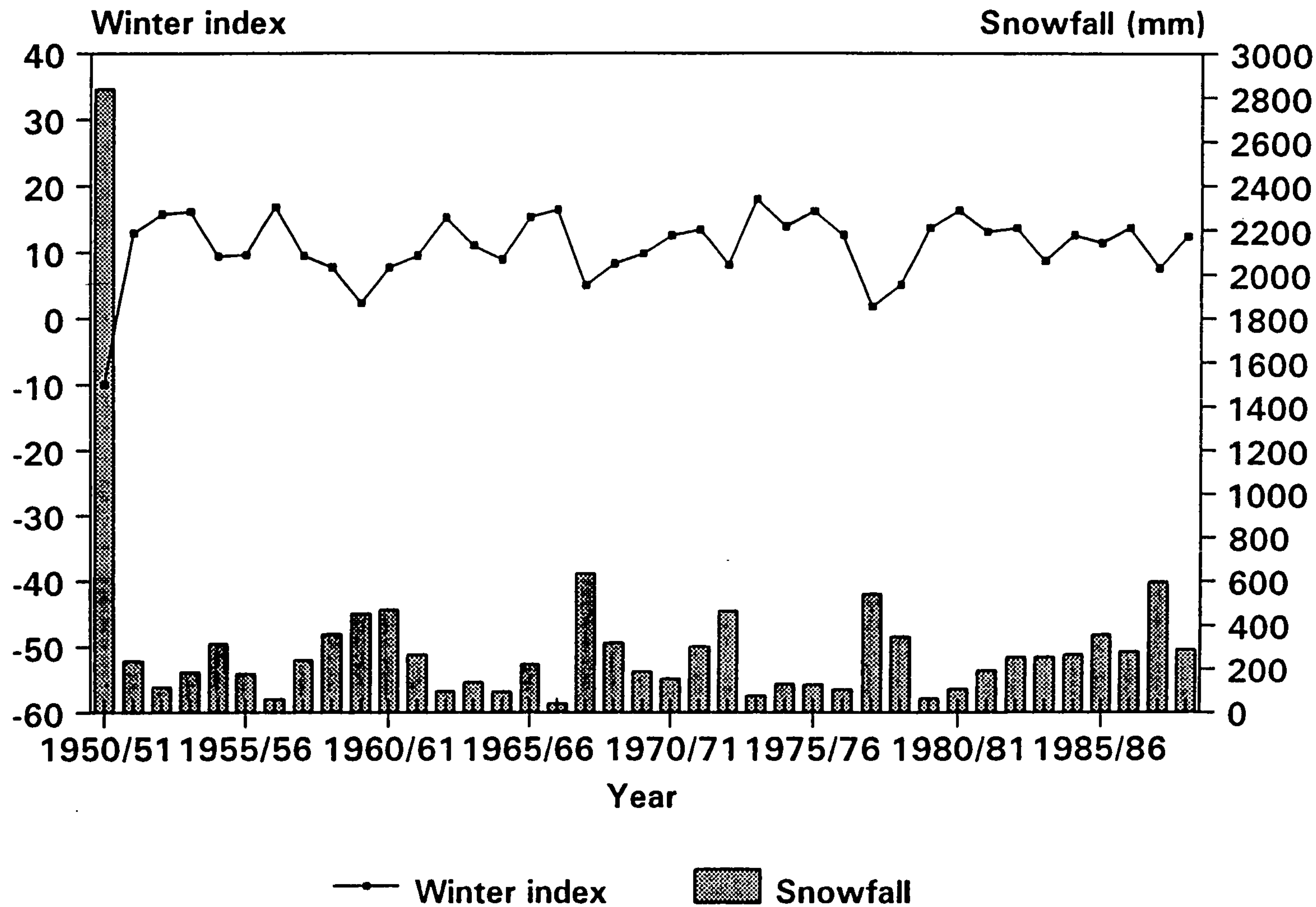

Figure 28. Winter index and snowfall (Oklahoma City, OK) (r = -0.81)

