Test and Evaluation Project No. 28: Anti-icing Technology, Field Evaluation Report

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U.S. Department of Transportation
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Research and Development
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FOREWORD

Very few tasks undertaken by State and local transportation agencies affect road users as directly as highway snow and ice control. Everyone knows that winter storms can wreak havoc on mobility and safety, yet most often their impacts are greatly mitigated by the diligence of highway maintenance professionals. Diligence continues to be a mainstay of snow and ice control operations, yet in recent years there has been such a revolution in the supporting technology that today, for example, these operations are beginning to be merged with aspects of intelligent transportation systems. Much of the technology revolution centers upon anti-icing, a proactive approach that focuses on preventing the development of a strong bond between the road and snow or ice by judicious use of deicing chemicals—thus allowing snow and ice to be removed readily by plowing. As an efficient practice that makes systematic use of available technologies and road and weather information, anti-icing can provide the benefits of increased wintertime mobility, productivity, and traffic safety at the lowest possible cost. Additionally, as a technique that promotes efficient chemical use and allows for the use of alternative deicing chemicals, anti-icing can be adapted to support goals of infrastructure preservation and environmental sustainability. Due to successful public- and private-sector partnerships that have developed around anti-icing, these benefits are being realized today.

This report describes Federal Highway Administration (FHWA) Test and Evaluation Project No. 28, Anti-Icing Technology (T&E 28). It is the research report that is the principal basis of Report No. FHWA-RD-95-2022, *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel*, which has been highly successful in promoting implementation of anti-icing practices in the U.S. Following an initial anti-icing evaluation during the Strategic Highway Research Program, T&E 28 was undertaken in recognition that anti-icing was an emerging technology having great potential for use nationwide. This has proven to be true.

The report provides a detailed glimpse at the state-of-the-art of U.S. anti-icing operations, and simultaneous road and weather conditions, prior to the 1996 publication of the anti-icing *Manual of Practice*. It will be useful to those who wish to examine the basis of the *Manual* and those who wish to track the continuing evolution of anti-icing technology. While the research was of vital use in developing the *Manual*, it also developed a framework in which to comprehensively view anti-icing, its supporting technologies, and the range of practices and technologies that can be implemented to support a successful anti-icing program. The report will be useful also to investigators who are developing and performing research, test, and evaluation studies in highway (and even runway) snow and ice control, and to those who wish to examine roadway conditions during winter storms.

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Research and Development

NOTICE

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16. Abstract

Highway anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant. Its operations consist of chemical applications and coordinated plowing. The prefix "anti" signifies the preventive nature of anti-icing and distinguishes it from deicing, which is the traditional practice of mechanically or chemically removing compacted snow or ice that is already bonded to pavement. Although anti-icing practices have been in use for many years, the term has evolved to mean a modern and efficient snow and ice control practice that makes systematic use of an array of new technologies such as road weather information systems, site-specific weather and pavement forecasts, portable pavement temperature sensors, and sophisticated spreader equipment, as well as conventional and traditional technologies and practices. Anti-icing can provide two major benefits: efficient use of labor and materials, and increased traffic safety.

The project reported in this document is Federal Highway Administration (FHWA) Test and Evaluation Project No. 28, Anti-Icing Technology (T&E 28). It is part of the FHWA Strategic Highway Research Program (SHRP) implementation. Its purpose was to implement and evaluate existing technologies that were tested and reviewed under SHRP project H-208, "Development of Anti-Icing Technology." T&E 28 included anti-icing testing over the course of two winters, and analysis of the resulting data. The testing comprised field operations and experiments by highway agency personnel, and the data analysis consisted of graphical and statistical analysis. The report describes the field evaluation experimental program, experimental details of the sites, the data analysis, results and interpretations of the experiments, a cost analysis, recommendations for anti-icing practice, and conclusions and recommendations for further work. The report is not a guide to anti-icing practice. The companion *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel* provides such a guide.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION

1.1 INTRODUCTION TO HIGHWAY ANTI-ICING

Highway anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant. Its operations consist of chemical applications and coordinated plowing. The prefix "anti" signifies the preventive nature of anti-icing and distinguishes it from deicing, which is the traditional practice of mechanically or chemically removing compacted snow or ice that is already bonded to pavement. In anti-icing operations, the first application of the snow- and ice-control chemical is sometimes before the start of freezing precipitation, sometimes after the precipitation begins, but always before a strong bond between the pavement and any ice or packed snow on the pavement surface has formed. Subsequent anti-icing operations are conducted either to prevent a strong ice-to-pavement bond or to prevent any bond from forming. In fact, all anti-icing operations, at the beginning of a storm and throughout the storm, are conducted for the same purposes: to prevent a bond from forming, or to mitigate the strength of any bond that does form. The overall goal of anti-icing is straightforward: to allow snow and ice to be readily removed from the highway, and to do so with efficient use of chemicals relative to traditional deicing practices, while maintaining acceptable road conditions.

Although anti-icing practices have been used for many years, the term has evolved to mean a modern snow and ice control practice that makes systematic use of an array of new technologies, such as road weather information systems, site-specific weather and pavement forecasts, portable pavement temperature sensors, and sophisticated spreader equipment, as well as conventional and traditional technologies and practices. With thoughtful, methodical, and vigilant use of available information sources, whether they be cutting-edge or traditional, anti-icing can provide two major benefits: efficient use of labor and materials, and increased traffic safety. Stated slightly differently, anti-icing has the potential to provide the benefit of increased traffic safety at the lowest attainable cost.

Anti-icing operations are clearly appropriate on routes where a high level of winter maintenance is required. The extent to which maintenance services will be provided on a road section is determined by management, who assign to the road section a "level of service." This will often establish a prescribed condition that winter maintenance operations must return the pavement to as soon as possible following a storm, as well as intermediate conditions that will be acceptable. Alternatively, it may establish the frequency of the operations rather than their performance. Whatever approach is used, the level of service will generally be based upon the importance of the road as revealed by the average hourly traffic. The highest level of winter maintenance service is often called a "bare pavement policy," reflecting the required condition at the end of operations and perhaps the desired condition throughout a storm.

Anti-icing operations are more suited to higher service level roads because the vigilance and timeliness required for success are consistent with the maintenance effort required by policy. Also the preventive nature of anti-icing is more consistent than is deicing with the objective of maintaining bare pavement throughout a storm. In fact, on higher service level roads in the United States, maintenance forces have been instinctively evolving to anti-icing practices from traditional deicing practices for years.

Tools and operations applicable to anti-icing practices are illustrated in figure 1. This figure, which outlines a winter maintenance program as a tree-like structure, depicts the level of service assignment at the top of the structure. The figure specifies only high level bare pavement strategies below the level of service

Winter Maintenance Program

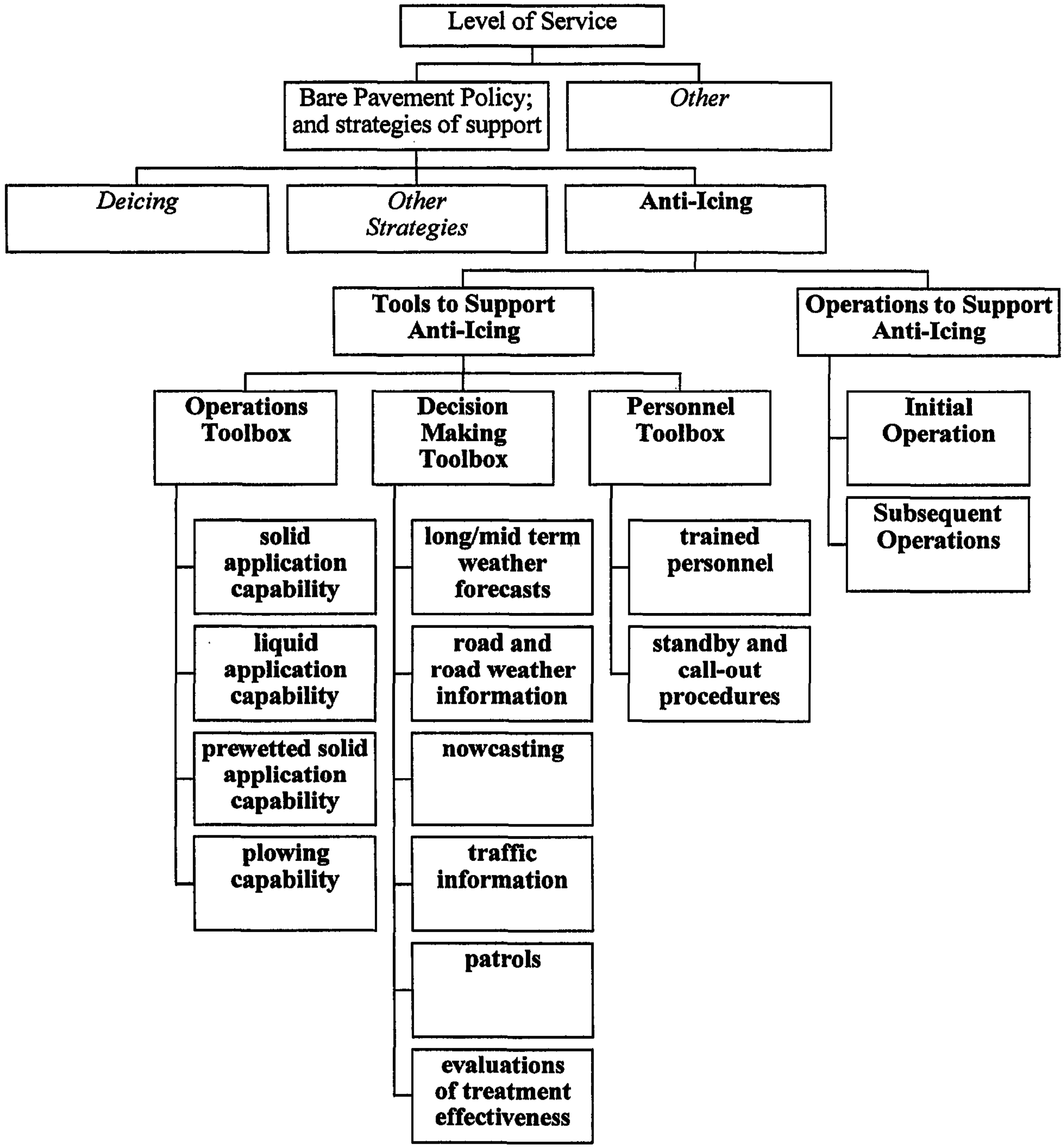


Figure 1. Outline of the components of anti-icing practices within the context of a winter maintenance program.

assignment, and anti-icing is the only bare pavement strategy specified. Other policies and strategies are outside the scope of this discussion and project and have not been pictured in the figure.

Support of an anti-icing strategy is divided into tools and operations. The supporting tools can be organized according to personnel, decision making, and operations toolboxes, which are further broken down according to capabilities, information sources, and procedures that may be available for a given operation. A toolbox analogy is followed to suggest that managers should use their available resources systematically as they would use mechanical or other tools in the course of a methodical repair job. Operations are broken down into initial and subsequent operations to convey the importance of the initial chemical treatment in anti-icing operations, and to signal that subsequent operations throughout a storm should follow the anti-icing strategy as well.

Further discussion of anti-icing practices according to the figure 1 outline is presented in the companion *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel.*(1) For this introduction, it suffices to present the outline as an illustration of the components of anti-icing, both to indicate the underlying complexities of anti-icing practices and to reveal that what may initially appear as an overly demanding practice can actually be thought of as an organized set of preparations, decisions, and operations.

1.2 INTRODUCTION TO FHWA TEST AND EVALUATION PROJECT NO. 28, "ANTI-ICING TECHNOLOGY"

The project reported in this and companion documents is the Federal Highway Administration (FHWA) Test and Evaluation Project No. 28, "Anti-Icing Technology" (T&E 28). It is part of the FHWA Strategic Highway Research Program (SHRP) implementation. Its purpose was to implement and evaluate existing technologies that were tested and reviewed under SHRP project H-208, "Development of Anti-Icing Technology."(2) Participants were the State highway agencies of California, Colorado, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Hampshire, New York, Ohio, Oregon, Washington, and Wisconsin. The project team included personnel from the contractor and FHWA. An expert task group was organized by FHWA to oversee the project and its products.

The project included anti-icing testing over the course of two winters and analysis of the resulting data. The testing comprised field operations and experiments by highway agency personnel, and the data analysis consisted of graphical and statistical analysis. This evaluation was the principal effort of the participating State agencies and the project team and dominates the documentable results of the project.

Implementation was promoted in two ways. First, the personnel at the experimental sites were tasked with developing their own anti-icing practices, using guidance provided by the project team. By this approach, the innovation of the site personnel was utilized as a resource, and the intuitive anti-icing developments made over the course of years at the sites were formalized and implemented. Second, the techniques of anti-icing were promoted during two national meetings sponsored by FHWA, training sessions of the project, oral presentations made by FHWA and project team personnel to national organizations and State agencies, and written presentations by the FHWA project manager appearing in highway newsletters and magazines. By this approach States could take the initiative to implement anti-icing practices outside of the experimental sites of the project and do so with sufficient guidance.

1.3 INTRODUCTION TO THIS REPORT

This report describes the anti-icing field evaluation experimental program, its results, and recommendations for practice. This report and additional site reports are meant to serve as reference documents for the evaluation program and as a basis for the recommendations made. As such they are heavy with data and analysis results, reflecting the many experiments that were conducted by the States.

The report is not a guide to anti-icing practice. The companion *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel* provides such a guide.(1) Other companion products of the project are a document *Test and Evaluation Project No. 28, "Anti-Icing Technology," Reports Summary of the Participating State Agencies*, a video *What is Anti-Icing*, and a video *Anti-Icing for Maintenance Personnel*.(3,4,5) The document *Preliminary Recommendations for Anti-icing Practices, A Guide for the Maintenance Manager* was developed after the first winter season of the project as a precursor to the project manual of practice.(6)

Following the introduction, this report includes chapters containing a description of the field evaluation experimental program; an outline of the experimental details of the sites; documentation of the field evaluation analysis process; results and interpretations of the experiments; a description and results of the cost analysis; recommendations for anti-icing practice; and a summary, conclusions, and recommendations for further work. Also included are appendices detailing the experimental instructions and site details, additional storm data that supplements the cost analysis, and references. Separate site reports include experimental details and results from the individual sites. (See references 7 through 18.) These reports include storms that could be analyzed according to the field evaluation process described in chapter 4.

2. FIELD EVALUATION EXPERIMENTAL PROGRAM

2.1 INTRODUCTION

The field evaluation included a two-winter, experimental anti-icing study at sites in California, Colorado, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Hampshire, New York, Ohio, Oregon, Washington, and Wisconsin, and analysis of the experimental data. The highway agencies in nine of these States—California, Colorado, Maryland, Minnesota, Missouri, Nevada, New York, Ohio, and Washington—participated in the preceding SHRP project H-208.[2] The remaining six—Iowa, Kansas, Massachusetts, New Hampshire, Oregon, and Wisconsin—joined these nine as participants in T&E 28.

The experimental program comprised field operations and experiments performed by State or county highway agency personnel, and graphical and statistical data analysis conducted by the contractor. The experiments were performed according to a process that allowed consistent analyses of the data from all sites. The process was designed to provide data whose analysis would lead to recommendations for good anti-icing practices. Even though the experimental process was ambitious, it accommodated more than complicated the field operations. As a consequence, however, the results of the study, while representative of realistic field operations, should not be misconstrued as those of highly controlled or statistically designed experiments.

The general approach of the anti-icing experiments, and many of the specific techniques of the experiments, were based upon the experimental concept and techniques of the preceding SHRP project H-208.[2] As in the SHRP project, the T&E 28 experiments were conducted at the different sites using different anti-icing and conventional treatments, and during a variety of storm events that reflected the nature of storms at each individual site and at the different geographical locations over the two-winter period of the study. The effectiveness measures were based on pavement surface measurements and observations, i.e., measurements of friction, and observational records of the pavement condition. Other data were recorded to establish weather, pavement, and traffic conditions throughout a storm in order to demonstrate and investigate relationships between the effectiveness measures and the conditions. Material, labor, and equipment usage were recorded as well, to establish the costs of achieving effectiveness.

Figure 2 illustrates the field evaluation site locations. There were 16 total. Eight—those in Maryland, Minnesota, Missouri, Nevada, New York, Ohio (two sites), and Washington—were locations of the SHRP project H-208 experiments.[2] The sites in California, Colorado, Iowa, Kansas, Massachusetts, New Hampshire, Oregon, and Wisconsin were newly added for this project. The States selected the new sites to accommodate the experimental process and requirements that are presented below and in appendix A. Information about the sites is presented in the following chapter and in appendix B.

Training visits were made to the States by project team members before each of the experimental seasons. The sessions covered two major topics: (1) anti-icing practices; and (2) the experimental process. Winter field visits were made to each site as well during the two seasons. The visits provided further guidance to the State participants on anti-icing practices and the experimental requirements.

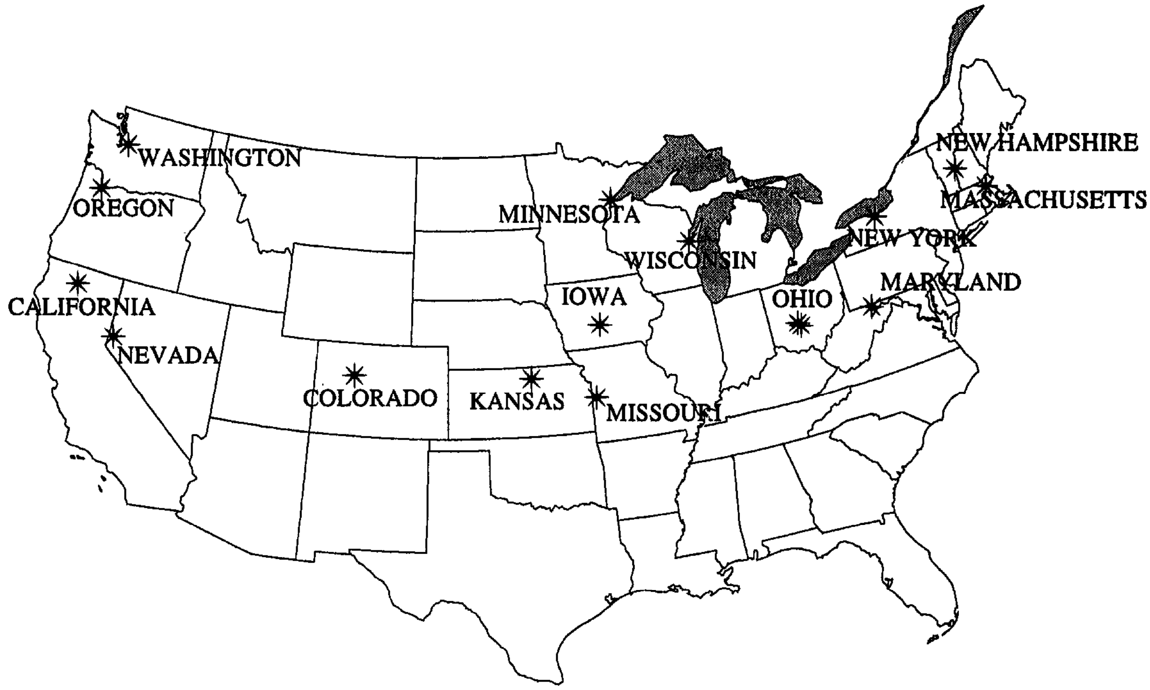


Figure 2. Field evaluation site locations in the 15 participating States.

2.2 SCOPE AND INSTRUCTIONS OF EXPERIMENTS

An experiment of the field evaluation program consisted of anti-icing operations on a test section, conventional operations on a control section, documentation of the operations, and data collection, i.e., measurements and observations, during a single storm. Several experiments could therefore be conducted at a given site over the course of a winter storm season. The anti-icing operations were conducted according to a general treatment strategy that was developed by personnel at the site. The strategy was followed throughout the season to provide data of its use for several storms, yet it was flexible to allow for variations in actual treatments required for different conditions and storm types. The conventional operations were the standard practice at the site, with no planned influence from the anti-icing operations. Appendix A includes the full instructions for the experiments. This section provides a shortened, narrative version of how the experiments were conducted and their scope.

Considerable documentation was provided by the States in each storm package. This documentation included weather and pavement temperature forecasts received by the agency; road weather information system (RWIS) data and other weather data available; logs of the operations, anti-icing decisions, and data collection; and traffic data. Operation logs included the type, proportions or concentration, and application rate of each major chemical component of all chemical treatments, the snow plowing operations, the type and application rate of any abrasives that were placed, and any other operations. Decision logs listed the decisions that were made and their reasons, and data collection logs documented the on-road data collection. Forms and instructions for the logs are included in appendix A. Comparison of the multiple logs served to correct inconsistencies and improved the data integrity.

The on-road data collection consisted primarily of precipitation observations, hard braking friction measurements, and pavement condition observations. Tables 1 and 2 list categories and definitions of precipitation and pavement condition, respectively. The observations were made by selecting the most appropriate of these categories. The friction measurements at all sites were made using a commercially available speed, distance, and friction meter that was installed in an agency's sedan or pick-up truck (the measurement vehicle) and connected to its speedometer system. (The meter calculates an estimate of the coefficient of friction using distance and velocity measurements before and after a hard braking action, and displays the value to the operator.) For consistency in data analysis and presentation, the friction measurements as well as pavement condition observations were made in the wheel paths of the driving lanes.

Setup of the experiments included selection of the test and control sections for the operations, as well as test and control measurement sections. All data from the measurement vehicle were collected in the measurement sections, which were established within the full test and control sections to obtain reasonable consistency of the measurements. Specifically, whereas the test section was the entire highway section at the site over which the anti-icing operations were performed, the test measurement section consisted of subsections of the test section that were uniform with regard to pavement cross-section, flatness, traffic, and other conditions. For example, a test measurement section was typically an otherwise continuous and uniform section of the test section without short stretches of the highway containing culverts, bridges, steep grades, and underpasses. The control measurement section was similarly designated. In addition, the measurement sections were chosen so that chemical applications would not be significantly contaminated by adjacent different treatments and discontinuous traffic patterns.

Typically the test section was longer than the test measurement section, and the control section was longer than the control measurement section. This was so that the treatments could be applied over a length of highway that was operationally feasible and convenient, and so that precipitation observations, friction measurements, and pavement condition observations could be made in a timely fashion under reasonably uniform conditions over only a part of the treated section.

To be able to quantify the central tendency of the measurement section friction data corresponding to the time of a pass of the measurement vehicle, several friction measurements were made during each pass. In general, at least seven friction measurement and observation sets were made at random locations during each pass on the test measurement section, and the same was done during each pass on the control measurement section. To allow examination of the temporal variation of conditions and friction throughout the storm, it was instructed that the measurement and observation passes were to be conducted at 30-min, 1-h, or 2-h intervals until the end of the operations, depending on the length of the storm. If for some reason (such as heavy traffic) friction measurements could not be made, the observations and judgments were to be made anyway.

An additional observation was made to judge if the driving lane of the test measurement section or the driving lane of the control measurement section provided better vehicle handling traction, or whether there was no perceivable traction difference between the two. This judgment was recorded after a complete pass of the measurement vehicle over both the test and control measurement sections.

Table 1. Categories and definitions for precipitation observations.

Light rain	Liquid droplets small in size falling at a rate insufficient to result in standing water (puddling) or visible run-off from a road.
Rain	Liquid precipitation falling at a rate sufficient to result in noticeable flow from a road surface or along a road gutter.
Freezing rain	Supercooled droplets of liquid precipitation falling on a surface whose temperature is below or slightly above freezing, resulting in a hard, slick, generally thick coating of ice commonly called glaze or clear ice. Non-supercooled raindrops falling on a surface whose temperature is well below freezing will also result in glaze.
Sleet	A mixture of rain and snow which has been partially melted by falling through an atmosphere with a temperature slightly above freezing.
Light snow	Snow falling at the rate of less than 13 mm/h (1/2 in/h); visibility is not affected adversely.
Snow	Snow falling at the rate of 13 mm/h (1/2 in/h) or greater; visibility may be reduced.
Blowing snow	Snow picked up by the wind from already deposited accumulations and transported across a road. Sometimes called a "ground blizzard."
None	No precipitation and no blowing snow.

Table 2. Categories and definitions for pavement condition observations.

Dry	No wetting of the pavement surface.
Damp	Light coating of moisture on the pavement resulting in slight darkening of portland cement concrete (PCC), but with no visible water drops.
Wet	Road surface saturated with water from rain or meltwater, whether or not resulting in puddling or runoff.
Slush	Accumulation of snow that lies on an impervious base and is saturated with water in excess of its freely drained capacity. It will not support any weight when stepped or driven on, but will "squish" until the base support is reached.
Loose snow	Unconsolidated snow, i.e., snow lacking intergranular bonds, that can be easily blown into drifts or off of a surface.
Packed snow	The infamous "snowpack" or "pack" that results from compaction of wet snow by traffic or by alternate surface melting and refreezing of the water that percolated through the snow or that flowed from poorly drained shoulders.
Frost	Also called hoarfrost. Ice crystals in the form of scales, needles, feathers, or fans deposited on surfaces cooled by radiation or by other processes. The deposit may be composed of drops of dew frozen after deposition and ice formed directly from water vapor at a temperature below 0°C (32°F) (sublimation).
Black ice	Popular term for a very thin coating of clear, bubble-free, homogeneous ice that forms on a pavement with a temperature at or slightly above 0°C (32°F) when the temperature of the air in contact with the ground is below the freezing point of water and small slightly supercooled water droplets deposit on the surface and coalesce (flow together) before freezing.
Glaze ice	A coating of ice thicker than so-called black ice that is formed from freezing rain, from freezing of ponded water, or from poorly drained meltwater. It may be clear or milky in appearance, and generally is smooth, although sometimes it may be somewhat rough.

Conducting these experiments was an ambitious undertaking for the States. Because of the complexity of the process, it was recommended in the instructions that, if an agency was unable to satisfactorily perform the experiments routinely, efforts should be focused on providing complete and good data for a limited number of storms. Further, rather than requiring that the experimental instructions be followed exactly, efforts were made to allow additional flexibility of the experimental processes to accommodate special operational or data collection requirements at the site.

3. SITE SURVEY

Responses to a site survey are included in appendix B. The responses were provided by personnel in each State, and were completed before or during the first winter of the project.

A test matrix for the 12 sites that have data contained in this report is included as table 3. This matrix contains information from the survey responses in appendix B regarding the site, snow and ice control materials used, RWIS installations, and forecast services.

Table 3. Test matrix for sites having data in this report.

Site	ADT	Principal Chemicals or Abrasives used on Control Section	Principal Chemicals or Abrasives used on Test Section	Site-Specific Weather/Pavement Data and Forecast Services
California; I-5 in Siskiyou County, near Mt. Shasta	22,000	salt, cinders, and mixtures of both	magnesium chloride-based solution; cinders if needed	RWIS installation within 3 km (2 mi) of site; RWIS-vendor pavement temperature/weather forecasts
Colorado; I-70 in western end of Glenwood Canyon just east of Glenwood Springs	8,000 to 10,000	sand treated with salt (8 percent by volume)	magnesium chloride-based solution; sand-salt mix when temperature too low for solution use	elaborate RWIS installation in the canyon; RWIS-vendor pavement temperature/weather forecasts
Iowa; I-35 in West Des Moines	22,000	salt and sand in 1:1 mix	sodium chloride solution (salt brine)	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts; 2nd weather forecast vendor
Kansas; U.S. 81 in Cloud County at Concordia; undivided highway with one travel lane in each direction	4,000	salt, sand, and mixtures of both	sodium chloride solution (salt brine) and/or solid fine salt prewet with salt brine	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts
Maryland; U.S. 219 in Garrett County; undivided highway with one travel lane in each direction	3,000	salt mixed with abrasives at salt-to-abrasives ratios from 1:9 to 1:1; and salt	salt and abrasives use at ratios listed at left for the control section, with earlier initial treatments and subsequent preventive treatments	weather monitoring station at maintenance station near site; handheld pavement temperature sensors
Missouri; U.S. 71in Cass County; divided highway with two travel lanes in each direction	6,000	salt and cinders mixed at 1:1 ratio	salt and cinders premixed at 1:1 ratio, prewet with calcium chloride solution at rate of 21 L/t (5 gal/ton) mix	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts; 2nd weather forecast vendor
Nevada; U.S. 395 in Reno; divided highway with two travel lanes in each direction	40,000	salt and sand mixed at 1:5 ratio	magnesium chloride-based solution; salt-sand mix if snowpack developed	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts; additional weather forecast consultants/vendors
New Hampshire; NH 10 in the towns of Hanover and Lyme; undivided highway with one travel lane in each direction	4,000 to 8,000	salt and abrasives treated with salt	potassium acetate-based solution; salt or abrasives if needed	weather station equipped with pavement temperature sensors placed at the site for the project; weather forecast vendor
New York; NY 104 in the Rochester metropolitan area within a few kilometers of Lake Ontario	13,000 to 25,000	salt and mixtures of salt-sand at 1:3 ratio	fine salt, conventional salt, calcium chloride prewetting solution at rate of 167 L/t (40 gal/ton) salt, and mixtures of salt-sand at 1:3 ratio	RWIS installation for research at the site; RWIS-vendor pavement temperature/weather forecasts; additional weather forecast consultants/vendors
Ohio; I-70 west of Columbus in Madison County	35,000	salt	salt prewet with calcium chloride solution at rate of 42 L/t (10 gal/ton) salt	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts
Ohio; I-71 southwest of Columbus in Franklin and Pickaway Counties	30,000	salt mixed with abrasives in 1:1 ratio	salt prewet with calcium chloride solution at rate of 42 L/t (10 gal/ton) salt	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts
Wisconsin; I-43 in the Green Bay metropolitan area	10,000	salt	sodium chloride solution (salt brine)	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts

4. FIELD EVALUATION ANALYSIS PROCESS

4.1 INTRODUCTION

The experimental process described in chapter 2 was designed to provide winter storm data sets for (1) generating graphical displays of storm operations and effectiveness data together with displays of simultaneous weather, pavement, and traffic conditions; (2) summarizing storm operations; (3) statistically analyzing effectiveness measures and significant differences between the effectiveness of test and control operations using nonparametric techniques; (4) establishing conditions under which anti-icing is effective; (5) reaching statistically based conclusions; and (6) making recommendations for practice.

With these intended tasks in mind, storm data sets were analyzed individually and in blocks of storms of a given season and site. An individual storm data analysis combined (1) elementary data analysis for qualitative presentation and interpretation; and (2) advanced data analysis for quantitative interpretation. The elementary analysis consisted primarily of data quality checks, simple mathematical and statistical calculations, plotting of data histories, printing of summary data, and qualitative examination of the data. It was preceded by entry of the storm data into a spreadsheet. The advanced analysis utilized statistical calculations and nonparametric statistical analyses to graphically display friction data distributions, tabulate observation and categorical data, and compare test and control operational effectiveness. It too was preceded by entry of data into a spreadsheet. A multiple storm data analysis consisted of further statistical calculations and nonparametric statistical analyses, but was developed to provide wider indications of the effectiveness of an anti-icing treatment strategy than would be provided by the analysis of an individual storm. While results from a single storm provided a close-up of the operations and their effectiveness, results from several storms at a site allowed the big picture to appear. Because it represented a season of test and control operations at a given site, a multiple storm analysis was called a full-season site analysis.

The individual storm and full-season analyses make up the field evaluation analysis process. Descriptions of the analyses, and comments on the interpretation approach, follow.

4.2 INDIVIDUAL STORM ANALYSIS

An analysis was conducted for a single storm when a quality check of the data package showed the data to be complete to an extent that meaningful and revealing data histories could be graphed. In general these graphs were generated for most storm data packages submitted, as they were actually part of the data quality check. They were not generated when RWIS, operations, or effectiveness data were not available. Statistical analyses were conducted and associated plots and tables were further generated for a storm when the submitted operations and temperature data were complete, and when the precipitation, pavement condition, and friction data clearly revealed the effectiveness of all or significant portions of the operations. While results of the single storm analyses are included in the following chapter, they may be more completely presented in the separate site reports of this project. (See references 7 through 18.) Examples of the results are presented in this chapter to describe the analysis.

4.2.1 Data History Graphs

As an example, data histories from the February 1-2, 1995 storm at the New York site are presented in figure 3. This figure contains 10 graphs, all with a common time scale. The left column includes histories of (a) the water equivalent precipitation rate from the RWIS data; (b) pavement surface and air temperatures, also from the RWIS data; (c) traffic rates on the test and control section driving lanes; (d) plowing, chemical, and abrasives operations on the test and control section driving lanes; (e) chemical application rates; and (f) abrasives application rates. The right column presents histories of

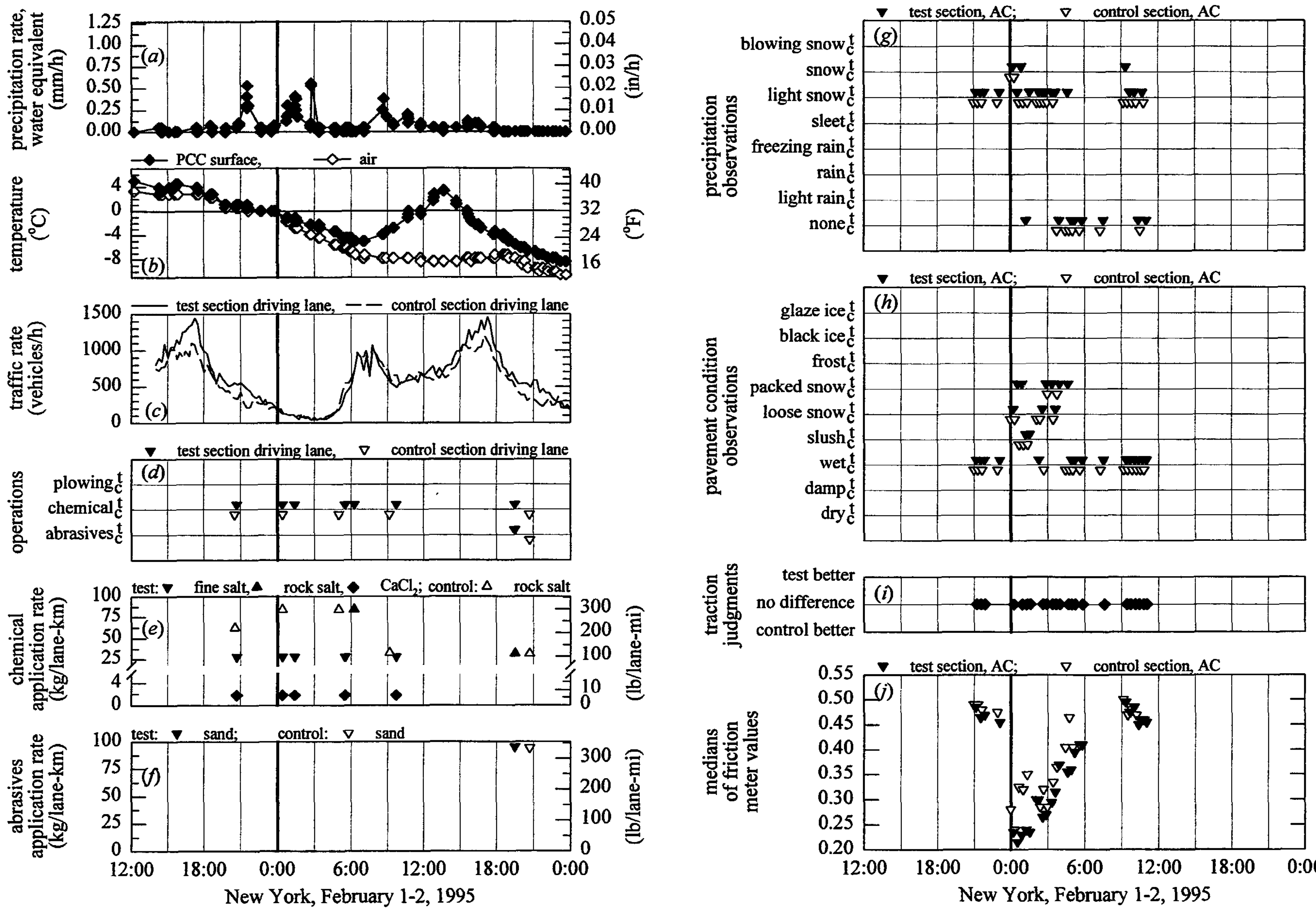


Figure 3. Example data histories from New York, February 1-2, 1995.

(g) the precipitation observations; (h) pavement condition observations; (i) traction judgments; and (j) friction meter values, all of which were recorded by the driver or passenger of the measurement vehicle. The observation graphs display the tables 1 and 2 categories of precipitation and pavement condition that could be selected during the on-road data collection.

Many features of figure 3 are common to nearly all data history presentations in this report, while other features are unique to the site. The common features include:

- The time scale is shown on the bottom graph in each column. It is labeled with the local 24-h clock time. The scale is shown with grid lines at 3-h increments and a heavier grid line at midnight or 0:00.
- The days of the graphs are designated by the abscissa axis title.
- All data on the histories with units are presented using both metric and English units.
- Legends are included just above a graph when needed. Data representing discrete events, observations, or measurements were typically plotted using symbols only. Data that were closely spaced in time, and that were generally representative of an underlying continuous variation such as RWIS numerical data, were plotted using both symbols and connecting lines or connecting lines only.
- Locations of RWIS data sensors are not indicated on the graphs. If RWIS sensors were present in both test and control sections, only the test section temperature data were plotted and used in subsequent analyses. No effort was made to present or analyze the difference between test and control section pavement temperatures, other than to confirm nearly equal magnitudes and variations when multiple but nearby sensors existed.
- A traffic rate value plotted at a given time is calculated using the number of vehicles passing the counter in the preceding counter data collection interval. For example, if the data collection intervals were 30 min, the rate plotted at 18:30 would be the number of vehicles crossing the counter from 18:00 to 18:30 divided by 0.5 h.
- All operations are plotted at the time of the beginning of the pass.
- The number of lanes used to calculate the application rates is the integer number of lanes over which material is spread and intended to be effective. By such calculations there is no distinction between narrow and wide spread widths for applications over one or more lanes.
- All application rates plotted for chemical solutions, whether for prewetting of solids or straight liquid applications, present the rate of the solute, or dry chemical, in the solution.
- The term rock salt is reserved for conventional coarse-crushed mineral sodium chloride, even when both fine and coarse-crushed mineral salt are used at a site.
- Where test and control section operations or data need to be distinguished, as on the operations, application rates, observations, and friction value graphs, filled symbols designate the test section data and open symbols designate the control section data. On the operations and observations graphs, which do not plot numerical values, test section data are presented slightly above control section data, and each is aligned with a "t" or "c" on the ordinate axis, for further distinction.
- The precipitation and observation data point plotted represents the mode (the most common) of the multiple observations made during a pass. It is plotted at the time of the beginning of the measurement pass.
- The traction judgments are plotted for the time at the beginning of the measurement pass.
- The friction value data point plotted is the median, i.e., the 50^{th} percentile, of the multiple friction measurements made during a pass. It is plotted for the time of the beginning of the measurement pass. The friction values are those of a hard braking action, either of conventional or anti-lock braking systems.

The information sources and data from each site vary, and thus the data presentations vary. Such variations include:

- Where precipitation rate is available from RWIS sensors it is plotted. However, often a simple Yes or No indication of precipitation was the only RWIS precipitation rate data available.
- The New York data generally included data from pavement temperature sensors in both asphalt concrete (AC) and portland cement concrete (PCC) surfaces, and data were collected and sometimes presented for both stretches of the test and control section. Appropriate distinctions are made on the New York data histories.

The friction median presentation technique is illustrated in figure 4, using the test section AC surface data of the February 1-2, 1995 storm at the New York site. As indicated, the use of the median as the measure of central tendency of the friction accommodates the distribution in the data during a pass, which deviates according to the variation in conditions along the measurement section and according to the repeatability of the meter and its operation. Comparison of the friction and observation data reveals how the friction values reflect the variation in pavement conditions during a pass, i.e., the friction values are less variable when conditions are constant or similar at the measurement locations, and more variable when different conditions such as wet and packed snow occur during the same pass. The figure also includes data from a pass with observations that did not include friction measurements.

The data history graphs are the primary indicator from the analysis process of the progress of the storm conditions, the test and control driving lane operations, and the effectiveness of these operations.

4.2.2 Operations Summary

The operations summary for the February 1-2, 1995 storm at the New York site is presented in table 4. It lists plowing and material application information. Similar information is presented for all storm data sets included in this report. Total material applications in kg (lb) are given per unit lane-km (lane-mi).

4.2.3 Categories for Data Analysis

To use the pavement condition observations, precipitation observations, pavement temperature measurements, and traffic rate measurements in categorical Chi-square statistical analyses, and to use these data to group friction measurements according to the section and/or conditions at the time of the measurements, the data categories in table 5 were established. They include categories for precipitation and pavement condition observations that were derived from the classes in tables 1 and 2, and categories for pavement temperature and traffic rate defined from numerical data. The pavement condition and precipitation observations were made at the time of the friction measurements, but the pavement temperature and traffic rate measurements were made at times that were independent of the times of the friction tests. To assign a pavement temperature or traffic rate category to the friction measurement, the most recently recorded numerical values were first associated with the friction measurement, and the category was then assigned.

4.2.4 Friction Data Statistics vs. Section (Tukey Box Plots)

Figure 5 presents a graph showing Tukey box plots of test and control section friction during the February 1-2, 1995 storm at the New York site. Each box plot in the figure is a distribution of all values measured for the section during the storm. The top of a box indicates the 75th percentile (i.e., 75 percent of the observations were at or below that friction value on the left scale), and the bottom indicates the 25th percentile. The line inside a box is the median, or the 50th percentile. The single line above a box is the 90th percentile and that below a box the 10th percentile.

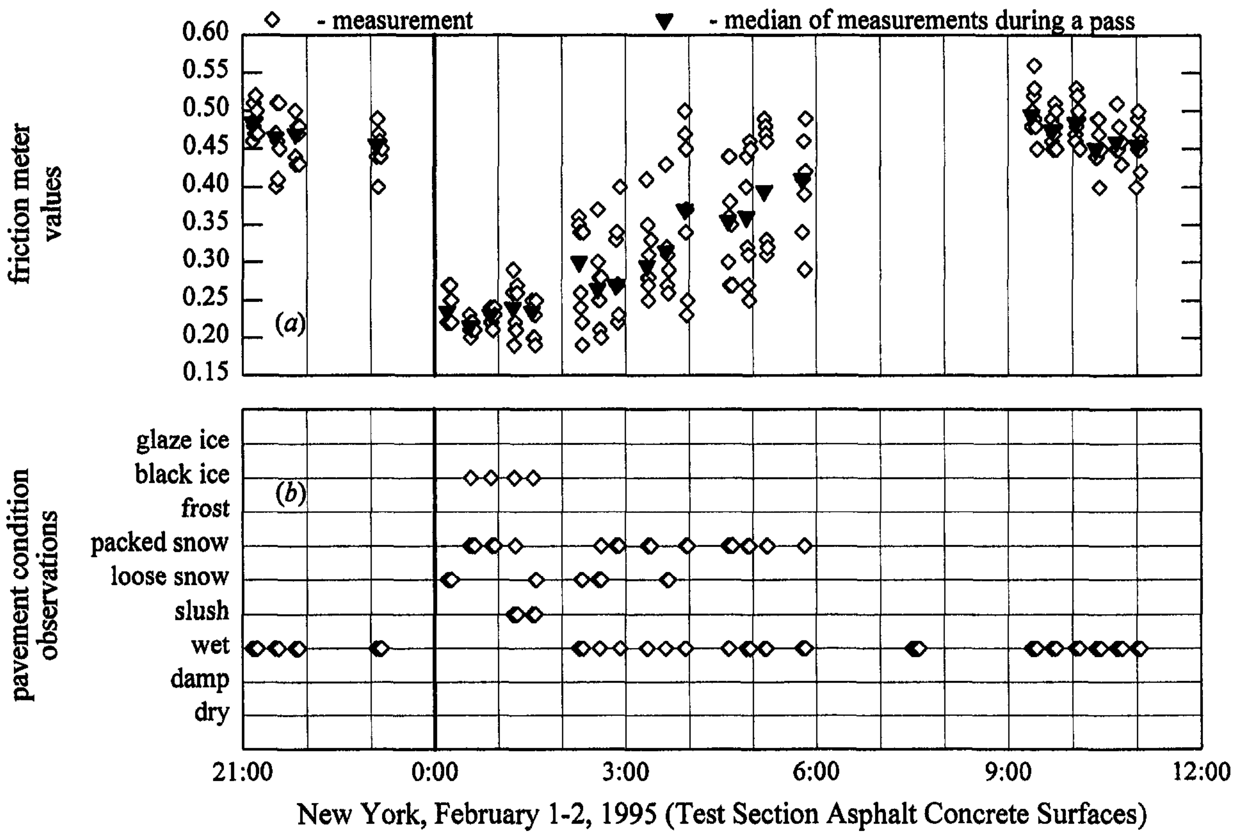


Figure 4. Example of (a) measured friction meter values, plotted with the median of the measurements of each pass, and (b) pavement condition observations corresponding to the measured friction values.

Table 4. Example summary of documented driving lane operations, from New York, February 1-2, 1995.

	test section	control section
total number of passes	7	5
number of passes with plowing	0	0
number of passes with fine salt application	5	0
total application kg/lane-km	141	
(lb/lane-mi)	(500)	
number of passes with rock salt application	2	5
total application kg/lane-km	116	295
(lb/lane-mi)	(412)	(1048)
number of passes with $CaCl_2$ prewetting solution	5	0
total $CaCl_2$ application kg/lane-km	9	
(lb/lane-mi)	(32)	
number of passes with abrasives application	1	1
total application kg/lane-km	95	94
(lb/lane-mi)	(338)	(335)

Table 5. Categories for data analysis.

a. **Precipitation observation categories** (Observers could select from eight categories when making their observations: none, light rain, rain, freezing rain, sleet, light snow, snow, or blowing snow. Six categories were formed from these eight and used for analysis.)

Category	Comment
none	
rain	includes light rain or rain observation
freezing rain	
sleet	
light snow	
snow	includes snow or blowing snow observation

b. **Pavement temperature T_p categories** (Measurements of pavement temperature, generally from a single temperature sensor during the experiments, were placed into one of six categories for analysis.)

Category	
$T_p \leq -13.3\ ^{\circ}C$	$(T_p \leq 8\ ^{\circ}F)$
$-13.3\ ^{\circ}C < T_p \leq -10\ ^{\circ}C$	$(8\ ^{\circ}F < T_p \leq 14\ ^{\circ}F)$
$-10\ ^{\circ}C < T_p \leq -6.7\ ^{\circ}C$	$(14\ ^{\circ}F < T_p \leq 20\ ^{\circ}F)$
$-6.7\ ^{\circ}C < T_p \leq -3.3\ ^{\circ}C$	$(20\ ^{\circ}F < T_p \leq 26\ ^{\circ}F)$
$-3.3\ ^{\circ}C < T_p \leq 0\ ^{\circ}C$	$(26\ ^{\circ}F < T_p \leq 32\ ^{\circ}F)$
$T_p > 0\ ^{\circ}C$	$(T_p > 32\ ^{\circ}F)$

c. **Traffic rate categories** (Traffic count measurements were used to calculate traffic rates, which were placed into one of six categories for analysis.)

Category
vehicles/h ≤ 50
50 < vehicles/h ≤ 100
100 < vehicles/h ≤ 200
200 < vehicles/h ≤ 400
400 < vehicles/h ≤ 600
vehicles/h > 600

d. **Pavement condition observation categories** (Observers could select from nine categories when making their observations: dry; damp; wet; slush; loose snow; packed snow; frost; black ice; or glaze ice. Seven categories were formed from these nine and used for analysis.)

Category	Comment
dry/damp	includes dry or damp observation
wet	
slush	
loose snow	
packed snow	
frost	
black/glaze ice	includes black ice or glaze ice observation

The distributions provide a graphical comparison of the test and control section data. A further comparison is provided by results of the Mann-Whitney rank sum statistical test, which reveals if the medians of the test and control friction are significantly different. The Mann-Whitney rank sum test is a nonparametric test, meaning that it does not presume that the data are drawn from normal populations that can be described by the parameters of a normal population, i.e., its mean and standard deviation. The graph in figure 5 includes the message "significant difference," indicating that the rank sum test found that the difference in the median values of the test and control data is greater than what would be expected by chance. In this and the individual site reports, a 5-percent or less probability of being wrong is accepted in concluding that a significant difference exists.