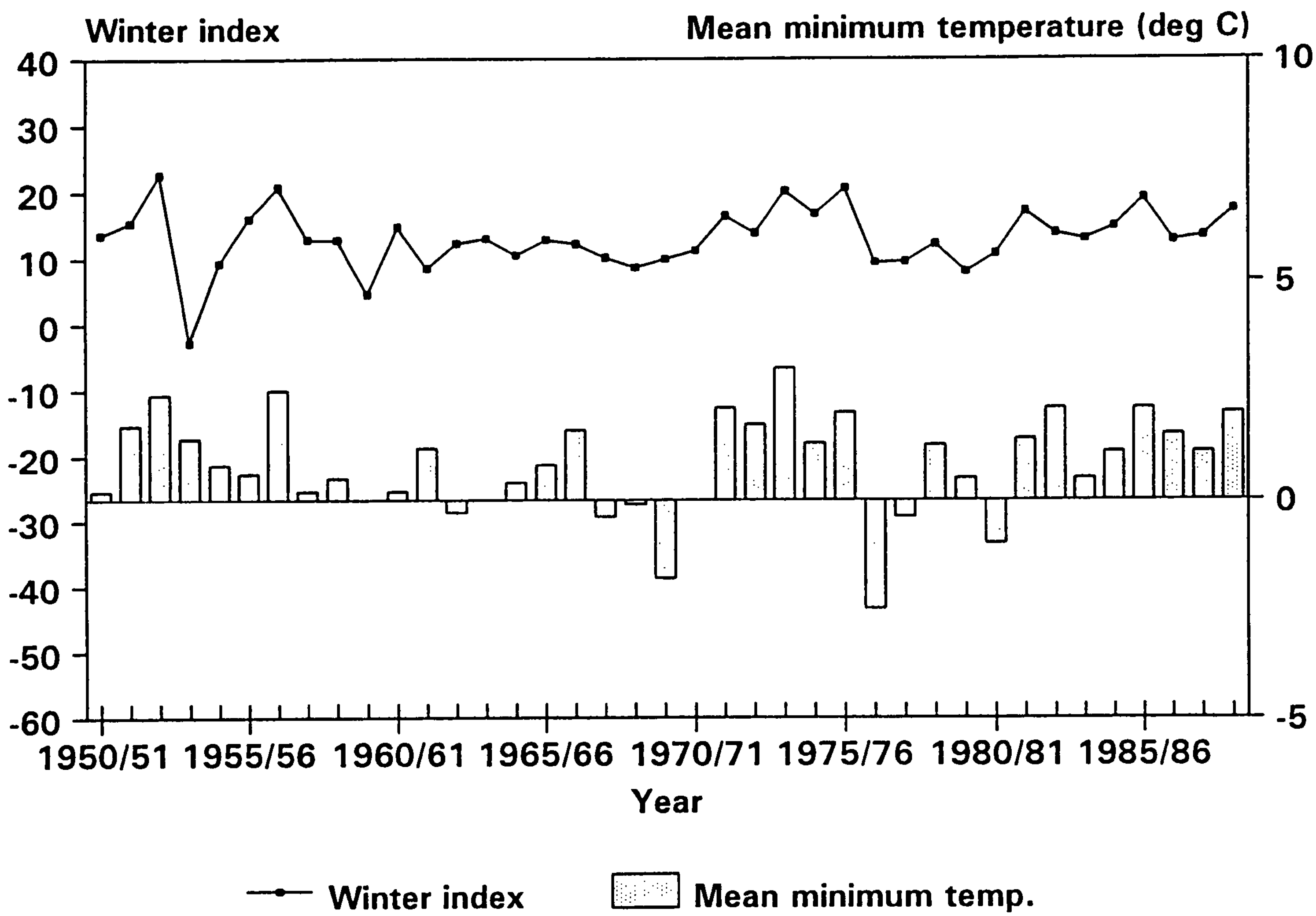

Figure 29. Winter index and mean minimum temperature (Raleigh Durham, NC) (r=0.53)

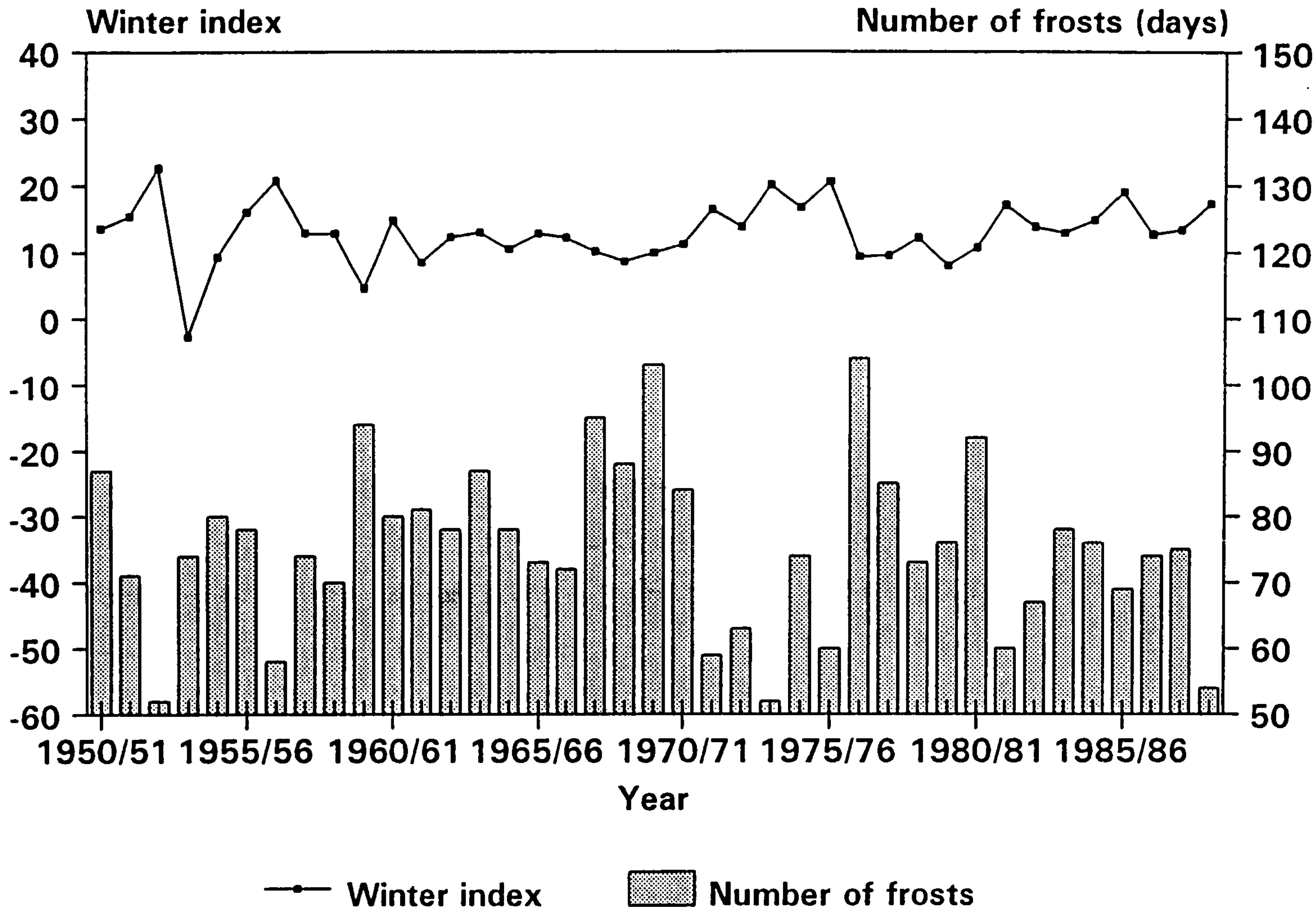

Figure 30. Winter index and number of air frosts
(Raleigh Durham, NC) (r = -0.63)