The friction data statistics and results of the Mann-Whitney rank sum test are tabulated in table 6, where further results of the test are provided. These and the plotted results in figure 5 were generated using the software package *SigmaStat™ Statistical Software*.[19] Reference is made to the user's manual of the package for results included in the table.[19]

4.2.5 Categorical Data Analysis

Analysis of the categorical data was conducted by assembling the data according to test and control sections within contingency tables, and then performing Chi-square statistical tests. Examples of contingency tables and results for the pavement condition, precipitation, pavement temperature, and traffic rate categorical data are shown in tables 7 through 10, respectively, for the February 1-2, 1995 storm at the New York site.

The original data of the contingency tables are the "counts" data shown for each combination of section and category. The counts data and the derived percentage data provide tabulated indications of both the conditions in the storm and the effectiveness of the operations. For example, examination of the tables show that the most common test section conditions at the times of the friction measurements were light snow, pavement temperatures in the -3.3°C to 0°C (26°F to 32°F) range, and traffic rates between 400 and 600 vehicles/h. With regard to effectiveness, the most common pavement condition observation was wet. Other data in tables 7 through 10 are results of the Chi-square calculations and tests of significant relation, or difference. As previously, these calculations were performed using *SigmaStat™ Statistical Software*.[19] A message indicating if there is a significant relation between the categorical data and the section is given. For example, in table 7, the result is that the pavement condition category and the section category were significantly related, indicating that there was a significant difference between test and control pavement conditions during the storm. Qualitative examination of the counts and expected counts, e.g., the greater number of packed snow observations on the test section, reveals that the difference favors the control section.

The pavement condition observation data were intended to be measures of effectiveness. The data and results of table 7 demonstrate how useful and conclusive the data can be, by the characterization of the pavement conditions for a storm, and by the comparison of the effectiveness of the test and control operations. The other categorical data were not measures of effectiveness but were indications of conditions during the storm. Analyses of these data allowed differences in the test and control conditions to be established. Ideally, the categorical analyses of an individual storm would reveal what these analyses demonstrated with regard to precipitation and pavement temperature: that there was no significant difference in precipitation or pavement temperatures at the times of the test and control measurements.

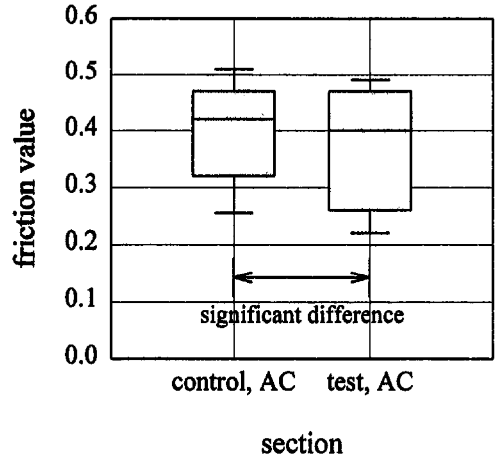


Figure 5. Example Tukey box plots of test and control friction data from New York AC sections, February 1-2, 1995.

Table 6. Example friction data statistics and results of the Mann-Whitney rank sum test, from New York AC sections, February 1-2, 1995.

Test and control AC sections:

Normality Test: Failed (P = <0.0001)

Group	N	Missing	Median	25%	75%
control	208	8	0.420	0.320	0.470
test	208	9	0.400	0.260	0.470

T = 36744.5 n(small) = 199 n(big) = 200 (P = 0.0080)

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.00799)

4.3 FULL-SEASON SITE ANALYSIS

In general, all storm data sets of sufficient quality from a season that included test section operations representative of the anti-icing treatment strategy at the site were included in the full-season analysis for the site. For seasons or sites where the number of analyzed storms of a season could not provide meaningful full-season results, the analysis was not conducted. While results of the full-season analyses are included in the following chapter, they are more completely presented in the site reports. (See references 7 through 18.) Examples of the results are presented here to describe the analysis process.

A full-season analysis included (1) a summary of the operations of the season, compiled from the operations summaries of the individual storms included in the full-season analysis; (2) calculations and presentations of friction distributions grouped according to factor variables using the table 5 categories; (3) Spearman rank order correlations of normalized friction vs. numerical variables including pavement temperature, precipitation rate, and traffic rate; and (4) analysis of the pavement condition, precipitation, pavement temperature, and traffic rate categorical data. The operations summaries and the categorical

Table 7. Example results of Chi-square analysis of pavement condition observation category vs. section, from New York AC sections, February 1-2, 1995.

Category		Control	Test
wet	Counts	139	119
	Expected Counts	129.0	129.0
	Row %	53.9	46.1
	Column %	66.8	57.2
	Total %	33.4	28.6
slush	Counts	16	11
	Expected Counts	13.5	13.5
	Row %	59.3	40.7
	Column %	7.7	5.3
	Total %	3.9	2.6
loose snow	Counts	35	26
	Expected Counts	30.5	30.5
	Row %	57.4	42.6
	Column %	16.8	12.5
	Total %	8.4	6.3
packed snow	Counts	17	46
	Expected Counts	31.5	31.5
	Row %	27.0	73.0
	Column %	8.2	22.1
	Total %	4.1	11.1
black/glaze ice	Counts	1	6
	Expected Counts	3.5	3.5
	Row %	14.3	85.7
	Column %	0.5	2.9
	Total %	0.2	1.4

Notes:

1. Power of performed test with alpha = 0.0500: 0.9764
2. Chi-square = 20.7 with 4 degrees of freedom. (P=0.0004)
3. The proportions of observations in different columns of the contingency table vary from row to row. The two characteristics that define the contingency table are significantly related.

data analyses were extensions of the techniques used for the individual storm analyses. For a full-season analysis they provided an overall indication of the operations and conditions throughout a season, and allowed comparisons of the test and control conditions and of the effectiveness of the test and control operations. The techniques of the friction distribution and Spearman correlation analyses are briefly discussed here.

4.3.1 Full-Season Friction Data Analysis

A full-season analysis of friction data consisted of calculations and presentations of friction distributions grouped by factor variables: pavement condition category, section, section and precipitation category, section and pavement temperature category; section and traffic rate category, and section and pavement condition category. Examples of the friction distributions of four of these groupings, from the 1993/1994 season at the New York site, are presented in figure 6. The distributions are shown as Tukey box plots. As described previously in section 4.2.4, the top of a box indicates the 75th percentile, the bottom indicates the 25th percentile, the line inside a box is the median, the single line above a box is the 90th percentile, and that below a box the 10th percentile.

Table 8. Example results of Chi-square analysis of precipitation observation category vs. section, from New York AC sections, February 1-2, 1995.

Category		Control	Test
none	Counts	62	63
	Expected Counts	62.5	62.5
	Row %	49.6	50.4
	Column %	29.8	30.3
	Total %	14.9	15.1
light snow	Counts	130	122
	Expected Counts	126.0	126.0
	Row %	51.6	48.4
	Column %	62.5	58.7
	Total %	31.3	29.3
snow	Counts	16	23
	Expected Counts	19.5	19.5
	Row %	41.0	59.0
	Column %	7.7	11.1
	Total %	3.9	5.5

Notes:

1. Power of performed test with alpha = 0.0500: 0.1716
2. The power of the performed test (0.1716) is below the desired power of 0.8000. (You should interpret the negative findings cautiously.)
3. Chi-square = 1.52 with 2 degrees of freedom. (P = 0.4680)
4. The proportions of observations in different columns of the contingency table do not vary from row to row. The two characteristics that define the contingency table are not significantly related.

Table 9. Example results of Chi-square analysis of pavement temperature category vs. section, from New York, February 1-2, 1995.

Category			Control	Test
-6.7 °C < T_p ≤ -3.3 °C	**(20 °F < T_p ≤ 26 °F)**	Counts	40	47
		Expected Counts	43.5	43.5
		Row %	46.0	54.0
		Column %	19.2	22.6
		Total %	9.6	11.3
-3.3 °C < T_p ≤ 0 °C	**(26 °F < T_p ≤ 32 °F)**	Counts	144	137
		Expected Counts	140.5	140.5
		Row %	51.2	48.8
		Column %	69.2	65.9
		Total %	34.6	32.9
T_p > 0 °C	**(T_p > 32 °F)**	Counts	24	24
		Expected Counts	24.0	24.0
		Row %	50.0	50.0
		Column %	11.5	11.5
		Total %	5.8	5.8

Notes:

1. Power of performed test with alpha = 0.0500: 0.1054
2. The power of the performed test (0.1054) is below the desired power of 0.8000. (You should interpret the negative findings cautiously.)
3. Chi-square = 0.738 with 2 degrees of freedom. (P = 0.6916)
4. The proportions of observations in different columns of the contingency table do not vary from row to row. The two characteristics that define the contingency table are not significantly related.

Table 10. Example results of Chi-square analysis of traffic rate category vs. section, from New York, February 1-2, 1995.

Category		Control	Test
vehicles/h ≤ 50	Counts	14	24
	Expected Counts	19.0	19.0
	Row %	36.8	63.2
	Column %	6.7	11.5
	Total %	3.4	5.8
50 < vehicles/h ≤ 100	Counts	26	32
	Expected Counts	29.0	29.0
	Row %	44.8	55.2
	Column %	12.5	15.4
	Total %	6.3	7.7
100 < vehicles/h ≤ 200	Counts	56	56
	Expected Counts	56.0	56.0
	Row %	50.0	50.0
	Column %	26.9	26.9
	Total %	13.5	13.5
200 < vehicles/h ≤ 400	Counts	44	8
	Expected Counts	26.0	26.0
	Row %	84.6	15.4
	Column %	21.2	3.9
	Total %	10.6	1.9
400 < vehicles/h ≤ 600	Counts	27	80
	Expected Counts	53.5	53.5
	Row %	25.2	74.8
	Column %	13.0	38.5
	Total %	6.5	19.2
vehicles/h > 600	Counts	41	8
	Expected Counts	24.5	24.5
	Row %	83.7	16.3
	Column %	19.7	3.9
	Total %	9.9	1.9

Notes:
1. Power of performed test with alpha = 0.0500: 1.0000
2. Chi-square = 76.7 with 5 degrees of freedom. (P = <0.0001)
3. The proportions of observations in different columns of the contingency table vary from row to row. The two characteristics that define the contingency table are significantly related.

The distributions in figure 6 are of a normalized friction. This is the original friction divided by a representative value for wet pavement friction. This value was chosen to be the median of all friction values of the full-season analysis that were made when the recorded pavement condition category was wet. The first graph in the figure, which shows friction distributions grouped according to pavement condition, reflects this process by the wet category median value of 1.0. This graph does not distinguish between test and control, whereas the other graphs do. The purpose of the first graph is to illustrate the variation of all of the friction values with the recorded pavement condition category, which serves as an indicator of the quality of the friction and pavement condition observations as independent measures of effectiveness for the site and season. The second graph compares all control section friction measurements of the season with all test section measurements; if a significant difference had been found, it would be indicated on the graph. The graph provides indications of the overall effectiveness of the operations as well, by showing where the distribution lies with respect to the friction of specific pavement conditions. The third and fourth graphs show friction vs. section and pavement temperature or precipitation conditions, and serve to reveal conditions under which the overall operations are most or least successful.

4.3.2 Spearman Rank Order Correlation

The nonparametric Spearman rank order test was used to examine correlations of test section friction with pavement temperature, precipitation, and/or traffic conditions. These correlations were conducted with numerical scale data to provide indications of underlying relationships beyond those provided by the analyses with friction distributions grouped according to categories.

4.4 RESULTS INTERPRETATION METHODOLOGY

The overall methodology for interpreting the field evaluation results can be described as a "forest before the trees approach." That is, an attempt was made in the case of each site where a number of storm packages were submitted to gain the broader understanding that a full-season analysis provided before interpreting individual storms. With the breadth of knowledge from a full-season analysis, the context of the individual storm operations and results was better understood, and the analysis results could be better interpreted. Interpretations of both individual storms and full-season analyses are included in the site reports. (See references 7 through 18.)

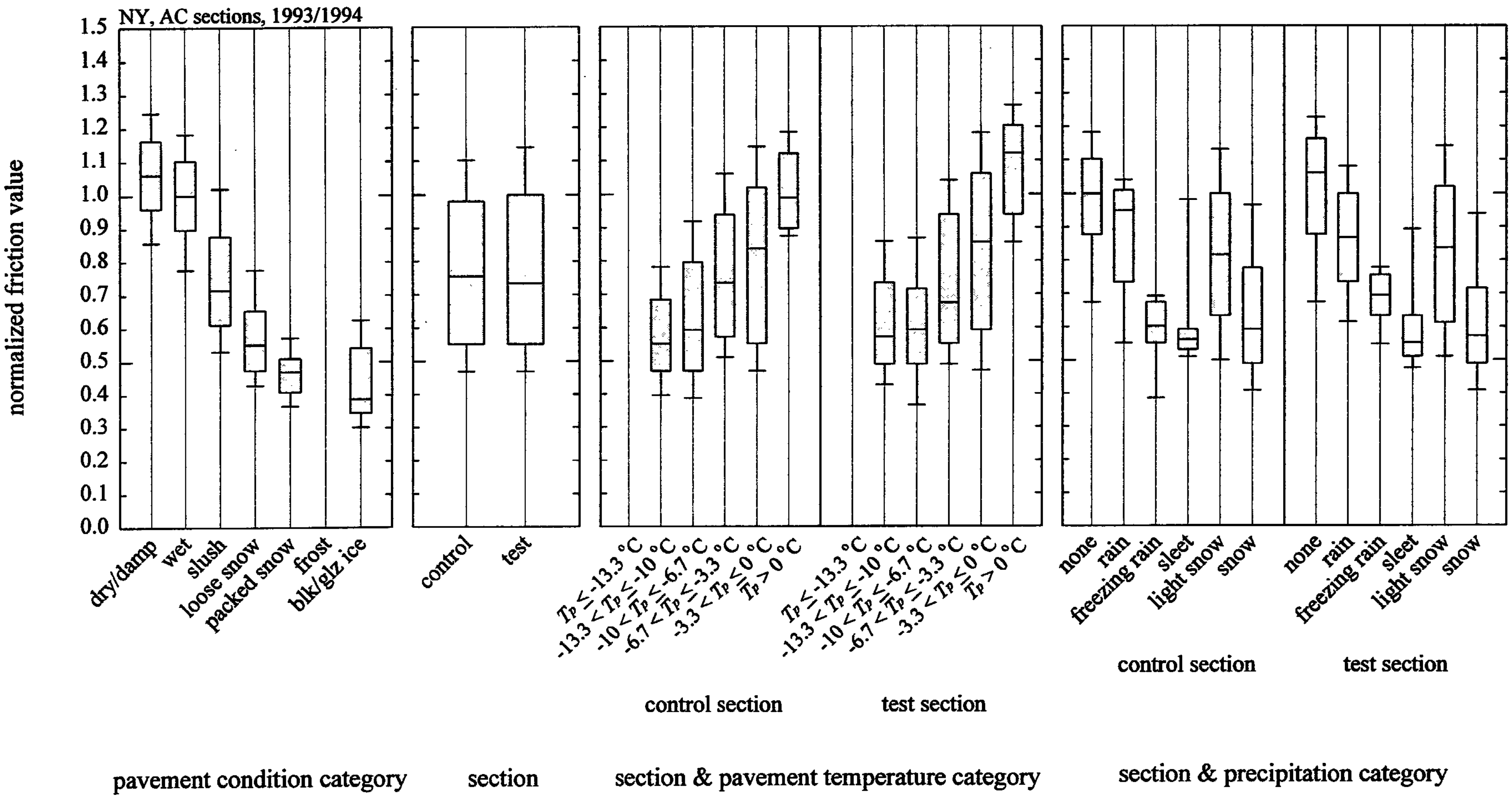


Figure 6. Examples of friction distributions vs. pavement condition category, section, section and pavement temperature category, and section and precipitation category, from New York AC sections, winter 1993/1994.

5. FIELD EVALUATION RESULTS AND INTERPRETATION

5.1 INTRODUCTION

This chapter presents results and interpretations of field experiments conducted by States participating in the project. As described previously, analyses were performed for individual storm data sets and for data sets of multiple storms from a given season and site. Whereas detailed results and interpretations of both individual storm and full-season data sets are presented in separate site reports, a subset of these results are presented here. (See references 7 through 18.) The included data sets were chosen from all of the analyzed data sets because they (1) illustrate techniques and benefits of anti-icing practices; (2) demonstrate how systematic anti-icing practices might lead to further improvements in snow and ice control practice; (3) provide a basis for recommending changes in practice; and (4) provided the basis for the practice described in the companion *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel*.[1]

Lists of the storm data sets whose analysis is included in the site reports are presented in table 11 for the 1993/1994 season and table 12 for the 1994/1995 season. The tables list the site, the storm date or dates, and the site and storm identification, which was also used to name computer files pertaining to the storms.

This chapter is organized according to different types of chemical operations. Section 5.2 presents data and results from solid and prewetted solid chemical application sites, section 5.3 covers sites where applications of chemical solutions were made, and section 5.4 pertains to sites where mixes of rock salt and abrasives were used. Summarizing data and results are presented in section 5.5.

5.2 DATA AND RESULTS FROM DRY- AND PREWETTED-SOLID CHEMICAL APPLICATION SITES

Data and results from the experimental site in New York, the Ohio Interstate 70 and Interstate 71 sites, and the Kansas site are presented here. At each site conventional sodium chloride rock salt was used on both the test and control sections. Calcium chloride or sodium chloride in solution was used as a prewetting liquid during most or all of the test section operations. In New York and Kansas a finer gradation of rock salt was used on the test section in addition to conventional coarse-crushed rock salt.

Table 13 lists the storm data sets presented and discussed in this section. More extensive analyses and interpretations of the data sets are presented in the corresponding site reports.

5.2.1 Data and Results From New York

The New York site is in the Rochester metropolitan area. It is within a few kilometers of Lake Ontario in the city of Webster.

The test and control sections were 11-km (7-mi) sections of NY 104 east of the Irondequoit Bay. For most of this length the highway has two travel lanes in each direction. Short distances between interchanges contain three lanes each way, and for 3 km (2 mi) the highway has service lanes in both directions. The pavement surface course is portland cement concrete over the westernmost 3 km (2 mi), and asphalt concrete over the easternmost 8 km (5 mi). The eastbound lanes were the test section, and the westbound lanes were the control section. Each section covered approximately 22 lane-km (14 lane-mi).

Table 11. Winter 1993/1994 storm data sets included in individual site reports.

Site	Storm Dates	Storm ID
California	February 6-7, 1994	CA0294A
California	February 18-20, 1994	CA0294D
Maryland	December 11-12, 1993	MD1293B
Maryland	December 18-19, 1993	MD1293C
Maryland	December 20-22, 1993	MD1293D
Maryland	December 24-27, 1993	MD1293F
Maryland	December 28-30, 1993	MD1293G
Maryland	January 3-6, 1994	MD0194A
Maryland	January 13-16, 1994	MD0194D
Nevada	December 2-3, 1993	NV1293A
Nevada	December 11-12, 1993	NV1293B
Nevada	December 14-15, 1993	NV1293C
Nevada	December 26-27, 1993	NV1293D
Nevada	February 10-11, 1994	NV0294B
Nevada	February 17, 1994	NV0294C
New Hampshire	December 19, 1993	NH1293B
New Hampshire	December 21, 1993	NH1293C
New Hampshire	December 29-30, 1993	NH1293D
New Hampshire	January 3-5, 1994	NH0194A
New Hampshire	January 7-8, 1994	NH0194B
New Hampshire	January 12-13, 1994	NH0194C
New Hampshire	January 27-28, 1994	NH0194D
New Hampshire	March 21-22, 1994	NH0394A
New Hampshire	March 27, 1994	NH0394B
New York	January 27-28, 1994	NY0194A
New York	January 29-30, 1994	NY0194C
New York	February 3, 1994	NY0294A
New York	February 4, 1994	NY0294B
New York	February 5-6, 1994	NY0294C
New York	February 7-10, 1994	NY0294D
New York	February 12-14, 1994	NY0294F
New York	February 15-16, 1994	NY0294G
New York	February 23-26, 1994	NY0294J
New York	March 2-3, 1994	NY0394A
New York	March 9-10, 1994	NY0394B
New York	March 15-17, 1994	NY0394C
Wisconsin	December 31, 1993- January 1, 1994	WI1293A
Wisconsin	January 4, 1994	WI0194A
Wisconsin	January 5-6, 1994	WI0194B
Wisconsin	January 10, 1994	WI0194C

Table 12. Winter 1994/1995 storm data sets included in individual site reports.

Site	Storm Dates	Storm ID
California	December 5-7, 1994	CA412A
California	December 11-12, 1994	CA412B
California	December 13-14, 1994	CA412C
California	January 22-23, 1995	CA501B
California	March 22-23, 1995	CA503A
Colorado	November 27-29, 1994	CO411C
Colorado	December 7-8, 1994	CO412A
Colorado	December 13-14, 1994	CO412B
Colorado	December 15-16, 1994	CO412C
Colorado	January 5-8, 1995	CO501A
Colorado	January 12, 1995	CO501B
Colorado	January 13, 1995	CO501C
Colorado	January 16, 1995	CO501D
Colorado	January 17-18, 1995	CO501E
Colorado	February 9-13, 1995	CO502A
Iowa	December 6, 1994	IA412A
Iowa	December 14-15, 1994	IA412B
Iowa	January 27, 1995	IA501A
Iowa	February 14-15, 1995	IA502A
Iowa	February 27, 1995	IA502B
Iowa	March 4-5, 1995	IA503A
Kansas	December 6-7, 1994	KS412A
Kansas	December 30, 1994 - January 1, 1995	KS412B
Kansas	January 27-28, 1995	KS501A
Kansas	February 13-14, 1995	KS502A
Kansas	February 27-28, 1995	KS502B
Kansas	March 6-7, 1995	KS503A
Missouri	December 31, 1994- January 1, 1995	MO412A
Missouri	January 5-6, 1995	MO501A
Nevada	November 9-10, 1994	NV411A
Nevada	November 10-11, 1994	NV411B
Nevada	December 11-12, 1994	NV412A
Nevada	December 12-13, 1994	NV412B
Nevada	December 14-15, 1994	NV412C
Nevada	January 4-5, 1995	NV501A
Nevada	January 6-7, 1995	NV501B
Nevada	January 10-11, 1995	NV501C
Nevada	January 14-15, 1995	NV501D
Nevada	January 23-24, 1995	NV501F
Nevada	January 26-27, 1995	NV501G
Nevada	February 13-14, 1995	NV502A
Nevada	March 20-21, 1995	NV503A
Nevada	March 22-23, 1995	NV503B

Site	Storm Dates	Storm ID
New Hampshire	January 2, 1995	NH501A
New Hampshire	January 6-7, 1995	NH501B
New Hampshire	January 11-13, 1995	NH501C
New Hampshire	February 4-5, 1995	NH502A
New Hampshire	February 15-16, 1995	NH502B
New Hampshire	February 27-28, 1995	NH502C
New York	January 6-7, 1995	NY501A
New York	January 20-21, 1995	NY501D
New York	January 23-25, 1995	NY501F
New York	January 25-27, 1995	NY501G
New York	January 28, 1995	NY501H
New York	February 1-2, 1995	NY502A
New York	February 4-7, 1995	NY502B
New York	February 7-8, 1995	NY502C
New York	February 10, 1995	NY502E
New York	February 11-12, 1995	NY502F
New York	February 23-25, 1995	NY502H
New York	March 8-9, 1995	NY503B
Ohio I-70	January 6-7, 1995	O0501B
Ohio I-70	January 8, 1995	O0501C
Ohio I-70	January 9-10, 1995	O0501D
Ohio I-70	January 20-24, 1995	O0501E
Ohio I-70	January 27, 1995	O0501F
Ohio I-70	February 3, 1995	O0502A
Ohio I-70	February 4, 1995	O0502C
Ohio I-70	February 10, 1995	O0502D
Ohio I-70	February 14-15, 1995	O0502E
Ohio I-71	January 6-7, 1995	O1501A
Ohio I-71	January 10, 1995	O1501D
Ohio I-71	February 3-4, 1995	O1502B
Ohio I-71	February 10, 1995	O1502D
Ohio I-71	February 15, 1995	O1502E
Wisconsin	January 10, 1995	WI501A
Wisconsin	January 19-20, 1995	WI501B
Wisconsin	February 14-15, 1995	WI502A
Wisconsin	March 4-5, 1995	WI503A

Table 13. Storm data sets showing operations using solid and prewetted chemical applications.