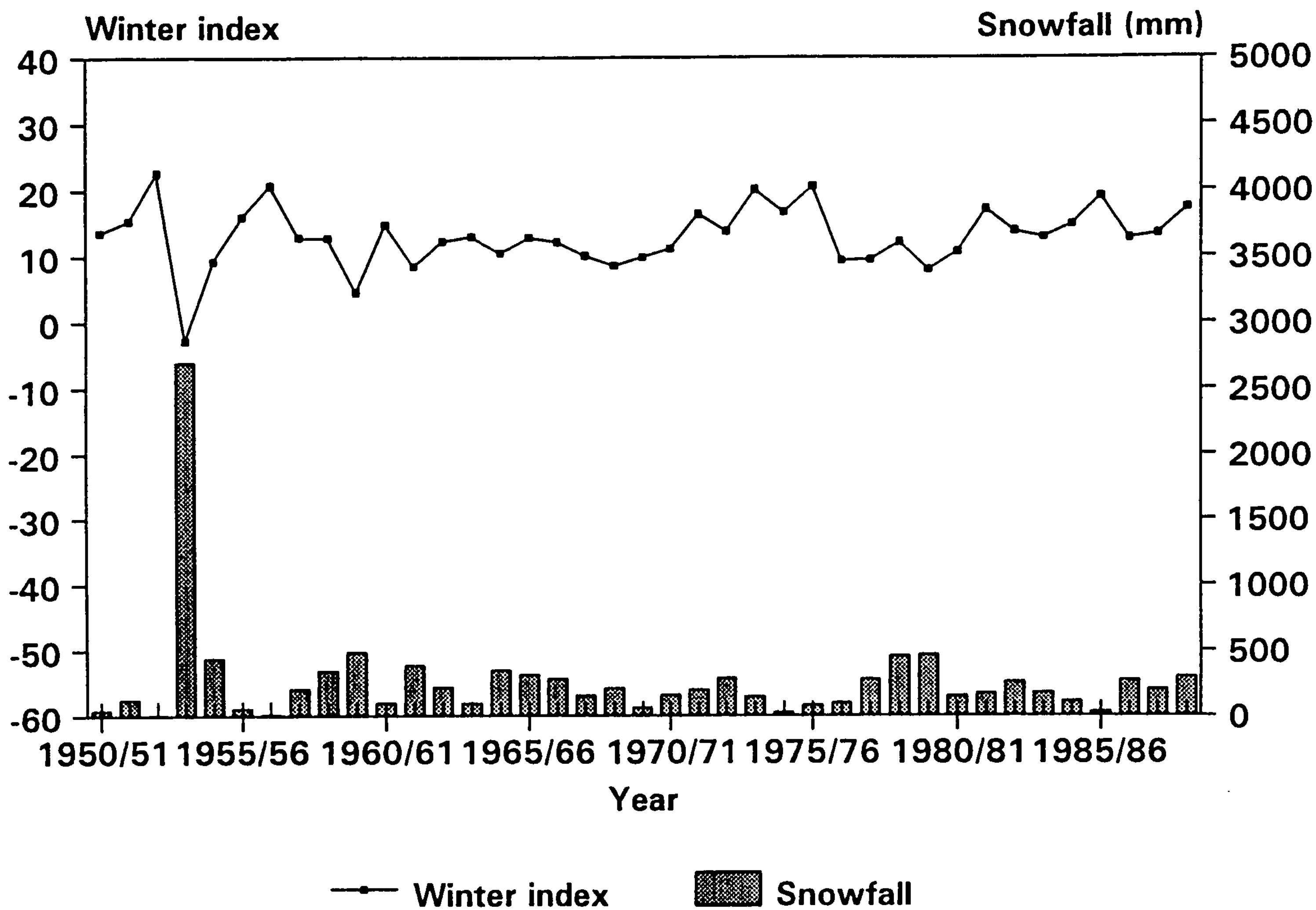

Figure 31. Winter index and snowfall (Raleigh Durham, NC)
(r = -0.71)

Appendix D

State Survey Results

This appendix presents a portion of the data obtained from questionnaires sent to all the states and the provinces of Canada. Data are as reported by each respondent.

Table 1. Snow and Ice Control Costs

State/ Province	Annual Costs ($ 1,000s)	Centerline Miles for Snow & Ice Control	Lane Miles for Snow & Ice Control	What Costs Are Not Included
AB	23,100	13,387	31,090	Cleanup, only highways included, no urban roadways.
AK	4,000	347	1,265	Costs for state highways only. No spring sand cleanup.
AL	200	11,000	NR	NR
AR	2,500	16,171	35,323	City and county.
CA	25,000	6,000	13,510	Includes only state highways. All costs associated with or created by snow/ice control activities are included.
CO	25,947	9,214	31,832	NR
CT	16,210	4,030	10,200	NR
DC	3,000	1,102	2,826	NR
GA	1,500	17,824	NR	City streets and county roads.
IA	16,000	10,481	24,880	NR
ID	5,735	4,950	11,122	City streets, county roads and spring sand cleanup are not included.