Site	Storm Dates	Storm ID
New York	January 6-7, 1995	NY501A
New York	January 23-25, 1995	NY501F
New York	February 1-2, 1995	NY502A
New York	February 7-8, 1995	NY502C
New York	March 8-9, 1995	NY503B
New York	February 12-14, 1994	NY0294F
Ohio I-70	January 20-24, 1995	O0501E
Ohio I-70	February 14-15, 1995	O0502E
Ohio I-71	January 6-7, 1995	O1501A
Ohio I-71	February 3-4, 1995	O1502B
Kansas	December 30, 1994 - January 1, 1995	KS412B
Kansas	March 6-7, 1995	KS503A

Measurements and observations of effectiveness were made on the outside (driving) lanes. The surface course at the location of a measurement and observation was noted so that the data from the PCC test and control sections could be analyzed separately from the data of the AC test and control sections. Individual PCC and AC analyses were conducted for the 1994/1995 winter season data, while analyses of only the AC test and control sections were conducted for the 1993/1994 winter season data.

The site is a New York State Department of Transportation (NYSDOT) research site, and is the location of experiments conducted for the previous SHRP project H-208.(2) NYSDOT has road weather information system and traffic data installations at the site. Wintertime average daily traffic is approximately 25,000 toward the west end of the test and control sections, and 13,000 toward the east end of the sections.

Analyses of 12 representative New York storm data sets from the 1994/1995 season, and 12 sets from the 1993/1994 season, are presented in detail in the site report.(15) The data histories and operations summaries for six of the storms are presented in figures 7 through 12 and table 14, respectively. Additional results are included in figures 13 through 15 and tables 15 through 19. Summary points and conclusions regarding the operations and their effectiveness over the course of the two seasons at the site are presented below.

5.2.1.1 Precipitation and pavement temperature

Snow and light snow dominated the precipitation at the site. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) and -6.7°C to -3.3°C (20°F to 26°F) categories, but 1/4 to 1/3 of the measurements and observations were made when the temperatures were -6.7°C (20°F) and below. Tables 53 and 54 in section 5.5 provide more detail regarding precipitation observations and pavement temperatures at the times of the friction measurements.

5.2.1.2 Operations

NYSDOT highway maintenance guidelines call for operations in snow and winter storms that are essentially anti-icing practices. Recommendations are to apply chemicals as soon as the event starts, to time the applications to prevent pack from forming, and not to use abrasives when salt works, all of which are important components of an anti-icing program.

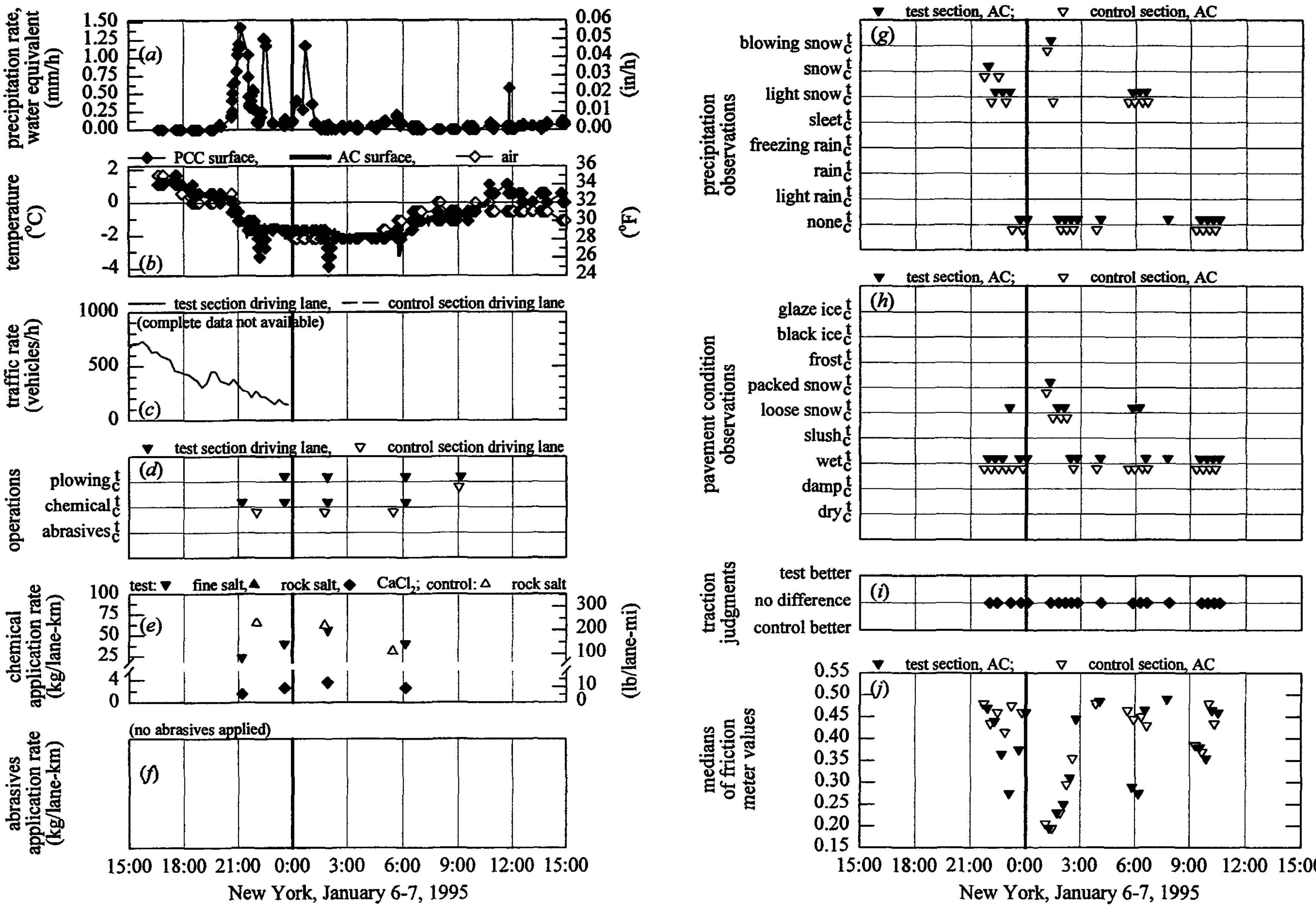


Figure 7. New York, storm NY501A, January 6-7, 1995, data histories.

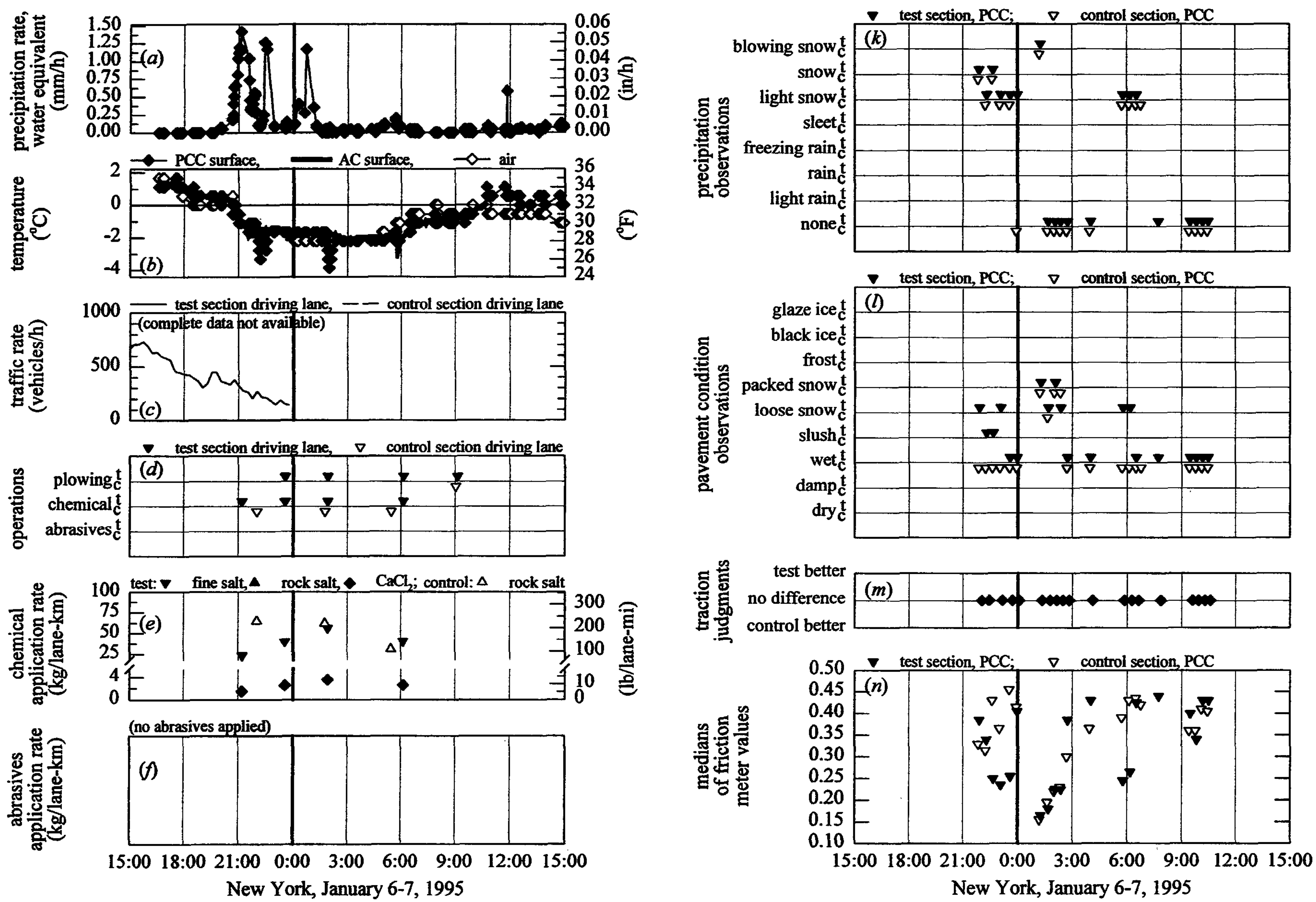


Figure 7. New York, storm NY501A, January 6-7, 1995, data histories (continued).

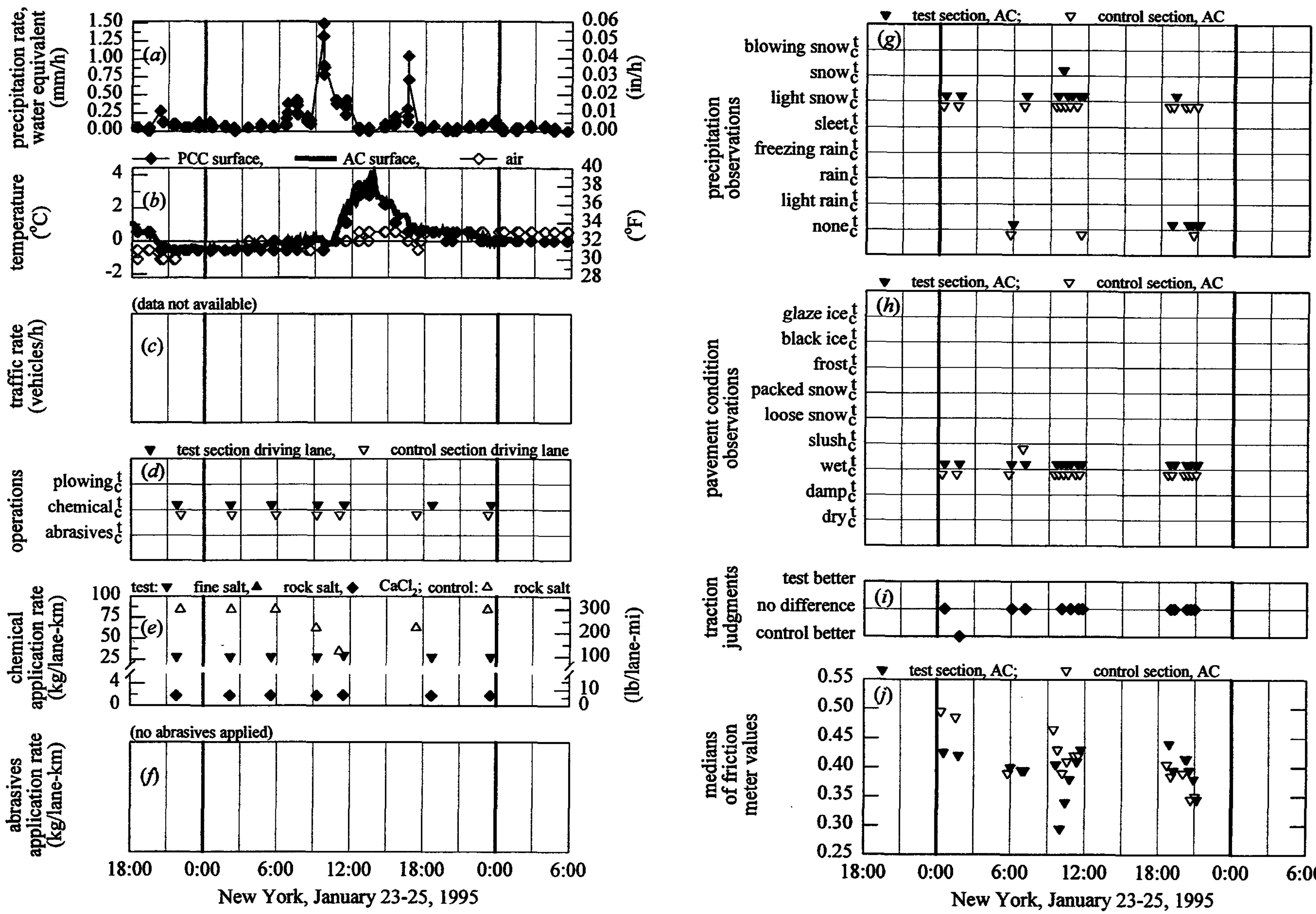


Figure 8. New York, storm NY501F, January 23-25, 1995, data histories.

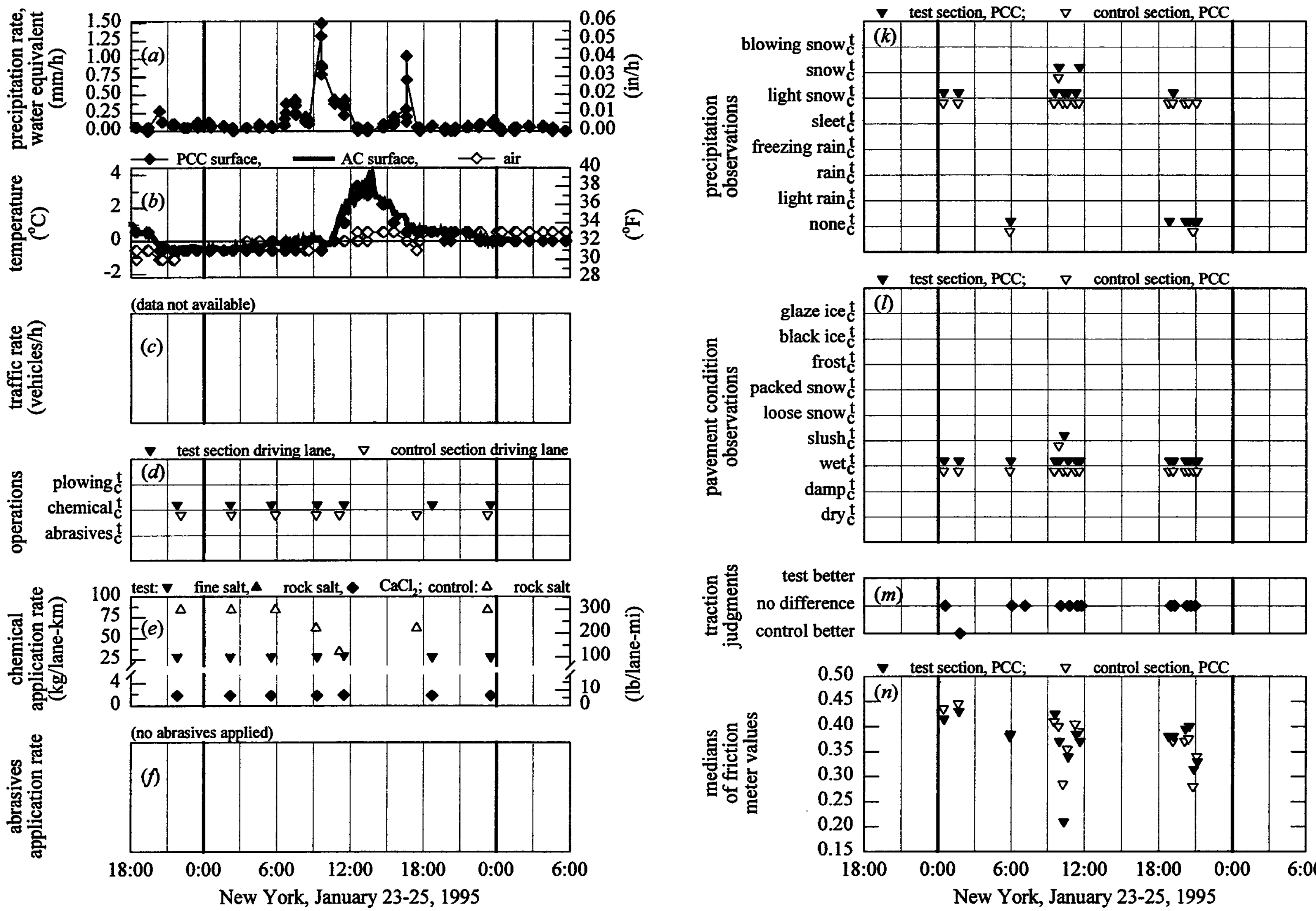


Figure 8. New York, storm NY501F, January 23-25, 1995, data histories (continued).

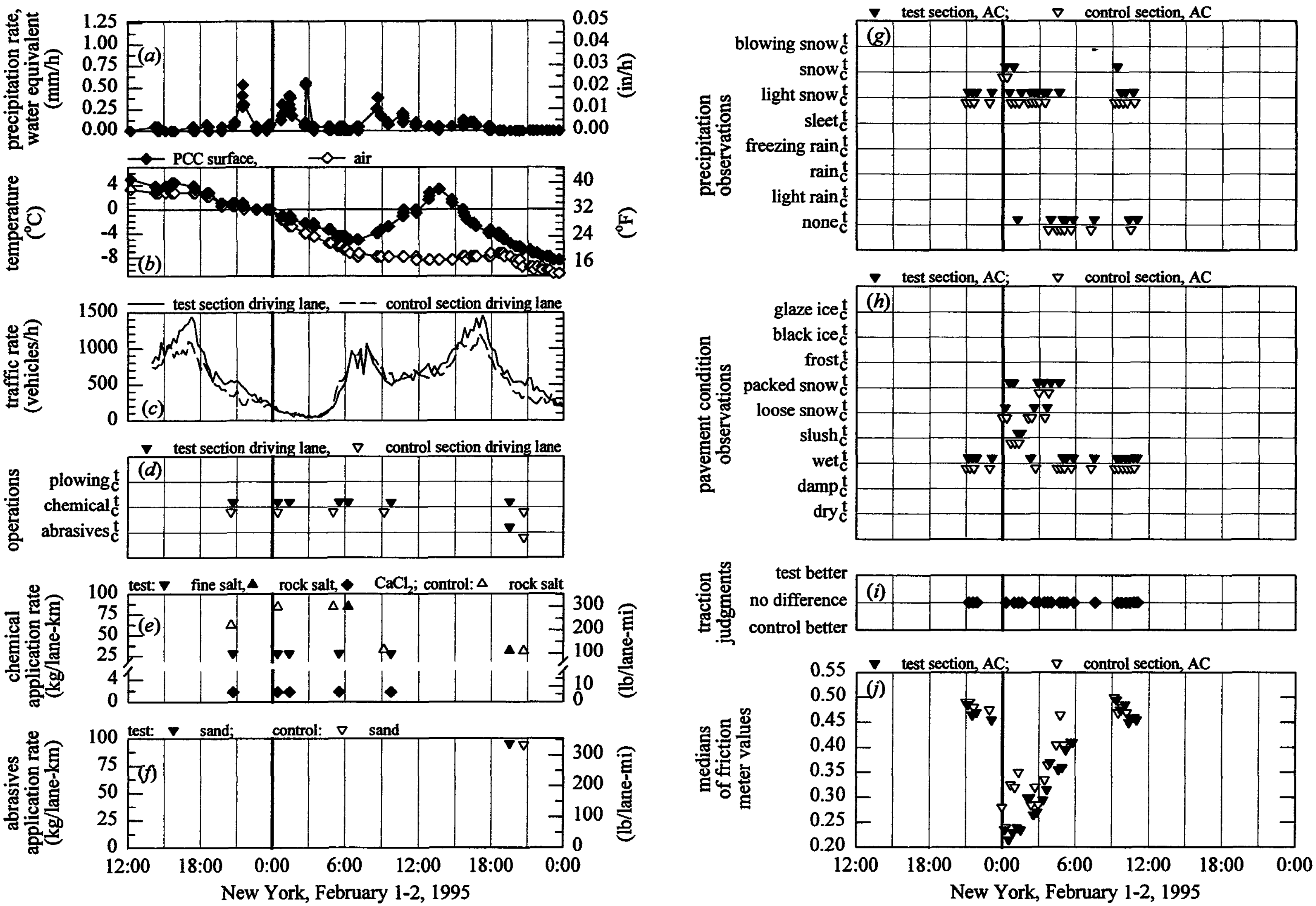


Figure 9. New York, storm NY502A, February 1-2, 1995, data histories.

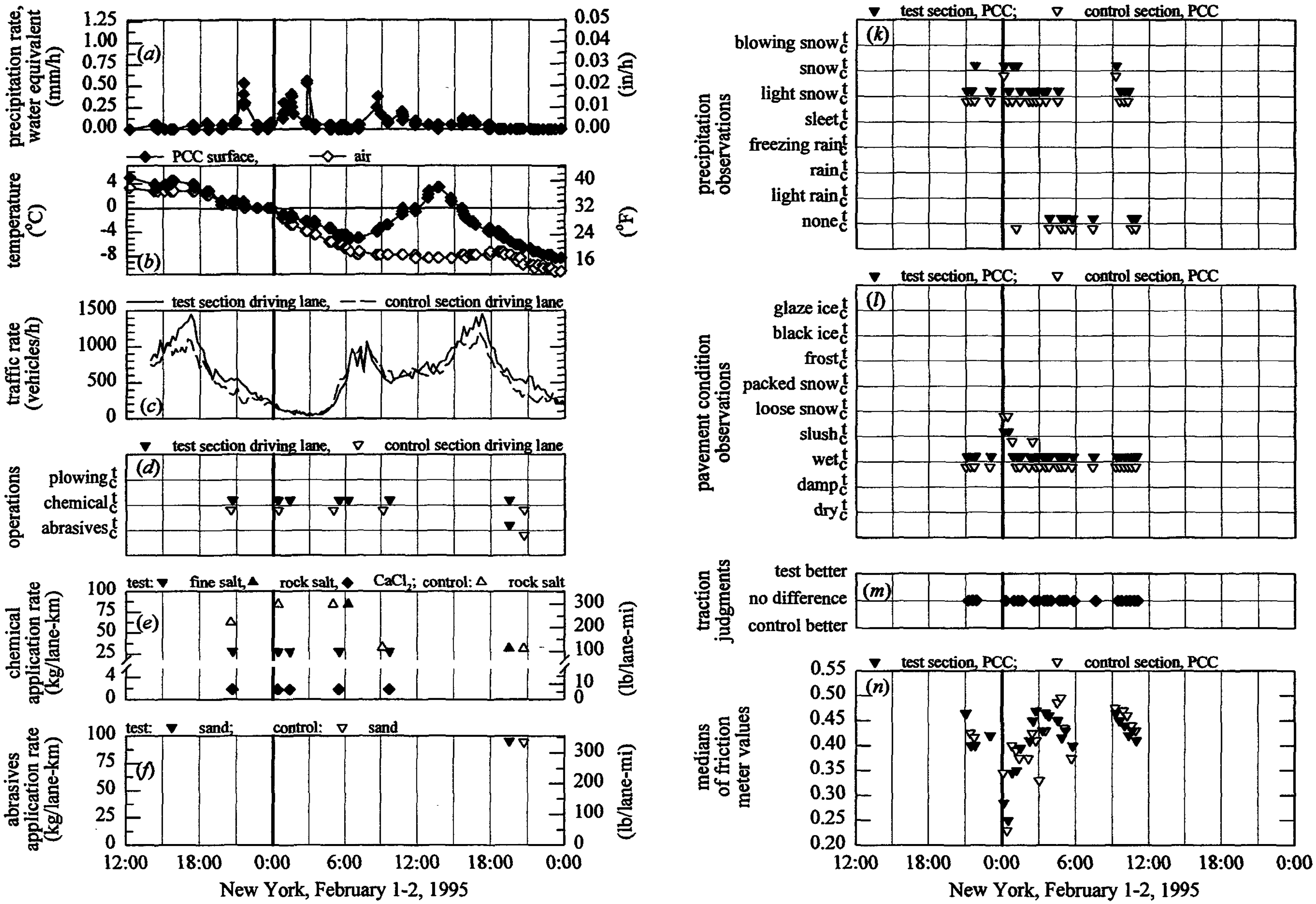


Figure 9. New York, storm NY502A, February 1-2, 1995, data histories (continued).