NR = No Response

Continued

Table 1 (continued). **Snow and Ice Control Costs**

State/ Province	Annual Costs ($ 1,000s)	Centerline Miles for Snow & Ice Control	Lane Miles for Snow & Ice Control	What Costs Are Not Included
IL	24,500	16,770	45,404	Only snow and ice control costs are included. None of the above items.
IN	8,900	11,285	28,203	Tracks labor and materials costs. Equipment costs are not tracked. Interstate, U.S., and state routes are included.
KS	5,000	9,800	20,000	City maintained connecting links, county roads, spring sand clean-up.
KY	7,346	27,316	58,909	NR
LA	625	17,215	38,894	City streets, parish roads, spring cleanup.
MA	35,000	2,881	12,540	NR
MB	18,000	12,210	28,739	NR
MD	14,000	5,183	14,895	NR
ME	17,635	3,811	7,988	NR
MI	27,000	10,272	28,299	NR
MN	25,660	12,102	29,085	NR
MO	18,600	32,285	73,640	NR
MT	5,000	8,117	19,006	NR
NC	8,500	76,549	162,525	NR
ND	2,250	7,332	16,561	NR
NE	5,950	10,808	21,707	NR
NF	24,000	5,200	10,500	NR
NH	16,000	3,693	8,068	NR
NJ	10,000	2,300	10,300	NR
NT	1,000	1,560	5,020	Removal of snow from culvert inverts, spring sand cleanup and stockpiling of winter chemicals, inclement weather.
NV	3,111	5,470	12,727	NR
NY	78,000	15,735	42,083	Cities, towns, villages, and counties.
OK	2,457	12,246	28,354	NR
ON	115,000	13,385	32,312	Non-Province roads.
OR	13,400	7,678	19,561	NR
PA	90,000	44,000	73,000	NR
SC	1,500	17,850	42,200	NR
SD	2,775	7,876	18,602	NR

NR = No Response

Table 1 (continued). Snow and Ice Control Costs

State/ Province	Annual Costs ($ 1,000s)	Centerline Miles for Snow & Ice Control	Lane Miles for Snow & Ice Control	What Costs Are Not Included
SK	13,200	15,400	31,700	City streets and county (rural municipality) roads.
TX	4,500	76,000	180,000	NR
				NR
UT	7,500	5,794	15,068	NR
VA	32,123	53,855	115,096	NR
VT	10,050	3,046	6,203	NR
WA	15,480	6,973	17,307	NR
WV	17,000	26,993	42,446	NR
WY	9,000	6,500	16,200	NR
YT	4,000	1,980	3,960	Overhead costs, camp operations, room & board, etc.

Table 2. Snow and Ice Control Overtime

State/ Province	% of Highway Maint. Budget for Overtime	Highest % of Overtime Pay Last 10 Yrs	Lowest % of Overtime Pay Last 10 Yrs
AB	5	NR	NR
AK	5	8	3
AL	5	NR	NR
AR	2	2	1
CA	0	0	0
CO	2	NR	NR
CT	13	12	9
IA	3	4	3
ID	5	6	3
IL	3	4	2
KS	2	NR	NR
KY	6	10	4
LA	0	3	0
MA	9	20	7
MD	7	NR	NR
MI	2	3	1
MN	2	NR	NR

NR = No Response

Continued

Table 2 (continued). Snow and Ice Control Overtime

State/ Province	% of Highway Maint. Budget for Overtime	Highest % of Overtime Pay Last 10 Yrs	Lowest % of Overtime Pay Last 10 Yrs
MO	2	NR	NR
MT	4	4	4
NE	0	0	0
NF	2	4	2
NH	8	8	6
NJ	10	8	7
NT	1	1	1
NV	4	4	3
ON	3	NR	NR
OR	5	8	3
PA	1	1	1
SC	5	7	3
SK	5	7	4
VA	2	2	1
WV	5	NR	NR
YT	6	NR	NR

NR = No Response

Table 3. Snow and Ice Control Materials Usage

State Prov.	Tons of Salt	Salt Tons/ Mile	Tons Dry Chemical	Dry Chem. Tons/Mile	Gals. Liq. Chemical	Liq. Chem. Gals./Mile	Tons of Abrasives	Abrasives Tons/Mile	Chemicals, Amounts and Costs
AB	180,000	300.00	0	0.00	0	0.00	800,000	300.00	Insignificant
AK	2,400	NR	NR	NR	NR	NR	39,000	NR	Calcium chloride: $382/ton
AL	0	0.00	NR	NR	0	0.00	NR	NR	NR
AR	2,269	0.13	452	0.03	0	0.00	19,634	1.11	NR
CA	29,400	3.40	1,075		10,400		166,000	NR	1,075 ton CMA, ton = $657.50 + tax. 300 gal. calcium chloride, gallon = $0.77 + tax. 42 gal freezgard + PCl, ton = $99.60 + tax
CO	7,365	NR	12	NR	0	0.00	490,840	NR	Calcium chloride: $13.40 per sack
CT	80,000	7.84	NR	NR	—N	R—	200,000	19.61	NR
DC	20,000	500.00	NR	NR	4,000	NR	1,000	NR	4,000 gals of calcium chloride at $1.33 per gal
GA	17,000	NR	100	NR	NR	NR	15,000	NR	100 tons calcium chloride (bags) at $350/ton
IA	65,742	264.00	3,057	0.12	5,908	0.24	141,775	5.70	NR
ID	170	0.01	NR	NR	38,000	36.00	371,650	33.42	Freezgard liquid deicer: 688-55 gal drums, cost approx. $80/ton. Qwiksalt + PCI granular salt substitute: 137 tons @ approx. $115/ton