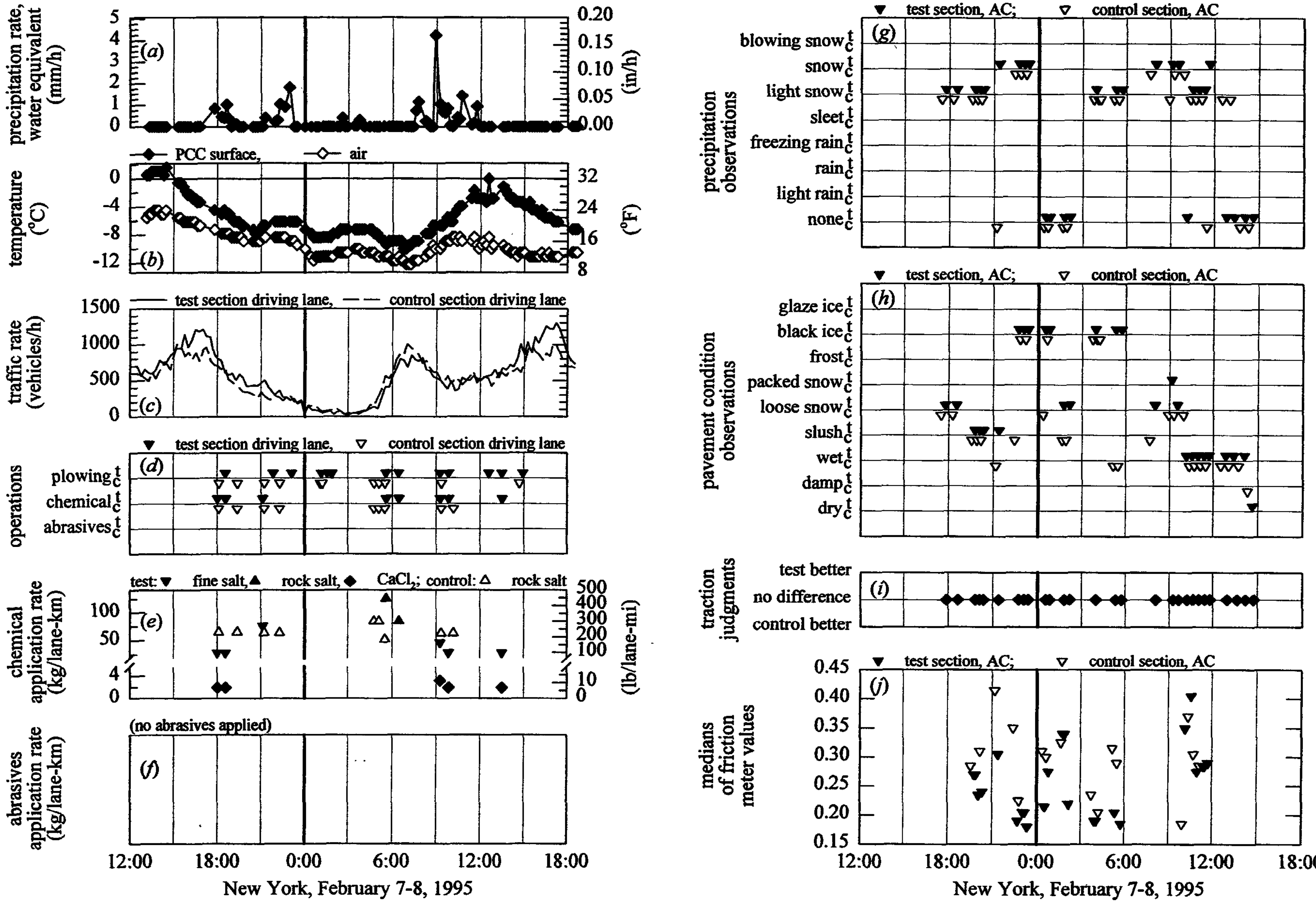


Figure 10. New York, storm NY502C, February 7-8, 1995, data histories.

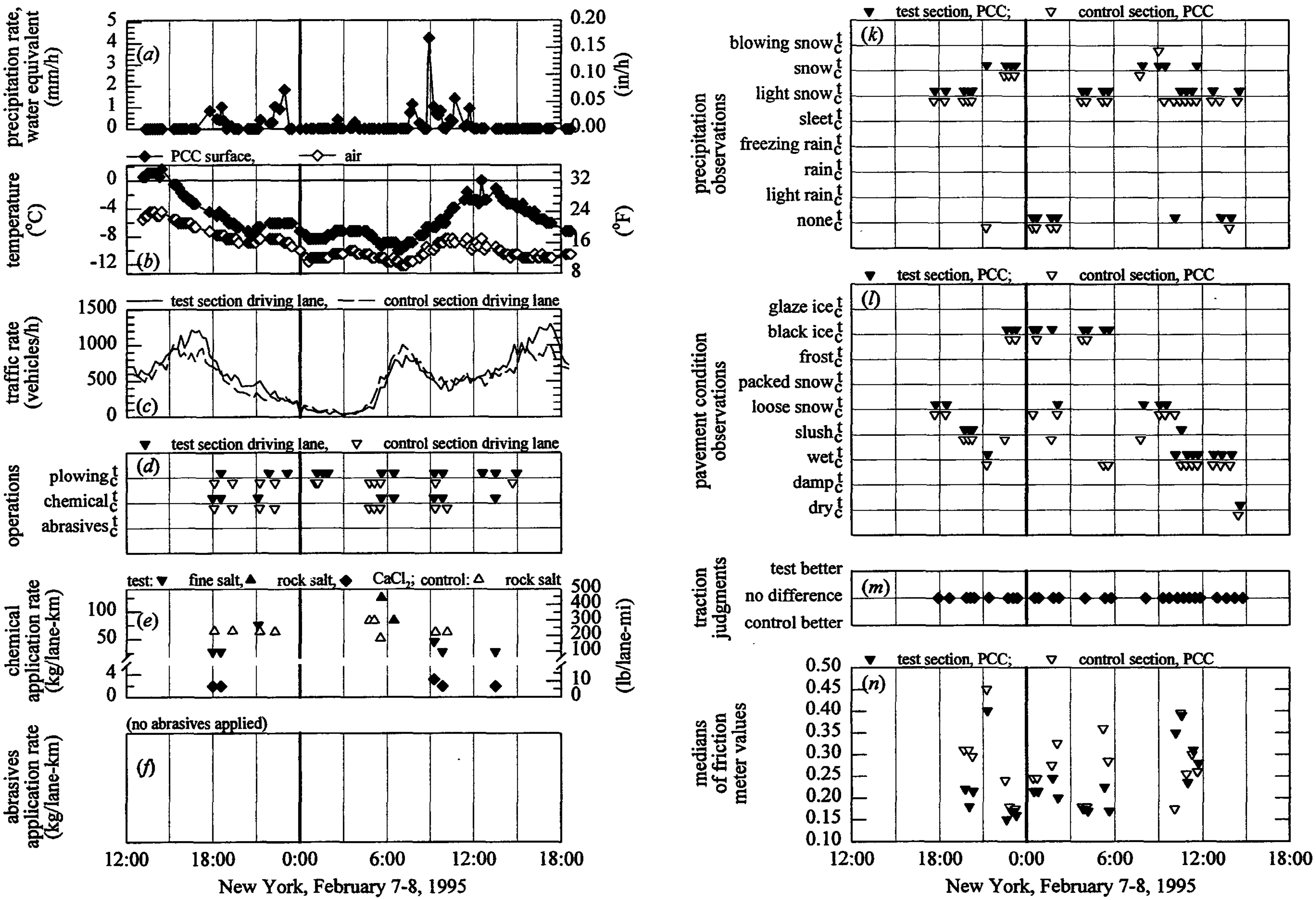


Figure 10. New York, storm NY502C, February 7-8, 1995, data histories (continued).

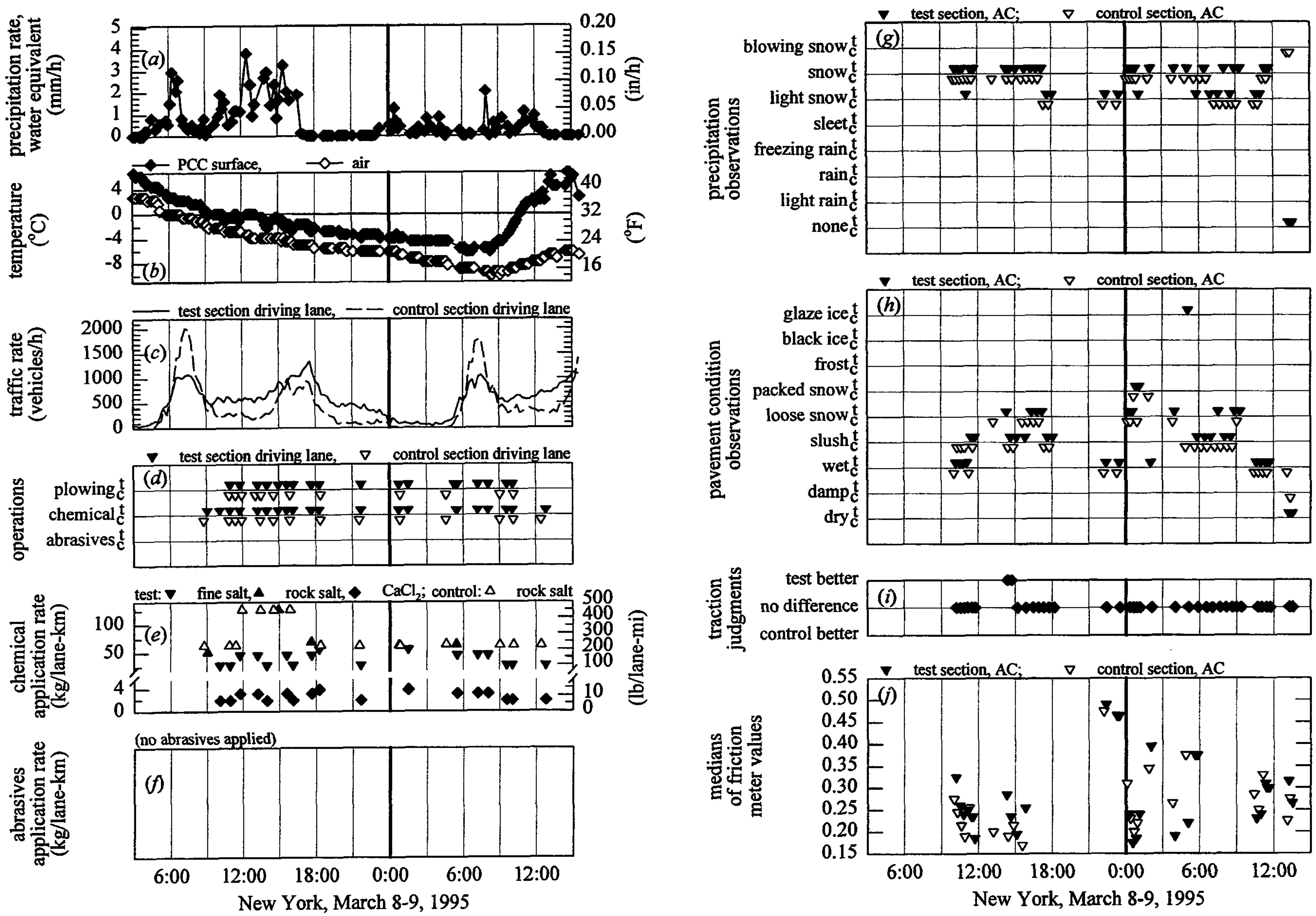


Figure 11. New York, storm NY503B, March 8-9, 1995, data histories.

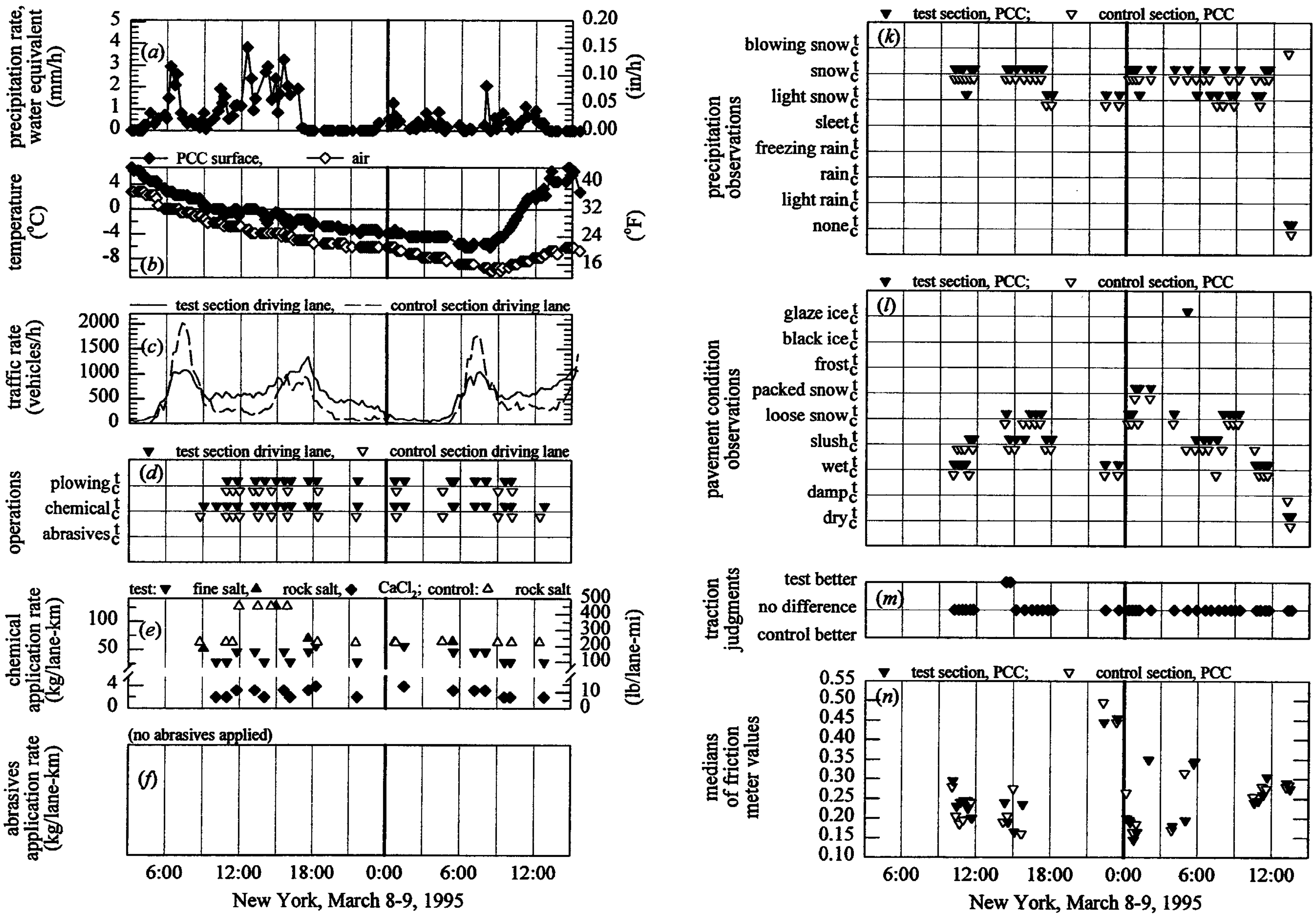


Figure 11. New York, storm NY503B, March 8-9, 1995, data histories (continued).

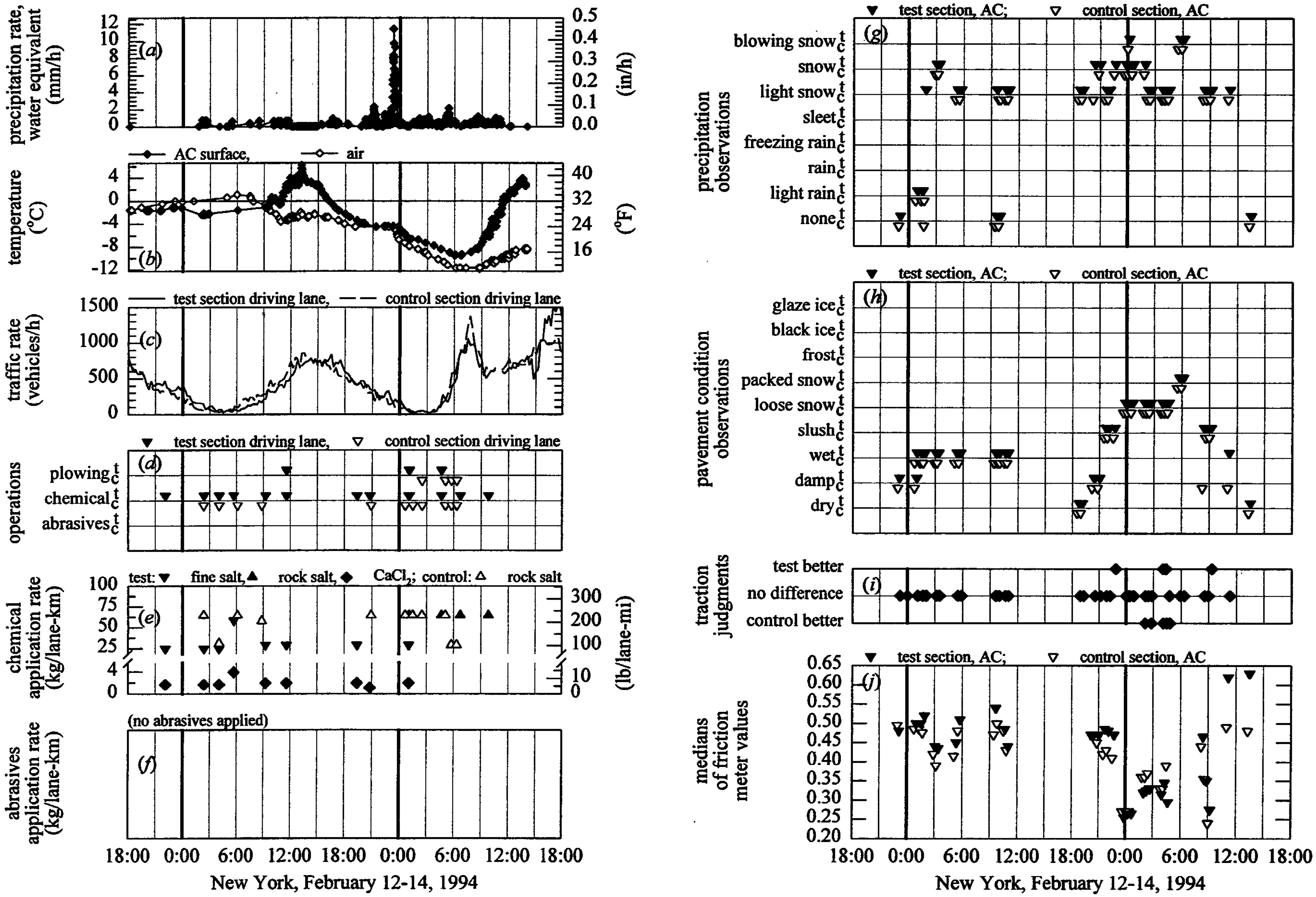


Figure 12. New York, storm NY0294F, February 12-14, 1994, data histories.

Table 14. New York storms NY501A, NY501F, NY502A, NY502C, NY503B, and NY0294F. Summary of documented driving lane operations on test and control sections.

	NY501A January 6-7, 1995		NY501F January 23-25, 1995		NY502A February 1-2, 1995		NY502C February 7-8, 1995		NY503B March 8-9, 1995		NY0294F February 12-14, 1994	
	test section	**control section**	**test section**	**control section**	**test section**	**control section**	**test section**	**control section**	**test section**	**control section**	**test section**	**control section**
total number of passes	5	4	7	7	7	5	16	13	23	17	13	11
number of passes with plowing	4	1	0	0	0	0	14	12	20	14	3	4
number of passes with fine salt application	4	0	7	0	5	0	6	0	17	0	9	0
total application kg/lane-km	161		199		141		236		665		266	
(lb/lane-mi)	(570)		(707)		(500)		(837)		(2358)		(945)	
number of passes with rock salt application	0	3	0	7	2	5	2	9	5	14	4	11
total application kg/lane-km		158		497	116	295	209	602	376	1141	259	601
(lb/lane-mi)		(560)		(1763)	(412)	(1048)	(742)	(2135)	(1335)	(4049)	(920)	(2132)
number of passes with $CaCl_2$ prewetting solution	4	0	7	0	5	0	5	0	17	0	9	0
total $CaCl_2$ application kg/lane-km	10		13		9		11		45		18	
(lb/lane-mi)	(36)		(45)		(32)		(39)		(160)		(63)	
number of passes with abrasives application	0	0	0	0	1	1	0	0	0	0	0	0
total application kg/lane-km					95	94						
(lb/lane-mi)					(338)	(335)						

Operations summaries for the 1994/1995 and 1993/1994 seasons are shown in tables 15 and 16, respectively. The test section chemical operations included applications of fine salt, which were usually prewetted with a 32-percent calcium chloride solution, and conventional rock salt. Over both seasons approximately 60 percent of the test section chemical operations on the driving lane were fine salt applications. Chemical operations on the control section were primarily applications of conventional rock salt. During the 24 storms that were analyzed, 4 percent more salt (rock salt, fine salt, or calcium chloride) was applied on the control section driving lane than on the test section driving lane. As indicated in the operations summaries for the seasons, abrasives were used on occasions on both the test and control section driving lanes. They were placed in a 3:1 mixture with rock salt. In only one pass of one of the six storms presented here (storm NY502A) was the mix applied.

Table 15. New York, winter 1994/1995. Summary of documented driving lane operations.

	test section	control section
total number of passes	134	103
number of passes with plowing	83	55
number of passes with fine salt application	72	1
total application kg/lane-km	2344	28
(lb/lane-mi)	(8318)	(101)
number of passes with rock salt application	31	78
total application kg/lane-km	1967	5110
(lb/lane-mi)	(6979)	(18131)
number of passes with either fine salt or rock salt application	103	79
total application kg/lane-km	4311	5139
(lb/lane-mi)	(15297)	(18231)
number of passes with $CaCl_2$ prewetting solution	68	1
total $CaCl_2$ application kg/lane-km	142	2
(lb/lane-mi)	(503)	(7)
number of passes with abrasives application	9	9
total application kg/lane-km	1013	1179
(lb/lane-mi)	(3595)	(4184)

Note: Data from storms NY501A, NY501D, NY501F, NY501G, NY501H, NY502A, NY502B, NY502C, NY502E, NY502F, NY502H, and NY503B.

Table 16. New York, winter 1993/1994. Summary of documented driving lane operations.

	test section	control section
total number of passes	110	105
number of passes with plowing	64	68
number of passes with fine salt application	56	0
total application kg/lane-km	2303	
(lb/lane-mi)	(8172)	
number of passes with rock salt application	41	85
total application kg/lane-km	3032	5187
(lb/lane-mi)	(10759)	(18405)
number of passes with either fine salt or rock salt application	97	85
total application kg/lane-km	5336	5187
(lb/lane-mi)	(18931)	(18405)
number of passes with $CaCl_2$ prewetting solution	55	1
total $CaCl_2$ application kg/lane-km	157	2
(lb/lane-mi)	(557)	(6)
number of passes with abrasives application	6	14
total application kg/lane-km	670	1554
(lb/lane-mi)	(2378)	(5515)

Note: Data from storms NY0194A, NY0194C, NY0294A, NY0294B, NY0294C, NY0294D, NY0294F, NY0294G, NY0294J, NY0394A, NY0394B, and NY0394C.