NR = No Response

Continued

Table 3 (continued). Snow and Ice Control Materials Usage

State Prov.	Tons of Salt	Salt Tons/ Mile	Tons Dry Chemical	Dry Chem. Tons/Mile	Gals. Liq. Chemical	Liq. Chem. Gals./Mile	Tons of Abrasives	Abrasives Tons/Mile	Chemicals, Amounts and Costs
IL	319,340	7.00	720	0.02	325,400	7.00	20,000	0.04	Calcium chloride liquid at $0.50/gallon; bagged at $200/ton
IN	254,861	9.04	72	NR	60,628	2.15	116,581	4.13	Calcium chloride 143,020 lbs at $0.07/lb dry; liquid 60,628 gal at $0.27/gal
KS	60,000	NR	0	0.00	0	0.00	70,000	NR	None
KY	82,000	2.90	1,000	NR	56,000	NR	0	0.00	Liquid calcium chloride: 56,000 gal @ $0.65/gal
LA	790	0.02	NR	NR	6,000	0.15	2,000	0.05	Ethylene glycol: 6,000 gals @ $6/gal
MA	206,000	16.43	0	0.00	0	0.00	115,000	9.17	NR
MB	34,000	2.00	0	0.00	0	0.00	88,000	5.70	NR
MD	NR	2.00	120	NR	NR	NR	NR	NR	NR
ME	60,000	7.50	194	0.07	13,056	1.60	480,000	60.00	NR
MI	300,000	10.60	NR	NR	NR	NR	200,000	7.10	NR
MN	132,000	4.54	294	0.01	9,156	0.31	280,000	9.63	NR
MO	100,000	0.10	5,000	NR	380,000	0.50	200,000	0.10	NR
MT	NR	NR	NR	NR	NR	NR	37,500	NR	NR
NC	51,325	2.20	0	0.00	0	0.00	NR	NR	NR
ND	9,000	NR	0	0.00	200,000	NR	75,000	NR	NR
NE	26,000	NR	850	NR	19,000	NR	82,350	NR	NR
NF	173,000	23.00	NR	NR	NR	NR	180,000	17.00	NR
NH	130,249	16.41	800	0.01	0	0.00	159,860	19.81	NR
NJ	67,200	7.20	NR	NR	450,000	46.90	3,770	NR	NR

NR = No Response

Table 3 (continued). Snow and Ice Control Usage

State Prov.	Tons of Salt	Salt Tons/ Mile	Tons Dry Chemical	Dry Chem. Tons/Mile	Gals. Liq. Chemical	Liq. Chem. Gals./Mile	Tons of Abrasives	Abrasives Tons/Mile	Chemicals, Amounts and Costs
NT	965	0.26	30	0.25	0	0.00	5,125	0.40	50/50 Calcium chloride/ sodium chloride blend. 32 tons, total cost $20,400
NV	11,352	0.90	50	NR	NR	NR	64,200	NR	NR
NY	665,000	16.00	NR	NR	NR	NR	780,000	19.00	NR
OK	60,000	2.00	NR	NR	NR	NR	300,000	10.00	NR
ON	638,000	0.15	0	0.00	0	0.00	1,100,000	0.50	CMA used experimentally only; cost ±$900/ton
OR	125	0.04	1	NR	3,381	NR	0	0.00	NR
PA	500,000	NR	NR	NR	NR	NR	900,000	NR	NR
SC	2,800	0.20	140	NR	NR	NR	8,500	0.60	NR
SD	11,489	NR	156	NR	NR	NR	94,088	NR	Sodium chloride: 12,479 tons = $332,932. Calcium chloride: 258 tons = $65,967
SK	58,000	NR	NR	NR	10,000	NR	60,000	NR	Liquid calcium chloride @ $1.30 (Cdn) per U.S. gallon
TX	7,000	0.04	NR	NR	NR	NR	100,000	0.56	NR
VA	110,957	3.70	1,293	NR	0	0.00	254,397	NR	NR
VT	89,000	14.00	NR	NR	NR	NR	125,000	19.00	NR
WA	7,587	0.20	2,376	0.02	8,460	2.50	170,341	0.50	NR
WV	0	0.00	0	0.00	0	0.00	0	0.00	NR
WY	7,800	0.50	0	0.00	0	0.00	14,800	1.00	NR
YT	620	NR	0	0.00	0	0.00	NR	NR	NR

NR = No Response

Continued

Table 4. Snow and Ice Control Policies

State/ Prov.	Policies:	Describe "other" to previous question	Describe any rules/penalties which limit flexibility to respond to changing weather or forecast events	Describe any cooperative efforts you have with other roadway maintenance organizations
AB	Bare pavement	NR	None exist	Special arrangements with cities, countries, municipal districts, adjacent provinces.
AK	Bare pavement	NR	Must pay overtime for callouts beyond normal scheduled work hours.	Work with municipality to coordinate efforts in snow removal.
AL	Other	NR	NR	NR
AR	Other	Bare pavement policy not possible during a storm, continuous until snow and ice removed.	N/A	N/A
CA	Bare pavement	Five levels of road classification	None	NR
CO	Other	PD-1055.2	N/A	We have annual meetings with adjoining states' maintenance and law enforcement personnel.
CT	Other	NR	NR	NR
DC	Bare pavement	None	None	Areawide plan involving federal government, State of Maryland, Commonwealth of Virginia, Metro Transit Authority, and suburban jurisdictions.
GA	Bare pavement	NR	None	None
IA	Other	NR	NR	NR