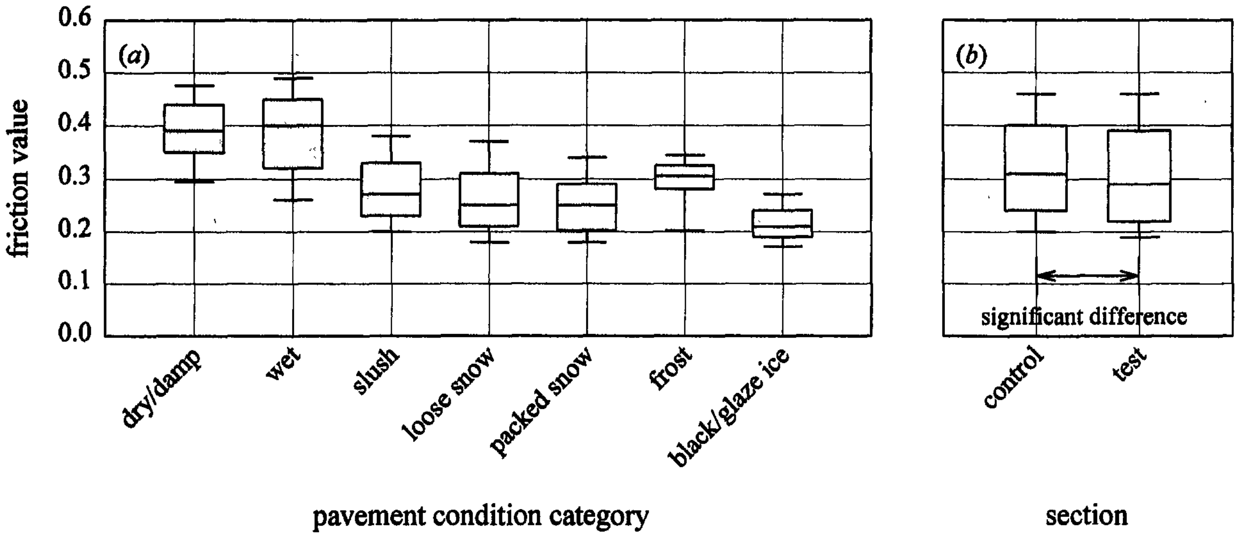


Figure 13. New York AC friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 17. Statistics of New York AC friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	330	131	0.390	0.350	0.440
wet	2043	285	0.400	0.320	0.450
slush	618	145	0.270	0.230	0.330
loose snow	1800	298	0.250	0.210	0.310
packed snow	288	33	0.250	0.203	0.290
frost	8	0	0.305	0.280	0.325
black/glaze ice	346	9	0.210	0.190	0.240

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	2728	439	0.310	0.240	0.400
test	2705	462	0.290	0.220	0.390

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

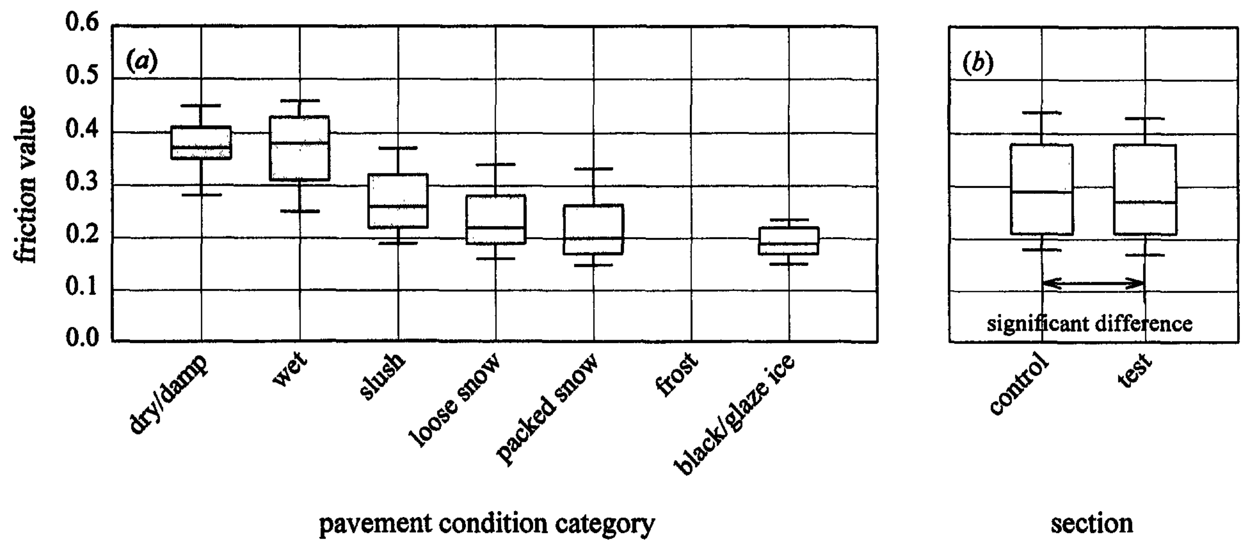


Figure 14. New York PCC friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 18. Statistics of New York PCC friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	151	68	0.370	0.350	0.410
wet	1073	140	0.380	0.310	0.430
slush	296	69	0.260	0.220	0.320
loose snow	867	173	0.220	0.190	0.280
packed snow	115	2	0.200	0.170	0.263
black/glaze ice	213	23	0.190	0.170	0.220

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	1358	231	0.290	0.210	0.380
test	1357	244	0.270	0.210	0.380

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

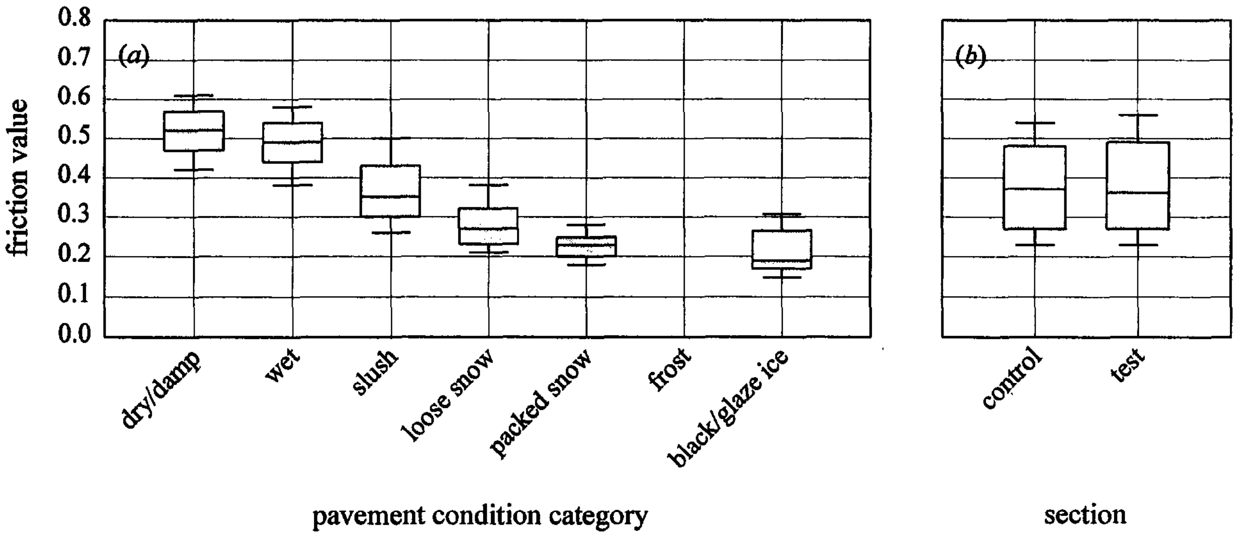


Figure 15. New York AC friction measurement data, winter 1993/1994. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 19. Statistics of New York AC friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1993/1994.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	234	0	0.520	0.470	0.570
wet	343	0	0.490	0.440	0.540
slush	428	0	0.350	0.300	0.430
loose snow	595	0	0.270	0.233	0.320
packed snow	35	0	0.230	0.200	0.250
black/glaze ice	19	0	0.190	0.170	0.265

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
test	913	0	0.360	0.270	0.490
control	741	0	0.370	0.270	0.480

The differences in the median values among the two groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

Tests of the salt gradations by NYSDOT provided the sieve and percent passing information in the table below. Both the fine salt and the conventional rock salt were mineral crushed rock salt. However, the term rock salt is used here to designate the conventional coarse crushed material, while the term fine salt refers to crushed salt at a finer gradation. The calcium chloride solution was to be used at a nominal rate of 167 L/t (40 gal/ton) of fine salt.

NYSDOT salt gradations.

Sieve Size	**Percent Retained**	
	conventional coarse crushed salt	**fine salt**
10 mm	2	
4.76 mm (No. 4)	29	0
2.38 mm (No. 8)	63	4
0.590 mm (No. 30)	90	70

Initial test section chemical applications, which were usually fine salt/$CaCl_2$-solution applications, were generally placed soon after snowfall had begun or when the pavement temperature was dropping toward freezing. Only a few of the applications were made in advance of precipitation. Initial control section operations often followed soon after the initial test section operations, but in many storms were conducted simultaneously or prior to the test section operation, reflecting mostly the anti-icing strategy of the conventional operations at the site. Benefits of prompt initial operations are seen in the control section data histories of storm NY501A (figure 7). Although the initial application of fine salt/$CaCl_2$-solution on the test section driving lane was at a rate that was too low to prevent an excessive drop in friction for the snowfall rates early in the storm, the initial rock salt application on the control section driving lane prevented a drop in friction like that on the test section. This application was made soon after a drop in pavement temperature below freezing and the beginning of snowfall when the pavement condition was wet. It clearly demonstrates that adequate early chemical applications can have a beneficial influence on friction.

Subsequent test section operations comprised fine salt, fine salt/$CaCl_2$ solution, rock salt, sand/salt mix, and plowing operations. The fine salt applications were generally prewetted with $CaCl_2$ solution as a matter of course, but occasionally were placed without prewetting. The various materials and application rates used on the test section, and the changes in the materials and rates during storms, reflect primarily a real-time systematic approach to anti-icing, but also the disorganizing influences at the site: surprising changes of weather and lake-effect precipitation, and the complex system of mainline, service, and ramp roadways. Decisions regarding material use and application rates were typically made by a supervisor aware of weather and pavement temperature forecast information, real-time RWIS data, pavement condition observations, friction measurements, and traffic volume. In a number of the New York data histories, subsequent chemical applications on both the test and control sections appear well timed and responsive to changing conditions, and produced desired results of increased friction and improved pavement conditions.

Comparison of supervisor's and operator's logs indicate that at times unnecessary operations were performed that were not consistent with the supervisor's intention. For example, storm NY501F shows a late morning increase in snowfall on January 24 that resulted in a temporary drop in friction. A subsequent rise in pavement temperature above freezing resulted in a rapid increase in friction. Test and control section chemical applications onto wet pavement following the snow shower and pavement temperature rise were performed even though the supervisor recognized that they were not necessary and sent trucks out with instructions only to plow shoulders. Unnecessary operations such as these could readily be reduced if operators were more aware of road and weather information when making discretionary operational decisions.

5.2.1.3 Pavement condition

For each season of asphalt concrete pavement condition observations, there was a significant difference between the overall seasonal test and control section pavement condition observations.[15] In addition to tables presented in this section, pavement condition observation data are tabulated in tables 56 and 57, which are presented later in section 5.5.

As tabulated immediately below, in 1994/1995 wet was the most common test section AC pavement condition observation, followed by loose snow, slush, black/glaze ice, dry/damp, and packed snow. Wet was also the most common control section observation, followed by loose snow, slush, dry/damp, black/glaze ice, and packed snow. The greater percentage of wet conditions together with the lesser percentages of black/glaze ice and packed snow conditions favors the control section.

1994/1995 New York AC pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	6	6
wet	40	36
slush	11	11
loose snow	34	33
packed snow	5	6
black/glaze ice	5	8

In 1993/1994, loose snow was the most common test section AC pavement condition observation, followed by slush, wet, dry/damp, packed snow, and black/glaze ice. Loose snow was the most common control section observation as well, followed by slush, wet, dry/damp, packed snow, and black/glaze ice. Percentages are indicated below. The greater percentage of wet conditions together with the lesser percentage of slush conditions favors the control section, while the lesser percentages of packed snow and black/glaze ice favor the test section.

1993/1994 New York AC pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	16	16
wet	20	18
slush	27	30
loose snow	32	32
packed snow	4	3
black/glaze ice	2	1

Observations of packed snow or black/glaze ice and friction measurements indicative of a sustained, bonded snowpack were reported only a few times during the two seasons. Most often the packed snow or black/glaze ice was short lived, as in storm NY502A (figure 9) at pavement temperatures dropping toward -5°C (the mid 20s Fahrenheit), and storm NY502C (figure 10) at lower pavement temperatures. On both test and control its breakup could usually be attributed to operations prior to the development of the snowpack, reflecting a weak bond to the pavement surface, and to operations during the period of the observations. Nearly half of the 1994/1995 packed snow or black/glaze ice observations were made in a single 3-d storm that was dominated by light snow, snow or blowing snow conditions and pavement temperatures below -6°C (20°F). The impressive overall success in preventing sustained snowpack conditions, on both the test and control sections, reflects vigilant, systematic, and successful anti-icing operations of NYSDOT in the difficult conditions of the site.

5.2.1.4 Friction

Tukey box plots of the 1994/1995 AC and PCC friction data are shown in figures 13 and 14, respectively. They are presented as functions of pavement condition category and section. Corresponding data are given in tables 17 and 18. The AC and PCC median friction values, shown in parts (b) of the figures, are higher for the control section than the test section, the differences are significant, and suggest, as do the pavement condition observations, that better pavement conditions were maintained on the control section.

Although higher raw friction values were observed in general on the AC test and control sections when compared to the PCC sections, the data normalized by the median of the friction values when wet conditions were reported are in close agreement, which suggests that the accumulative effects of the test or control operations was similar on the AC and PCC sections. (No formal analysis of the AC vs. PCC results was conducted.)

For the AC pavement during the 1993/1994 season, there is no significant difference between the test and control median friction values, although the control section value is slightly higher. Tukey box plots of the 1993/1994 AC data are shown in figure 15, and corresponding data are presented in table 19.

As indicated in figure 13, figure 14, and figure 15, the medians of test and control friction values for both seasons are generally consistent with the pavement condition category slush, which reflects the periods of relatively low pavement temperatures at the site during the two seasons.

Analysis of the 1993/1994 test section friction as a function of pavement temperature, precipitation rate, and traffic rate (presented below in section 5.5, figures 58 through 60) shows that reductions in friction should generally be expected with decreasing pavement temperature, increasing precipitation rate, and decreasing traffic rate during a storm even when successful anti-icing operations are being conducted. The analysis indicated that friction was most affected by pavement temperature. Precipitation rate had the next biggest influence, followed by traffic rate. Improvements in anti-icing practices will not eliminate reductions in friction during winter storms, but should moderate the reductions in friction that are commonly experienced.

Further graphical presentations of New York normalized friction data are presented below in section 5.5, figures 71 through 73.

5.2.1.5 Application rates

The NYSDOT operations in light snowstorms of short and long duration show that when (temperature) conditions warrant chemical use, periodic applications of salt at approximately 28 kg/lane-km (100 lb/lane-mi) are adequate to maintain roads at acceptable levels of friction and prevent the formation of packed snow. In such storms plowing is usually not conducted, or only occasionally, and the frequency of the operations is controlled primarily by chemical requirements. The data histories of storm NY501F, shown in figure 8, illustrate successful operations in mostly light snow conditions, and indicate that wet pavement conditions can be maintained with regular fine salt/$CaCl_2$-solution applications at approximately 28 kg/lane-km (100 lb/lane-mi) when pavement temperatures are near freezing levels. The use of more than twice as much chemical on the control section had a benefit only during a brief snow shower. Examination of other NY storm data sets suggest that when pavement temperatures are lower, e.g., in the range -2°C to -7°C (into the 20s Fahrenheit), loose snow, slush, or wet pavement conditions can be maintained in light snowstorms, without development of packed snow, by periodic applications of salt at 28 kg/lane-km (100 lb/lane-mi).

NYSDOT operations in otherwise light snowstorms that contain short periods of moderate or heavy snow, show that periodic applications of salt at approximately 28 kg/lane-km (100 lb/lane-mi) are appropriate during the light snow conditions, but that chemical application rates at the beginning of and during the heavier snow periods should typically be doubled from the rate for light snow conditions. In such storms plowing is mainly conducted after or during periods of heavier snow, so that removal of undiluted chemical by plowing operations is generally not a problem, and the frequency of the operations is controlled primarily by chemical requirements. A limited period of heavier snow should be treated as "a storm within a storm," i.e., anti-icing operations should be conducted just prior to or at the beginning of the intense snow period to reduce the likelihood that snowpack will develop or be sustained by a strong bond. Use of reliable short-term forecasting tools would facilitate the timing of these operations, but they would otherwise be natural extensions of the responses to heavy snow seen in current snow and ice control practice. These timing and application rate recommendations are made because the operations and effectiveness measures of several storms for both test and control sections demonstrate that anti-icing operations, prior to the development of packed snow following heavier snowfall, can prevent the development of a strong bond between the packed snow and the pavement, and thus prevent packed snow conditions that cannot be readily broken by subsequent maintenance except by deicing operations. However, the data also show that packed snow and the accompanying reduction in friction regularly occurred as a result of a period of heavier snow during an otherwise light snowstorm, and that fine salt or rock salt application rates close to 55 kg/lane-km (200 lb/lane-mi) were more successful than application rates of 28 kg/lane-km (100 lb/lane-mi) in preventing excessive reductions in friction and sustained packed snow conditions. The storms NY501A, NY502A, NY502C, and NY0294F are characterized by light snow and snow, and the data histories shown in figure 7, figure 9, figure 10, and figure 12, illustrate variations of precipitation, pavement conditions, and friction that suggest the potential benefit of "storm within a storm" anti-icing operations. The first two of these storms show operations at pavement temperatures between -4°C and 0°C (25°F and 32°F), and the latter two show operations at pavement temperatures as low as -10°C (14°F).

NYSDOT operations in moderate or heavy snowstorms of long duration show that periodic applications of salt at 42 to 56 kg/lane-km (150 to 200 lb/lane-mi) are effective when temperature conditions warrant chemical use. In such storms the frequency of the operations is controlled primarily by plowing requirements, and removal of undiluted chemical by plowing operations is likely when excessive application rates are used. Thus, it is important to limit chemical applications to rates that are not wasteful. These recommendations are made because NYSDOT operations and effectiveness measures, particularly during storm NY503B (figure 11), demonstrate that frequent chemical applications in the range of the rates given above, conducted with plowing operations, were successful in preventing packed snow conditions during prolonged heavy snowfall. Control operations at longer cycle times and higher application rates, although successful anti-icing operations, required additional solo plowing passes and were not as effective even though more chemical was used. The anti-icing success of the control section operations does indicate, however, that if the desired frequency of plowing/chemical application passes can not be maintained during prolonged heavy snow periods, increasing the chemical application rate can effectively offset the lower number of passes. The increase should be limited, of course, to an amount of chemical that can go into solution and be effective within the period before the following operation in order to prevent chemical waste.

5.2.1.6 Effects of NYSDOT fine salt and prewetting on pavement condition

Where early observations and measurements are available (e.g., storm NY502A, figure 9), there is not enough evidence to suggest that the prewetted fine salt applied at the beginning of a storm is more effective than coarse crushed rock salt applied at the beginning of a storm. In later stages of storms (e.g., storm NY502A), comparisons of the effectiveness of subsequent fine salt and rock salt operations suggest that fine salt was no faster acting than the rock salt. The overall seasonal indication that better pavement conditions were maintained on the control section (from the friction measurements and pavement condition observations) supports these observations from individual storms. These results are contrary to the expected chemical and physical effects of finer gradation and prewetting of salt. Most importantly, however, these results are also contrary to observations by NYSDOT personnel, who have indicated that by using the prewetted finer gradation salt they were indeed successful in preventing bouncing and loss of chemical. These contradictions appear to indicate that more early storm measurements are necessary to establish the improved effectiveness of fine salt, or that the T&E 28 measurement techniques were not sensitive enough to detect improved effectiveness due to the observed success.

Applications of prewetted rock salt were conducted only a few times during the 24 storms analyzed. Although during one storm there is an indication of greater effectiveness of the prewetted rock salt compared to straight rock salt, discussion of prewetted rock salt will be left until later sections in this chapter.

5.2.2 Data and Results From Ohio I-70 Site

The Ohio I-70 site is in central Ohio, west of Columbus in Madison County. The test and control sections were 10-km (6-mi) sections of Interstate 70 between mile markers 80 and 86. At this location the highway includes three travel lanes in each direction, and the pavement surface course is asphalt concrete. The westbound lanes were the test section, and the eastbound lanes were the control section. Each section covered 29 lane-km (18 lane-mi). Measurements and observations of effectiveness were made on the outside driving lanes.

The site is the location of experiments conducted for the previous SHRP project H-208.[2] ODOT has road weather information system and traffic data installations at the site. Wintertime average daily traffic is approximately 35,000.

Analyses of nine Ohio I-70 storm data sets from the 1994/1995 season are presented in detail in the site report.[16] The data histories and operations summaries for two of the storms are presented in figure 16, figure 17, and table 20. Additional results are included in figure 18, table 21, and table 22. Summary points and conclusions regarding the operations and their effectiveness over the course of the season at the site are presented below. In figures and tables presented in this and later sections, the abbreviation O0 is used to designate the Ohio I-70 site and to distinguish it from the I-71 site, which in turn is identified by the abbreviation O1.

5.2.2.1 Precipitation and pavement temperature

Light snow and snow dominated the season's precipitation observations. Two of the Ohio I-70 data sets provided anti-icing operations and effectiveness data for freezing rain events. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) and -6.7°C to -3.3°C (20°F to 26°F) categories. About 6 percent of the temperatures were in the > 0°C (> 32°F) category. Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

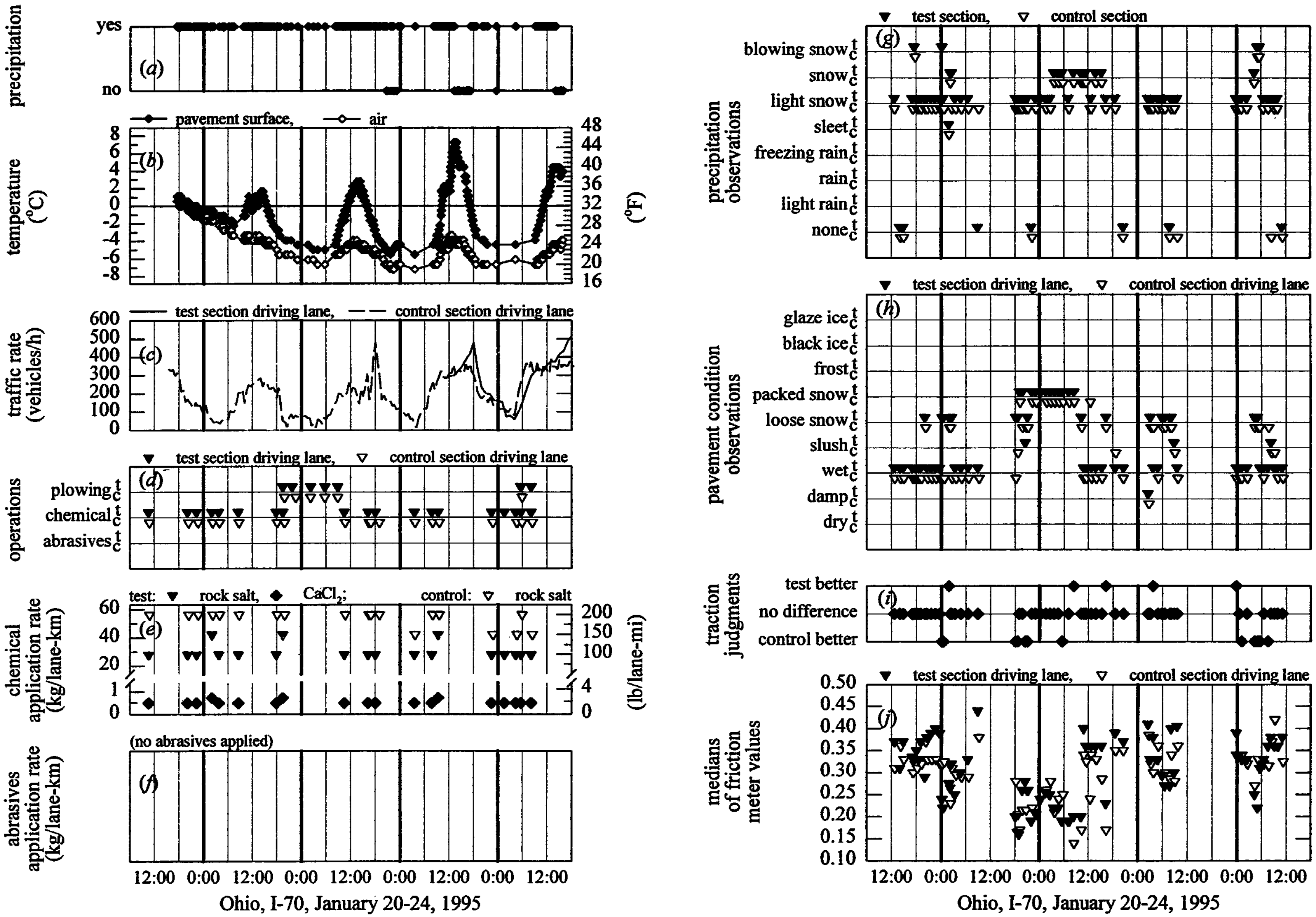


Figure 16. Ohio, I-70, storm O0501E, January 20-24, 1995, data histories.