NR = No Response

Table 4 (continued). Snow and Ice Control Policies

State/ Prov.	Policies:	Describe "other" to previous question	Describe any rules/penalties which limit flexibility to respond to changing weather or forecast events	Describe any cooperative efforts you have with other roadway maintenance organizations
ID	Other	Various levels of service	NR	Cooperative agreements with various cities and highway districts for snow removal on state routes through cities.
IL	Other	Policy	Each year, 2,600-person workforce is subsidized by approximately 600 hourly, temporary employees to maintain snow route integrity. The hourly employees are not always available to the extent required.	Snow routes are well defined for state or efforts by others. In emergencies, various agencies assist each other to the extent possible. Contractual equipment can be requested in emergencies. Districts may come to the aid of others.
IN	Bare pavement, Other	Bare pavement on Class 1 (high volume) roads; require one bare wheel track on Class 3; attempt bare pavement ASAP.	None applicable	No formal cooperative agreements.
KS	Bare pavement, Snow bottom	Class A routes: near normal surface conditions (ADT over 2,500). Class B routes: minimum, treated snow-packed (ADT 750-2500). Class C routes: minimum one-way traffic (ADT under 750).	NR	The districts communicate, generally by telephone, with the bordering states for mutual cooperation. Installation of SCAN snow/ice detection system in Kansas City-Olathe Metro area through agreement with the State of Missouri and the City of Kansas City, Missouri.
KY	Bare pavement	Three priorities: Bare pavement on Priorities A & B. Spot treatment of Priority C.	None	Some swapping of routes with local government.
LA	NR	NR	Determined by district administrators	None
MA	Other	NR	NR	NR
MB	Other	NR	NR	NR
MD	Bare pavement	NR	NR	NR

NR = No Response

Continued

Table 4 (continued). Snow and Ice Control Policies

State/ Prov.	Policies:	Describe "other" to previous question	Describe any rules/penalties which limit flexibility to respond to changing weather or forecast events	Describe any cooperative efforts you have with other roadway maintenance organizations
ME	Bare pavement	NR	NR	NR
MI	Bare pavement	NR	NR	NR
MN	Other	NR	NR	NR
MO	Other	NR	NR	NR
MT	Other	NR	NR	NR
NC	Bare pavement, Other	NR	NR	NR
ND	Bare pavement, Other	NR	NR	NR
NE	Other	NR	NR	NR
NF	Bare pavement, Snow bottom	NR	NR	NR
NH	Bare pavement, Other	NR	NR	NR
NJ	Bare pavement	NR	NR	NR
NT	Other	Cat. 1: Bare surface ASAP or within 48 hours. Cat. 2: Center bare within 24 hr and bare when possible. Cat. 3-5: Maintain reasonably clear when equipment available.	N/A	Have mutual agreement with Yukon government to assist each other on a section of Dempster Highway that has deep cuts and is subject to severe winter storms.
NV	Bare pavement	NR	NR	NR
NY	Bare pavement, Other	Safest road possible given the climatological conditions	4-hr minimum call-in time.	None
OK	Other	NR	NR	NR

NR = No Response

Table 4 (continued). Snow and Ice Control Policies

State/ Prov.	Policies:	Describe "other" to previous question	Describe any rules/penalties which limit flexibility to respond to changing weather or forecast events	Describe any cooperative efforts you have with other roadway maintenance organizations
ON	Bare pavement, Snow bottom, Other	Standard relates to traffic volumes.	No impediments, but rather premium payments. Maximum permissible hours worked overcome by establishing an adequate shift system.	We plow through small communities and share interchange components and short isolated sections.
OR	Other	NR	NR	NR
PA	Other	NR	NR	NR
SC	Other	NR	NR	NR
SD	Other	Continue operations until all routes are passible and traffic is moving safely.	None	Cities of over 2,500 population are responsible for snow and ice control of State highways within their limits.
SK	Bare pavement, Other	NR	Overtime pay for Sunday work.	None
TX	Other	NR	NR	NR
UT	Bare pavement	NR	NR	NR
VA	Other	NR	NR	NR
VT	Bare pavement, Other	NR	NR	NR
WA	Bare pavement, Snow bottom	NR	NR	NR
WV	Other	NR	NR	NR
WY	Bare pavement, Other	NR	NR	NR
YT	NR	NR	Standby pay. 4-hr minimum for callout after regular hours.	N/A

NR = No Response

Table 5. State Highway Agency Internal Weather Information Dissemination

State/ Prov.	Provide temp. info?	Provide dew point info?	Provide humidity info?	Provide icy road info?	Provide snow/ slush info?	Provide precip. info?	Provide wind info?	Provide atmos. pressure info?	If you provide other info, please describe
AB	NR	NR	NR	y	y	y	NR	NR	NR
AK	y	n	n	y	y	y	y	n	Animals in area (moose, caribou).
AR	n	n	n	y	y	y	n	n	NR
CA	y	y	y	y	y	y	y	y	NR
CO	NR	NR	NR	y	y	y	y	NR	NR
CT	n	n	n	y	y	y	n	n	NR
GA	NR	NR	NR	y	y	y	NR	NR	NR
IA	n	n	n	y	y	y	n	n	NR
ID	n	n	n	y	y	y	y	n	NR
IL	n	n	n	y	y	n	n	n	NR
IN	n	n	n	y	y	n	n	n	NR
KY	NR	NR	NR	y	y	NR	NR	NR	Road closures.
LA	NR	NR	NR	NR	NR	NR	NR	NR	Ice warning signs on bridges.
MA	n	n	n	y	y	y	n	n	NR
MB	n	n	n	y	y	y	y	n	NR