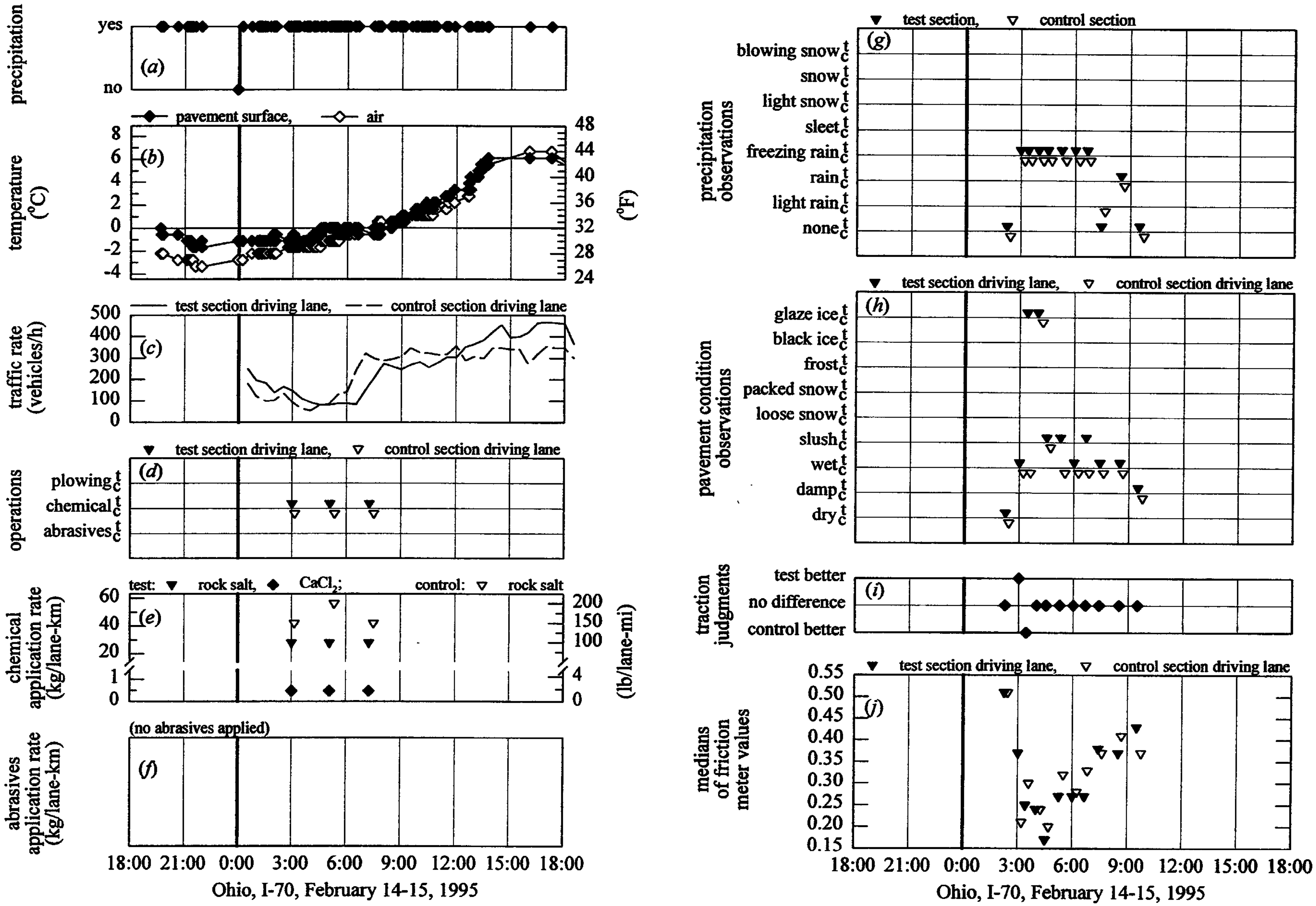


Figure 17. Ohio, I-70, storm O0502E, February 14-15, 1995, data histories.

Table 20. Ohio, I-70, storms O0501E and O0502E. Summary of documented driving lane operations on test and control sections.

	O0501E January 20-24, 1995		**O0502E** February 14-15, 1995	
	test section	**control section**	**test section**	**control section**
total number of passes	23	23	3	3
number of passes with plowing	7	6	0	0
number of passes with rock salt application	19	19	3	3
total application kg/lane-km	578	1015	85	141
(lb/lane-mi)	(2050)	(3600)	(300)	(500)
number of passes with $CaCl_2$ prewetting solution	19	0	3	0
total $CaCl_2$ application kg/lane-km	10		1.4	
(lb/lane-mi)	(35)		(5)	

Table 21. Ohio, I-70, winter 1994/1995. Summary of documented driving lane operations.

	test section	**control section**
total number of passes	54	53
number of passes with plowing	11	8
number of passes with rock salt application	49	49
total application kg/lane-km	1466	2339
(lb/lane-mi)	(5200)	(8300)
number of passes with $CaCl_2$ prewetting solution	49	0
total $CaCl_2$ application kg/lane-km	25	
(lb/lane-mi)	(89)	

Notes:
Data from storms O0501B, O0501C, O0501D, O0501E, O0501F, O0502A, O0502C, O0502D, and O0502E.
Plowing operations not fully documented for storms O0502A and O0502C.

5.2.2.2 Operations

For Interstate routes, ODOT standard operating procedure for snow and ice control calls for applications of salt, abrasives, or chemically treated abrasives from 28 to 85 kg/lane-km (100 to 300 lb/lane-mi) as soon as possible when snow or ice begins to accumulate. For chemical applications, this timing is consistent with anti-icing practice.

The operations summary for the 1994/1995 season is shown in table 21. The test section chemical operations included rock salt applications that were prewetted with a 30 percent calcium chloride solution, at a nominal rate of 42 L/t (10 gal/ton) of salt. Chemical operations on the control section were applications of straight rock salt. During the nine storms that were analyzed, 57 percent more salt (rock salt or calcium chloride) was applied on the control section driving lane than on the test section driving lane. Average rock salt application rates per pass were 48 kg/lane-km (169 lb/lane-mi) on the control section and 30 kg/lane-km (106 lb/lane-mi) on the test section. Due to labor, equipment and logistics restrictions, ODOT did not conduct control operations according to their conventional practice, as recommended in the experimental instructions of the project. Instead, the control operations were conducted using the same vehicle as, and sequentially to, the test operations.

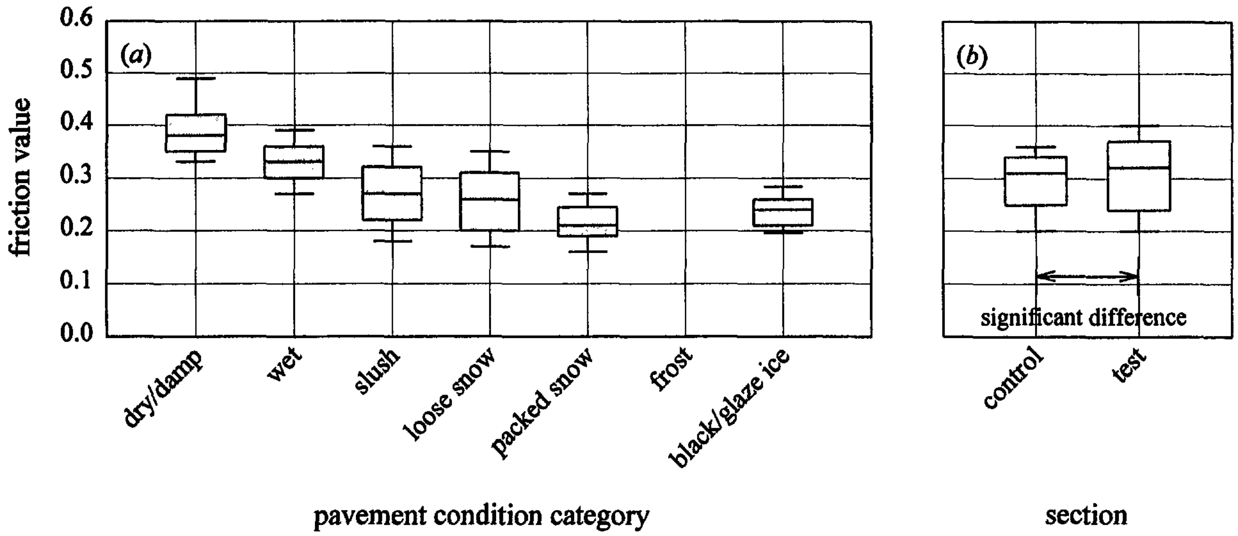


Figure 18. Ohio, I-70 friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 22. Statistics of Ohio, I-70 friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	120	0	0.380	0.350	0.420
wet	1157	0	0.330	0.300	0.360
slush	263	0	0.270	0.220	0.320
loose snow	518	0	0.260	0.200	0.310
packed snow	164	0	0.210	0.190	0.245
black/glaze ice	21	0	0.240	0.210	0.260

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	1120	0	0.310	0.250	0.340
test	1123	0	0.320	0.240	0.370

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

The initial chemical applications were generally placed when the pavement conditions were wet, slushy, or lightly snow covered. None of the applications were made well in advance of a storm. However, the timing of the initial applications was generally earlier than standard ODOT practice, and were evidently well-timed. Subsequent application passes were generally made only as needed and in prompt response to worsening or changing conditions. Operational decisions were made using forecast information, pavement temperature and other RWIS data, and observational data including patrol observations. ODOT has used these capabilities for several years, and routinely does so as part of their conventional practice.

5.2.2.3 Pavement condition

Pavement condition observation data are tabulated in tables 56 and 57, which are presented later in section 5.5, and in the table immediately below. Wet was the most common test section pavement condition observation of the season, followed by loose snow, slush, packed snow, dry/damp, and black/glaze ice. On the control section, wet was followed by loose snow, slush, packed snow, dry/damp, and black/glaze ice. No significant difference was found between the test and control section data.(16) The low percentages of packed snow and black/glaze ice observations indicate an overall anti-icing success.

1994/1995 Ohio I-70 pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	5	5
wet	51	52
slush	13	10
loose snow	22	24
packed snow	7	7
black/glaze ice	1	1

All packed snow observations of the season, for both the test and control sections, occurred in the storm O0501E, for which data histories are shown in figure 16. These packed snow observations occurred during the Saturday night and Sunday morning of this storm, over a period close to 15 h. Although the observer indicated that the snowpack appeared loose, its duration, as plowing operations were ongoing, suggests that it was bonded to the pavement surface.

The chemical application prior to the development of the packed snow in this storm was begun more than 2 h after the temperature of the pavement dropped below freezing. Friction values and pavement condition observations at the time of the chemical application suggest icy conditions existed below a loose snow cover. An inadequate chemical base caused by this delay in operations appears to be the primary reason for the development and duration of the pack. The pack broke with increasing pavement temperatures, following periodic plowing operations without chemical applications.

Other operational responses to changing conditions and pavement temperatures throughout this and other storms at the site were prompt, and demonstrate appropriate and beneficial uses of RWIS data for operational decisions. The Ohio I-70 operations in general provide an example of the evolving use and the benefits of both modern and traditional technology in anti-icing operations, demonstrate an efficient use of chemicals, and demonstrate effective anti-icing operations without abrasives applications.

5.2.2.4 Friction

Tukey box plots of the test and control section friction data are shown in figure 18 (b); corresponding data are given in table 22. The comparison shows a wider distribution in the test section friction values but a higher median than the control values. The difference is significant, and indicates that better pavement conditions were maintained on the test section relative to the control section, even though less chemical was used. As indicated by figure 18 (a), both test and control sections had high overall median friction for the season, consistent with the pavement condition category "wet," which indicates an overall anti-icing success at the site. Thus, from both the point of view of reduced chemical use and improved effectiveness, the overall anti-icing success of the test section operations was clearly greater than that of the control section operations.

Further graphical presentations of Ohio I-70 normalized friction data are presented below in section 5.5, figure 74.

5.2.2.5 Application rates

The ODOT prewetted salt operations in light snowstorms support the interpretation regarding application rates given previously for the New York data. That is, when (temperature) conditions warrant chemical use, periodic applications of prewetted salt at approximately 28 kg/lane-km (100 lb/lane-mi) are adequate to maintain roads at acceptable levels of friction and prevent the formation of packed snow. The data histories of storm O0501E, shown in figure 16, illustrate successful operations in the light snow conditions of January 23, and suggest that wet, slush, or loose snow pavement conditions with reasonable friction levels can be maintained with regular salt/$CaCl_2$-solution applications at approximately 28 kg/lane-km (100 lb/lane-mi) when pavement temperatures are as low as -5°C (the mid 20s Fahrenheit). The use of more chemical on the control section had no apparent benefit.

In otherwise light snowstorms that contain short periods of moderate or heavy snow, the ODOT operations further support the "storm within a storm" operational approach discussed previously, i.e., that periodic applications of salt at approximately 28 kg/lane-km (100 lb/lane-mi) are appropriate during the light snow conditions, but that chemical application rates at the beginning and during the heavier snow periods should typically be doubled from the rate for light snow conditions. The Ohio operations shown in figure 16 illustrate that test section chemical application rates were sometimes increased during periods of increased snowfall, but not until after friction had dropped excessively. As indicated by the January 20-21 operations before and after midnight in response to the blowing snow and snow, the control section conditions were generally better and less variable, while the test section friction dropped sharply in a short period. If the test section chemical application prior to the blowing snow and snow had been placed at the higher application rate, it is likely that the pavement conditions would not have deteriorated.

The storm O0502E data histories shown in figure 17 illustrate operations in freezing rain conditions. The operations reflect good use of forecast information for decision making and prompt responses to short term forecasts and worsening conditions. Both the test and control initial chemical applications, which came just after the first observations of glaze ice, together with a slight increase in pavement temperature, resulted in higher friction and slush or wet pavement conditions. These and subsequent applications appeared to prevent further glaze ice and therefore continuing glaze ice conditions during the early part of morning rush hour, even though the freezing rain continued into this period. The improvement of the pavement conditions and increases in friction after the initial glaze ice period reflect an overall anti-icing success. The higher applications of rock salt on the control section driving lane appear more suited to the freezing rain conditions encountered.

5.2.2.6 Effects of prewetting on pavement condition

Considering that the primary differences between the test and control operations were that (1) the application rate of rock salt was typically higher on the control section; and (2) the test section rock salt applications were prewetted with a calcium chloride solution, the greater effectiveness of the test section operations appears to be attributable solely to the prewetting of the rock salt.

5.2.3 Data and Results From Ohio I-71 Site

The Ohio I-71 site is in central Ohio, southwest of Columbus in Franklin and Pickaway Counties. The test and control sections were 10-km (6.5-mi) sections of Interstate 71 from mile markers 91.5 to 98. The highway includes two travel lanes in each direction at the site, and the pavement surface course is asphalt concrete. The southbound lanes were the test section, and the northbound lanes were the control section. Each section covered 21 lane-km (13 lane-mi). Measurements and observations of effectiveness were made on the outside driving lanes.

The site is the location of experiments conducted for the previous SHRP project H-208.[2] ODOT has road weather information system and traffic data installations at the site. Wintertime average daily traffic is approximately 30,000.

Analyses of five Ohio I-71 storm data sets from the 1994/1995 season are presented in detail in the site report.[17] The data histories and operations summaries for two of the storms are presented in figure 19, figure 20, and table 23. Additional results are presented in figure 21, table 24, and table 25. Summary points and conclusions regarding the operations and their effectiveness over the course of the season at the site are presented below. As mentioned previously, the abbreviation O1 is used to designate the Ohio I-71 site in figures and tables presented in this and later sections.

5.2.3.1 Precipitation and pavement temperature

Snow, light snow, and rain dominated the season's precipitation observations. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) category.

Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

5.2.3.2 Operations

As mentioned previously, ODOT standard operating procedure for snow and ice control on Interstate routes calls for applications of salt, abrasives, or chemically treated abrasives as soon as possible when snow or ice begins to accumulate. For the chemical applications this timing is consistent with anti-icing practice.

The operations summary for the 1994/1995 season is shown in table 24. The test section chemical operations included rock salt applications that were prewetted with a 30 percent calcium chloride solution, at a nominal rate of 42 L/t (10 gal/ton) of salt. Chemical operations on the control section were usually applications of rock salt in a 1:1 mix with abrasives ("ice grits," i.e., #9 stone), but occasionally straight applications. During the five storms that were analyzed, *eight times* more salt (rock salt or calcium chloride) was applied on the control section driving lane than on the test section driving lane. Also, 1791 kg/lane-km (6355 lb/lane-mi) of abrasives were applied on the control section, whereas no test section abrasives applications were made. Average rock salt application rates per pass were 69 kg/lane-km (245 lb/lane-mi) on the control section and 11 kg/lane-km (40 lb/lane-mi) on the test section. Average control section abrasives applications were 66 kg/lane-km (235 lb/lane-mi).

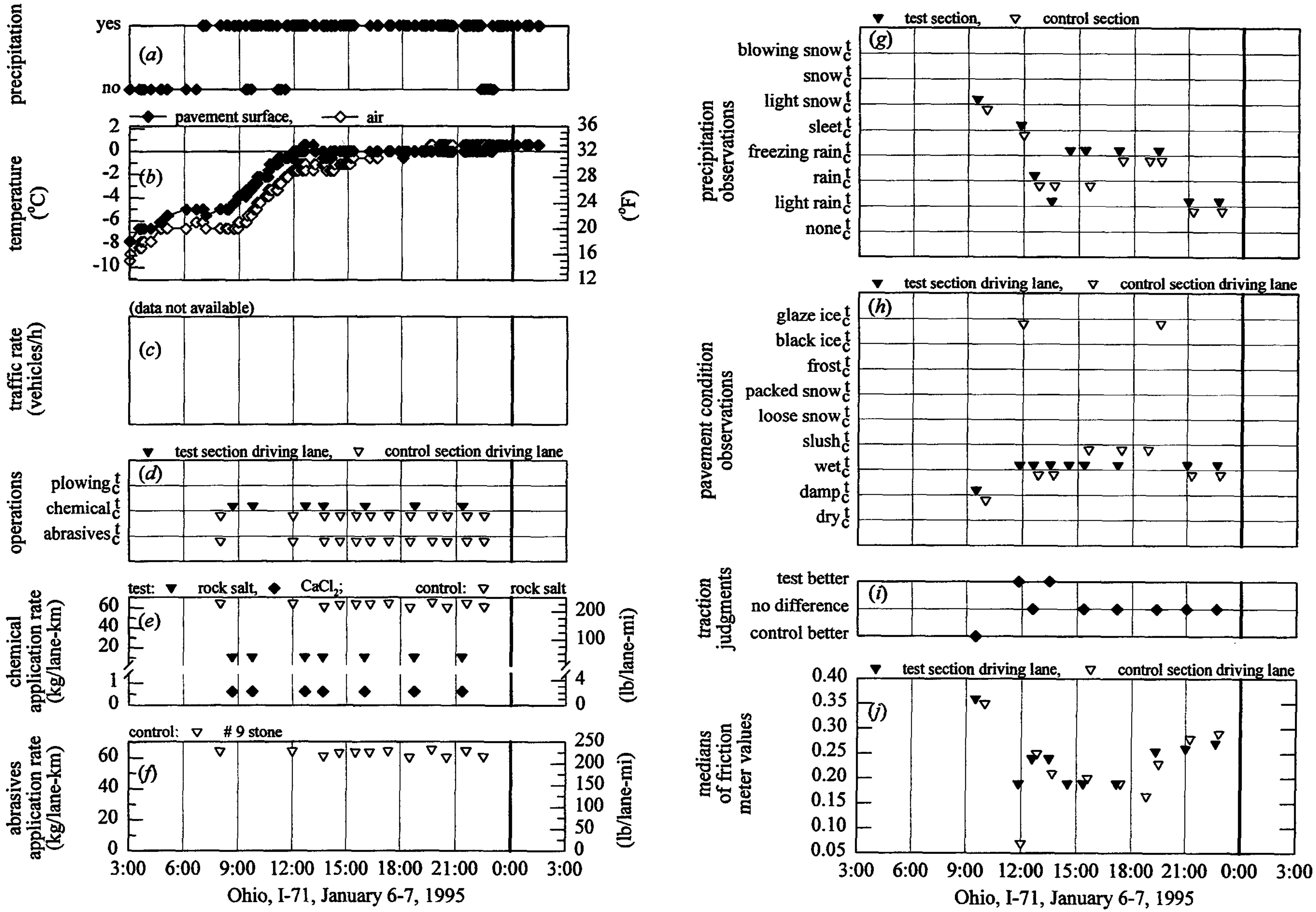


Figure 19. Ohio, I-71, storm O1501A, January 6-7, 1995, data histories.

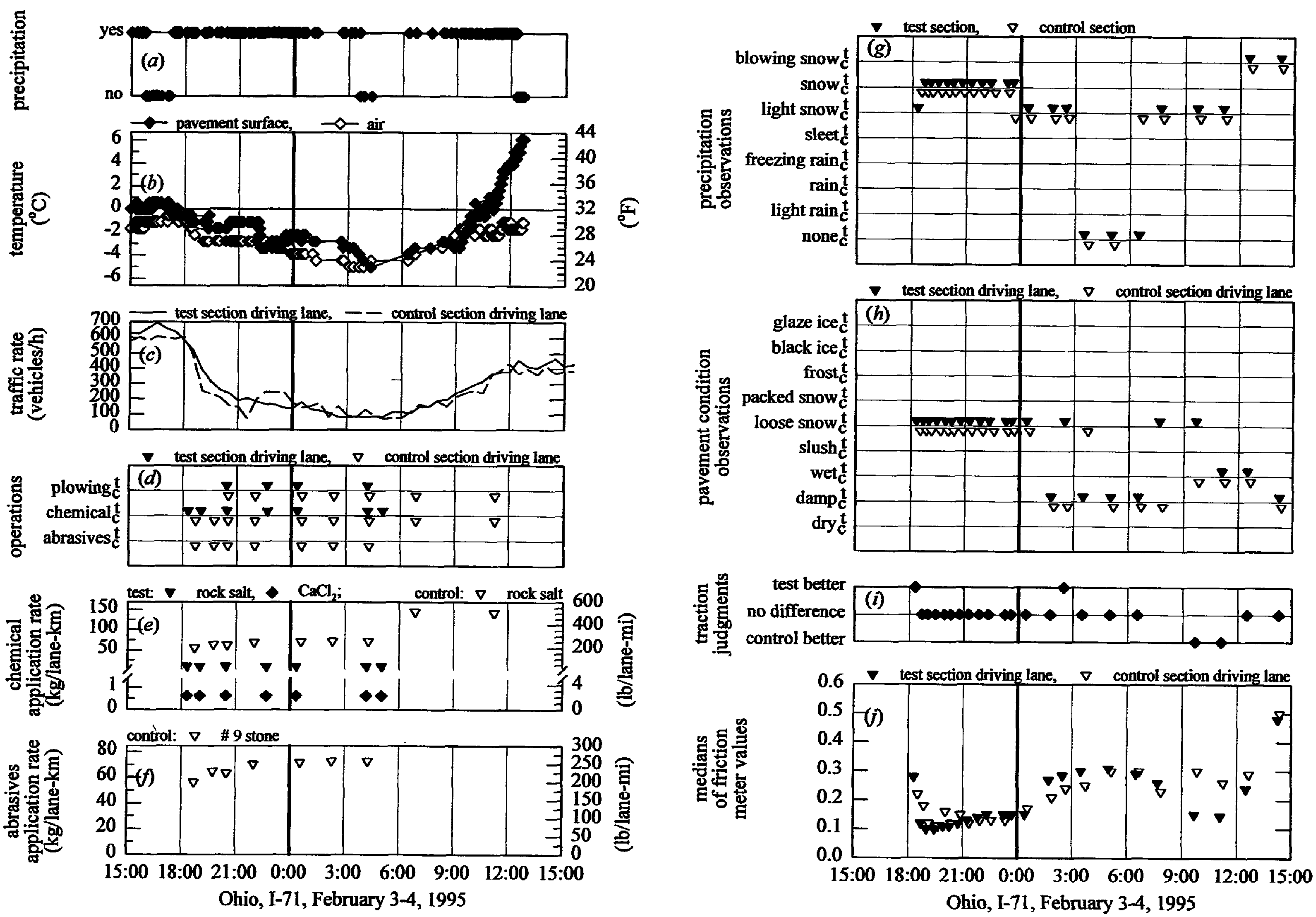


Figure 20. Ohio, I-71, storm O1502B, February 3-4, 1995, data histories.