Table 5 (continued). State Highway Agency Internal Weather Information Dissemination

State/ Prov.	Provide temp. info?	Provide dew point info?	Provide humidity info?	Provide icy road info?	Provide snow/ slush info?	Provide precip. info?	Provide wind info?	Provide atmos. pressure info?	If you provide other info, please describe
MD	n	n	n	y	y	y	n	n	NR
ME	y	n	n	y	y	y	n	n	NR
MN	n	n	n	y	y	n	n	n	NR
MT	y	n	n	y	y	n	y	n	NR
NC	NR	NR	NR	y	y	y	NR	NR	NR
ND	NR	NR	NR	y	y	NR	NR	NR	NR
NE	NR	NR	NR	y	y	NR	NR	NR	NR
NF	n	n	n	y	y	y	n	n	NR
NH	y	n	n	y	y	y	n	n	NR
NT	n	n	n	y	y	y	n	n	Dust, fog, blowing snow, whiteouts.
NV	n	n	n	y	y	n	y	n	NR
OK	NR	NR	NR	y	y	NR	NR	NR	NR
OR	NR	NR	NR	y	NR	NR	NR	NR	NR
PA	y	NR	NR	NR	NR	y	y	NR	NR
SC	NR	NR	y	y	y	NR	NR	NR	NR

NR = No Response

Continued

Table 5 (continued). State Highway Agency Information Dissemination

State/ Prov.	Provide temp. info?	Provide dew point info?	Provide humidity info?	Provide icy road info?	Provide snow/ slush info?	Provide precip. info?	Provide wind info?	Provide atmos. pressure info?	If you provide other info, please describe
SD	NR	NR	NR	y	y	y	NR	NR	Visibility.
SK	NR	NR	NR	y	y	NR	NR	NR	NR
TX	NR	NR	NR	y	y	NR	NR	NR	NR
UT	NR	NR	NR	y	y	y	y	NR	NR
VA	n	n	n	y	y	n	n	n	NR
VT	y	NR	NR	y	y	y	y	NR	NR
WA	n	n	n	y	y	n	y	n	NR
WV	y	NR	NR	y	y	y	NR	NR	NR
WY	NR	NR	NR	y	NR	y	NR	NR	NR
YT	NR	NR	NR	y	y	y	NR	NR	General road conditions.

NR = No Response

Table 6. Weather Impacts

State/ Prov.	What is your perception of weather, its short-term and long-term predictability, and impacts on your maintenance operations?	Describe important thresholds which trigger action on the part of your agency	Describe any "out-of-ordinary" weather impact problems your agency must deal with
AB	Weather is one of the biggest factors in our maintenance programs in winter more so than summer. It is very difficult to predict weather on a long term basis. Rain, snow, and dryness have a large impact on our maintenance operation.	Temperatures when applying sand-salt, snow depth when plowing, dryness when applying dust control chemical, rain amount when blading gravel roads.	Freezing rain storms, wind erosion, variable conditions within a relatively small area.
AK	In Alaska, it snows in the winter and is usually frozen from mid-October until mid-March.	Plow and sand after every snowstorm, use chemicals when temp. nears 32°F and rising, sand when roads are slick.	Avalanche control after heavy snows or accumulation.
AR	Storms in Arkansas are generally predictable and of short duration. Long-term storms uncommon to Arkansas, cause extensive damage to roadways and bridges.	Plowing started when accumulation begins. Wind velocities rarely cause closures. Salt and abrasives are applied on hills, curves, and stopping-starting areas.	NR
CA	NR	Snow depth trigger is at beginning of snow-fall to place abrasives and chemical to retard pack from bonding to pavement. Wind velocity for controlling high-sided vehicles is supervisor's judgement call. Temperature for salting/sanding; guidelines in maintenance manual and judgement.	State Route 50, Echo Summit, elevation ≈7,500 ft, avalanche zone. State Route 88, Carson Pass, elevation ≈8,500 ft, avalanche zone.
CO	Short-term predictability can help in sudden emergency situations, but long-term predictability and dependable accuracy have major impact on budget, i.e., minimize overtime, maximize manpower and equipment, etc.	Dry road policy — sanding and plowing begins at onset of storm at the discretion of the supervisor (some reliance on ice sensing system for pavement temperature, ambient temperature, wind speed and direction).	Avalanche control on several mountain passes. Road closures due to blizzard conditions on Eastern Colorado plains.

NR = No Response

Continued

Table 6 (continued). Weather Impacts

State/ Prov.	What is your perception of weather, its short-term and long-term predictability, and impacts on your maintenance operations?	Describe important thresholds which trigger action on the part of your agency	Describe any "out-of-ordinary" weather impact problems your agency must deal with
DC	Unpredictable. Disrupts services such as trash pickup.	0-2 inches of accumulation: abrasive spreading. 2 or more inches of accumulation: plowing. 8+ inches of accumulation: hauling/disposal.	Special events, either planned or otherwise, in and around the City which dislocate the already high traffic volume.
GA	Short-term predictability has minor impact on work activity decisions and makes alternative work planning more necessary. Long-term predictability has little or no impact.	There are no formal thresholds. Decisions are made locally based on actual road conditions, type of precipitation, and forecast.	None.
ID	Winter maintenance activities typically account for 15-20 percent of our total maintenance budget in Idaho. This is, therefore, a subject that is very important to us and receives a lot of attention.	See enclosed "Winter Maintenance Guidelines"	We have avalanche problems, and we have had an extensive study done on this. We have taken special measures to be prepared for such occurrences.
IL	We have found that having experienced, able supervisors and putting information, such as weather forecasts, and the necessary resources in their hands is the most important element in successful snow and ice control operations.	We follow field experience in callouts, spreading and plowing operations depending on predicted accumulations, temperatures, and wind velocities.	The multilane Chicago Expressways and ADTs over 140,000 require extraordinary planning and performance.
IN	Through proper scheduling of maintenance activities (priority, routine, and alternate activities), if weather affects the scheduled activity, the manager has other options to provide meaningful work. We attempt to schedule meaningful work, even during winter months, to minimize the influences of weather. Local managers follow current public forecasts to help determine which activity is most suitable from a predetermined list of acceptable activities.	Calcium chloride is typically used with salt at 20°F or below. State police determines road closures. Sand or salt/sand mixtures are primarily used for ice only; any snow accumulation is removed either mechanically or chemically.	Only "whiteout" caused by high winds. Snow fences and natural vegetation are used where possible.

NR = No Response

Table 6 (continued). Weather Impacts

State/ Prov.	What is your perception of weather, its short-term and long-term predictability, and impacts on your maintenance operations?	Describe important thresholds which trigger action on the part of your agency	Describe any "out-of-ordinary" weather impact problems your agency must deal with
KS	Winter storm conditions in Kansas are very hard to predict, especially on a long-term basis. Major storms have a high priority on maintenance operations.		Twenty-inch snow storms, especially when such storms occur back-to-back.
KY	No clear-cut perception.	Snow accumulation on roadway triggers callout of crews.	None.
LA	Due to the geographical location of our state, certain areas are frequently the victim of a natural disaster. Hurricanes and storms occur along the Gulf Coast, floods occur along the major rivers, and tornadoes strike across the state; snow and ice storms create hazardous conditions during emergencies; affected districts contact and maintain liaison with the Civil Defense Agencies.	Supervisory inspection in radio-equipped vehicles on a continuous basis when temperature and weather reports indicate snow and ice are beginning to accumulate (threshold for triggering salting/sanding).	

NR = No Response

Continued

Table 6 (continued). Weather Impacts

State/ Prov.	What is your perception of weather, its short-term and long-term predictability, and impacts on your maintenance operations?	Describe important thresholds which trigger action on the part of your agency	Describe any "out-of-ordinary" weather impact problems your agency must deal with
NT	Weather information and predictability would help reduce the effects, permit development of alternate procedures, or improve scheduling relating to: 1. Sudden heavy rainfall and rapid melt of snow cover can cause washouts or severe erosion. 2. Placing and removal of weight restrictions. 3. Prolonged dry spells can aggravate dust problems on gravel roads. 4. Periods of strong winds can cause blowing dust or snow, while temperature inversions can cause whiteouts or fog, thereby reducing visibility. 5. Freezing rain causing slippery conditions on pavements and to a lesser extent on gravel roads. 6. Effect on opening and closure dates on winter roads with ice or snow surfaces. 7. Temperatures are important in the development of the weight-bearing capacity of ice or its ultimate melting in most cases in the spring. 8. Rapid temperature changes do change the effectiveness of ice control chemicals. 9. Strong/frequent winds cause snow blockage of dust on highways such as the Dempster or blockage of ice roads.	Onset of plowing: not before 5 cm of snow on pavement or 8 cm on gravel unless storm is over. Temperature for salting: 0-5°C for straight sodium chloride, and then a scale for calcium chloride/sodium chloride blends down to -18°C. Temperature for sanding: hills, intersections, railway crossings and curves to be sanded when required with no temperature limitation. 18°C and lower: sand only to be applied to slippery sections.	Blowing snow causing road blockage in cuts. Warm weather and deep snow on ice slow natural development of weight-bearing capacity. Warm temperatures cause permafrost to melt in some areas causing grades to slough.

NR = No Response

Table 6 (continued) Weather Impacts

State/ Prov.	What is your perception of weather, its short-term and long-term predictability, and impacts on your maintenance operations?	Describe important thresholds which trigger action on the part of your agency	Describe any "out-of-ordinary" weather impact problems your agency must deal with
NY	Weather is responsible for almost all our operations five months of the year. Both long-term and short-term predictability are improving with time.	NR	Lake-effect snows.
ON	Provincial weather varies considerably (835 x 10^6 acres). Some areas have large, slow-moving storms that are predictable. Others have sporadic short-term squalls that are unpredictable. Some areas have wind effects that cause maintenance demands even when there is no current precipitation.	NR	Wind effects, low visibility.
SD	Long-term weather forecasts from present weather sources are of very little value. Short-term forecasts are a little better, but are hard to use to schedule operations because of variances from one location to another.	We have no written standards for threshold actions. Generally, threshold action is based on crew experience: approximately 2 in of snow to start plowing; slippery surface existing or expected to begin sanding; highways are closed to traffic when visibility is reduced to 1,000 ft. due to blowing snow.	None.
SK	NR	Snow depth: plowing; visibility: plowing; wind: treat or not treat; temperature: treat, no treat, or type of treatment.	NR
YT	Rapid changes in local conditions mean that general forecasts issued for an area are often off the mark.	Plowing: 1.5-5.0 cm depending on road. Sanding with salt is only carried out between 0°C and -7°C.	i. Blowing snow, poor visibility. ii. Extreme temperatures, equipment failure.

NR = No Response

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