Table 23. Ohio, I-71, storms O1501A and O1502B. Summary of documented driving lane operations on test and control sections.

	O1501A January 6-7, 1995		**O1502B** February 3-4, 1995	
	test section	**control section**	**test section**	**control section**
total number of passes	7	12	7	9
number of passes with plowing	0	0	4	7
number of passes with rock salt application	7	12	7	9
total application kg/lane-km	78	760	78	761
(lb/lane-mi)	(278)	(2695)	(278)	(2700)
number of passes with $CaCl_2$ prewetting solution	7	0	7	0
total $CaCl_2$ application kg/lane-km	4		4	
(lb/lane-mi)	(15)		(15)	
number of passes with abrasives application	0	12	0	7
total application kg/lane-km		760		473
(lb/lane-mi)		(2695)		(1678)

Table 24. Ohio, I-71, winter 1994/1995. Summary of documented driving lane operations.

	test section	**control section**
total number of passes	22	31
number of passes with plowing	4	7
number of passes with rock salt application	22	31
total application kg/lane-km	250	2142
(lb/lane-mi)	(889)	(7599)
number of passes with $CaCl_2$ prewetting solution	22	2
total $CaCl_2$ application kg/lane-km	14	6
(lb/lane-mi)	(49)	(21)
number of passes with abrasives application	0	27
total application kg/lane-km		1791
(lb/lane-mi)		(6355)

Note: Data from storms O1501A, O1501D, O1502B, O1502D, and O1502E.

The initial chemical applications were generally placed when the pavement conditions were snow-covered or icy. None of the applications were made in advance of a storm. However, from the evidence that bonded snowpack or ice was avoided on the test section in all of the storms, the initial test section applications were adequately timed. Subsequent application passes were generally made as needed and in response to worsening or changing conditions. Operational decisions were made using forecast information, pavement temperature and other RWIS data, and observational data including patrol observations. As at the I-70 site, ODOT has used these capabilities for several years, and routinely does so as part of their conventional practice.

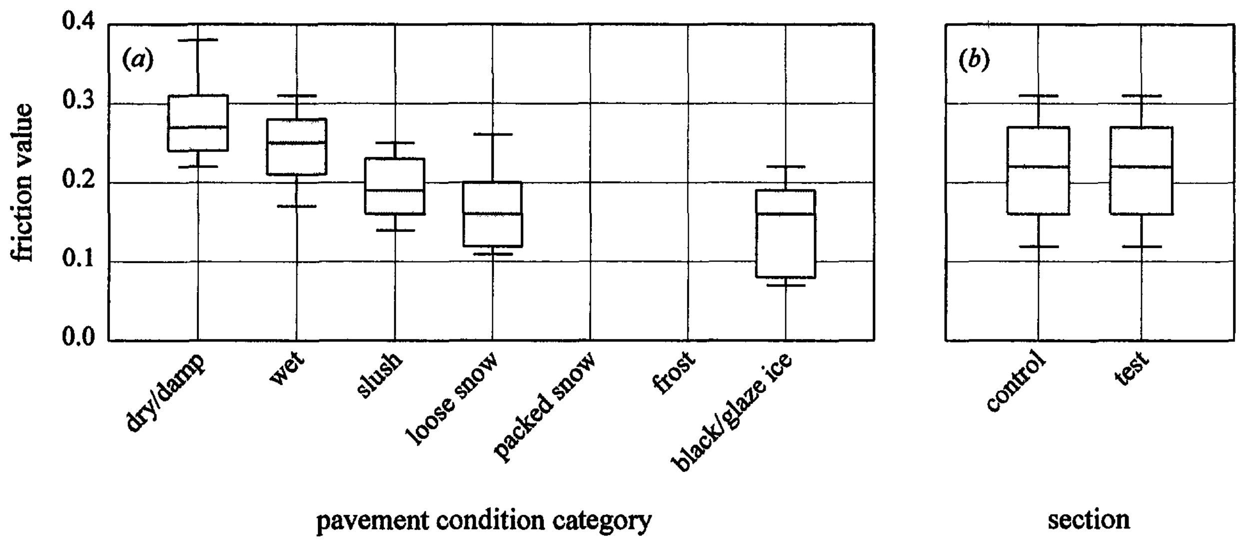


Figure 21. Ohio, I-71 friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 25. Statistics of Ohio, I-71 friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	138	0	0.270	0.2400	0.310
wet	264	0	0.250	0.2100	0.280
slush	25	0	0.190	0.1600	0.230
loose snow	278	0	0.160	0.1200	0.200
black/glaze ice	30	0	0.160	0.0800	0.190

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	368	0	0.220	0.160	0.270
test	350	0	0.220	0.160	0.270

The differences in the median values among the two groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50^{th}, 25^{th}, and 75^{th} percentiles of the friction measurements in the group.

5.2.3.3 Pavement condition

Pavement condition observation data are tabulated in tables 56 and 57, which are presented later in section 5.5, and immediately below. Loose snow was the most common test section pavement condition observation of the season, followed by wet, dry/damp, slush, and black/glaze ice (<1 percent). On the control section, loose snow was followed by wet, dry/damp, black/glaze ice, and slush. The difference between the test and control observations is significant and favors the test section.[17] The lack of packed snow observations and the low percentages of black/glaze ice observations indicate an overall anti-icing success, especially on the test section.

1994/1995 Ohio I-71 pavement condition observations

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	21	17
wet	33	39
slush	3	2
loose snow	36	42
black/glaze ice	7	0

5.2.3.4 Friction

Tukey box plots of the test and control section friction data are shown in figure 21 (b) and corresponding data are given in table 25. The comparisons show identical distributions and medians. Both test and control sections had overall median friction values for the season that were consistent with the pavement condition categories "wet" or "slush" (figure 21 (b)). Thus, from the point of view of the radically reduced chemical and abrasives use, the overall anti-icing success of the test section operations was greater than that of the control section operations.

Further graphical presentations of Ohio I-71 normalized friction data are presented below in section 5.5, figure 75.

5.2.3.5 Application rates

Data histories of the storm O1501A (figure 19) indicate similar friction results during generally successful anti-icing operations on the test and control sections, although far less material was used on the test section and at application rates below 14 kg/lane-km (50 lb/lane-mi). The histories further show that pavement conditions were slightly better on the test section. These results are remarkable considering the rain and freezing rain conditions, the pavement temperatures close to freezing, and the relative amounts of chemical and abrasives used. No beneficial effect of the abrasives is evident.

Data of the storm O1502B illustrate the effectiveness, during sustained snowfall, of the low application rate operations of the test section and the salt/abrasives operations of the control section. As indicated in figure 20, the snow began at 6 p.m. and intensified quickly, with pavement temperatures decreasing through the evening from approximately -1°C (30°F) to -5°C (23°F). In response, prewetted rock salt was placed on the test section at the low rate, and the salt/abrasives mix was placed on the control section. Frequent and periodic applications were made, together with plowing later in the storm. The application rate of the prewetted rock salt was apparently inadequate for the early storm conditions: the friction dropped sharply early in the storm to values consistent with packed snow. A less rapid but similar drop in friction was seen on the control section, indicating that the control section operations were apparently inadequate as well. The poor responses were partly due to the lack of plowing before 8 p.m., when the plows were put on the trucks. However, the test section salt application rate was well below the

42 to 55 kg/lane-km (150 to 200 lb/lane-mi) rates suggested above for moderate or heavy snowstorms of long duration. The control section rates were in this range, but the salt was placed with abrasives.

5.2.4 Data and Results From Kansas Site

Analyses of six Kansas storm data sets from the 1994/1995 season are presented in detail in the site report.[10] The data histories and operations summaries for two of the storms, KS412B and KS503A, are presented in figure 22, figure 23, and table 26. Discussion of the Kansas site and these storms is presented here. Information regarding the full-season analysis is not discussed here, but is included in section 5.5.

The Kansas experiments were conducted on U.S. 81 in Cloud County, on highway sections to the north and south of Concordia. Operations were conducted out of the Kansas Department of Transportation (KDOT) sub-area maintenance station in Concordia.

The test section was a 13-km (8-mi) section of U.S. 81 from milepost 204 to milepost 212, which is north of Concordia. The control section was an 11-km (7-mi) section south of Concordia from milepost 190 to 197. The highway at this location has one travel lane in each direction, and is not divided. The test section covered approximately 27 lane-km (17 lane-mi), while the control section covered 22 lane-km (14 lane-mi). The pavement surface course is asphalt concrete.

KDOT has a road weather information system (RWIS) installation at milepost 205, and a traffic data installation 10-km (6-mi) north of the site. Annual average daily traffic (ADT) is slightly less than 4000. Their initial use of the RWIS and associated weather and pavement temperature forecasting capabilities was during the two seasons of this project.

5.2.4.1 Precipitation and pavement temperature

Light snow, snow, and freezing rain dominated the precipitation in the storms KS412B and KS503A. For the storm KS412B (figure 22), freezing rain was reported just prior to midnight on December 30. It was followed by light snow and then heavier snow in the early hours of December 31. Pavement temperatures remained above freezing until about 1 a.m. on December 31. The reported event continued into January 1, with a daytime period on December 31 in which the pavement temperature rose just above freezing for only a short time. Following this the pavement temperature dropped steadily.

For the storm KS503A (figure 23), wind and blowing snow, a common condition at the site, were major concerns for the operations. (Figure 23 contains an additional graph of the wind speed history. It is shown as part (c).) The storm began with reports of freezing rain on the test section, followed by increasing wind speed and precipitation changing to snow. Pavement temperatures dropped below freezing soon after the increase in wind speed and the beginning of snowfall, and dropped steadily until a rapid mid-day rise during the second day of the storm.

5.2.4.2 Operations

For Interstate routes, KDOT snow and ice control policy calls for applications of chemicals, abrasives, and/or chemical-abrasive mixtures to prevent ice and snowpack conditions. For chemical applications, this is consistent with anti-icing practice. For less important routes, such as U.S. 81 at the experimental site, there is no mention of preventing ice or snowpack. Mixtures of chemicals and abrasives may be used as required during storms, whereas chemicals, abrasives, and/or chemical-abrasive mixtures may be used after storms.

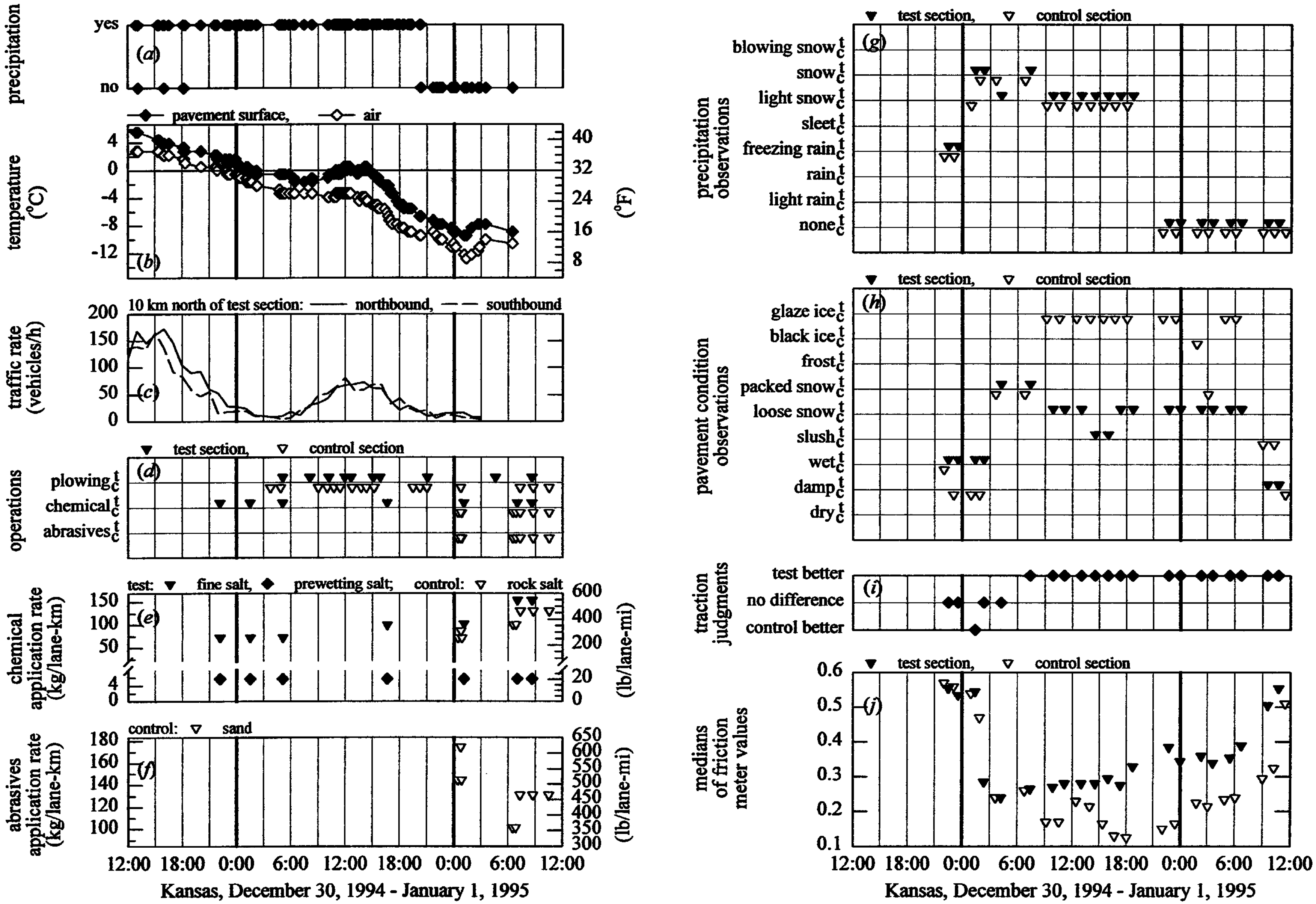


Figure 22. Kansas, storm KS412B, December 30, 1994 - January 1, 1995, data histories.

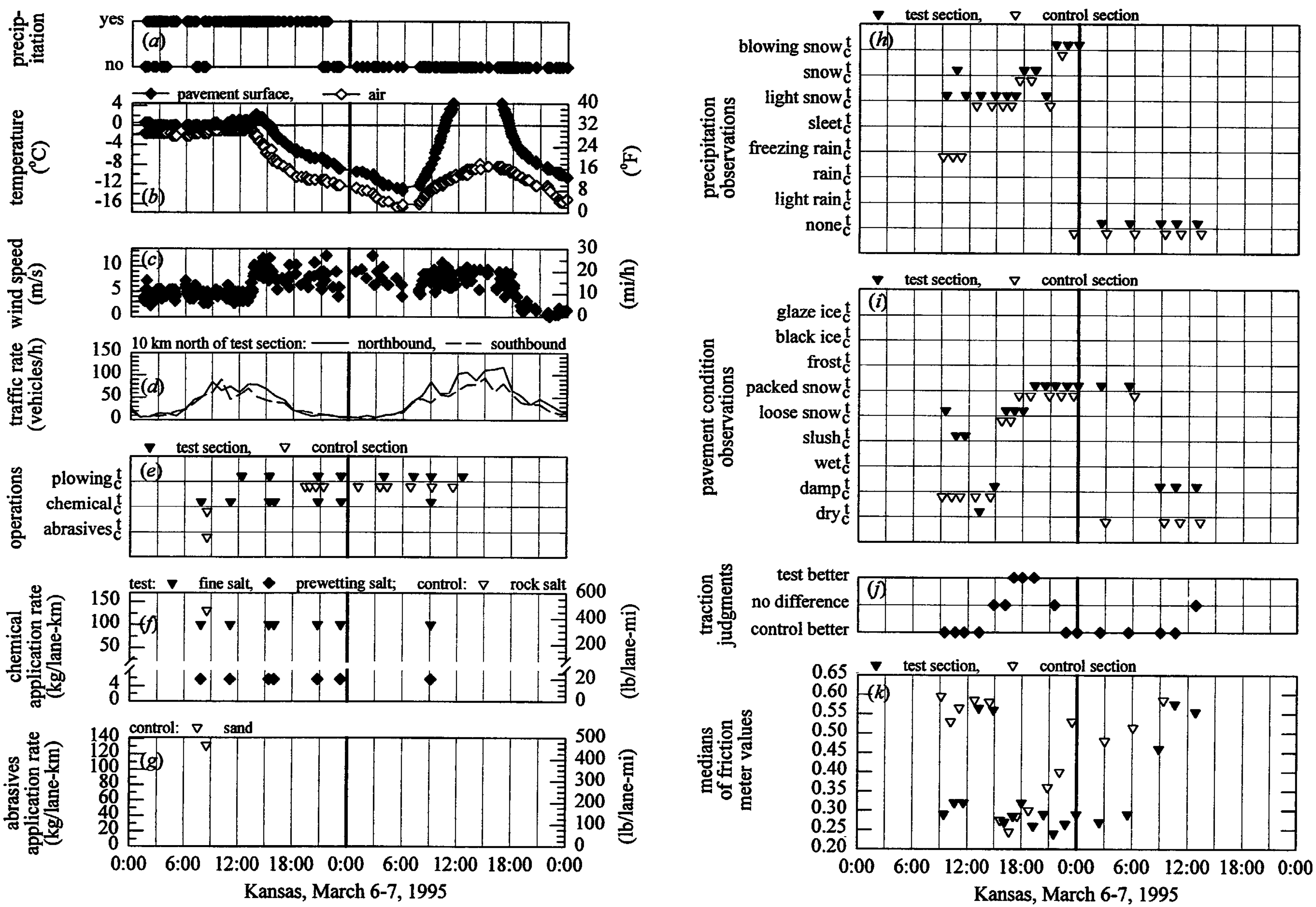


Figure 23. Kansas, storm KS503A, March 6-7, 1995, data histories.

Table 26. Kansas, storms KS412B and KS503A. Summary of documented driving lane operations on test and control sections.

	KS412B December 30, 1994 - January 1, 1995		KS503A March 6-7, 1995	
	test section	control section	test section	control section
total number of passes	15	21	11	11
number of passes with plowing[1]	10	17	8	10
number of passes with rock salt application[2]	7	8	7	1
total application kg/lane-km	730	828	702	131
(lb/lane-mi)	(2590)	(2938)	(2492)	(465)
number of passes with NaCl prewetting solution	7	0	7	0
total prewetting salt application kg/lane-km	40		40	
(lb/lane-mi)	(142)		(141)	
number of passes with abrasives application[2]	0	8	0	1
total application kg/lane-km		1060		131
(lb/lane-mi)		(3762)		(465)

Note:
[1]Northbound and southbound plowing passes in control section were generally not conducted sequentially; a noted control section plowing pass here and on data histories is generally for 1/2 of the section.
[2]Does not include spot treatments on control section.

At the site, conventional KDOT operations call for applications of abrasives and rock salt, and mixtures of both. In the storms presented here only mixtures (at two ratios) were applied on the control section. The salt used is of the "medium" gradation listed in the table immediately below. The abrasive used is sand. Often the conventional practice at the site is to apply chemical only on vital areas such as curves, hills, intersections and bridges. KDOT recognizes that this can prevent chemical-induced melting of blowing snow and retention of blowing snow by wet pavement. After a storm roads are treated until the pavement is bare.

KDOT salt gradations.

Sieve Size	**Percent Retained**	
	medium salt	**fine salt**
12.7 mm (1/2 in)	0	0
9.53 mm (3/8 in)	3	0
4.76 mm (No. 4)	42	trace
2.38 mm (No. 8)	81	1
1.19 mm (No. 16)	92	36
0.590 mm (No. 30)	95	66
0.297 mm (No. 50)	97	81
0.149 mm (No. 100)	98	91
0.074 mm (No. 200)	99	97

The operations strategy on the test section called for applications of a sodium chloride solution (salt brine) and/or solid salt—at the "fine" gradation listed in the table above—prewetted with salt brine. No abrasives were to be used. Only prewetted fine salt was used on the test section in the two storms discussed here.

For storm KS412B, as indicated in figure 22, the operations were essentially anti-icing on the test section and deicing on the control section. The initial treatment on the test section was prewetted salt at about 11 p.m. on December 30. Including this treatment, three prewetted fine salt applications were made on the test section during the first night of the storm, and further applications were made subsequently. Following the early snowfall, both sections were plowed. No chemicals were applied on the control section until after midnight of January 1, except in spot applications to critical areas. Both test and control were treated with substantial chemical applications at the end of the operations when the pavement temperatures were quite low but (likely) increasing. Slightly less chemical was used on the test section compared to the control section. Abrasives were used on the control section but not on the test section. Totals are given in table 26.

For storm KS503A (figure 23 and table 26), the operations provided an example of the conventional KDOT practice of trying to prevent chemical-induced melting of blowing snow and retention of blowing snow by wet pavement. The initial operation on the control section was an application of a 1:1 medium salt/abrasives mix. Subsequent control operations were plowing only with some spot applications of the mix late in the operational period. They intentionally avoided the use of chemicals during the low temperature and blowing snow conditions. Although the maintenance supervisor expected problems due to snow retention on the test section in these conditions, chemicals were applied as part of the experimental program. As a result, considerably more chemical was applied on the test section than on the control section.

5.2.4.3 Pavement condition and friction

For the storm KS412B (figure 22), the pavement condition observations, the friction measurements, and the traction judgments indicate that the test section conditions were better than the control section conditions, which is supported by statistical analysis of the storm data.[10] The results clearly indicate that the anti-icing chemical and plowing operations were far more effective in providing better pavement conditions and higher friction throughout and following the storm, even though both sections experienced a drop in friction due to a short period of snowfall and a drop in pavement temperature to freezing early in the storm. While the anti-icing operations did not provide bare pavement, they did succeed in preventing a deterioration to sustained snowpack or icing conditions, allowing plowing and subsequent chemical operations to achieve slow but steady increases in pavement friction. This success was not achieved on the control section.

For storm KS503A (figure 23), heavier snow and blowing conditions were reported around 6 p.m. on March 6, after which plowing operations were begun on the control section, the first operations since the initial application of the salt/abrasives mix. Following these there was a steady rise in friction on the control section until the end of observed precipitation. In contrast, test section operations continued periodically following the initial operation, and the test section friction remained low well beyond the time that control section friction increased. Traction judgments favored the control section throughout this period as well. Operations on both sections were completed soon after pavement temperatures rose above freezing on March 7, well after precipitation had ended, but before the winds died.

Notes supplied by the supervisor included the following descriptive summary, which explains why the control section outperformed the test section:

> "In the control section we treated only what was absolutely necessary with sand only as to trap as little snow as possible. This gave some traction in the icy areas and hopefully would not create a thick snowpack. With the blowing snow and cold air and pavement temperatures, most of the snowpack came off in the night.

"In the test section we treated all of the section which trapped some blowing snow. We knew this would happen but we were trying to get a loose snowpack and keep high friction readings in the test section.

"Sorry to say it did not work. ... The test section was almost completely covered with a loose snowpack. This was not a total failure because it came off just about as quick as the few hard snowpacked spots in the control section.

"For this storm with the high winds and the low temperatures, the anti-icing was a mix. Clean-up on the control section was spotty but the spots were hard packed. In the test section, however, clean-up was the complete section. Both sections cleaned up about the same time. So you can choose between cleaning up spots of hard snowpack or a lot of loose snowpack."

While the supervisor indicated that there are advantages to both the test and control operations, the pavement condition, friction, and traction data indicate that the control strategy to prevent the trapping of snow in blowing/cold conditions was far more effective, and was in fact the best strategy to follow after those conditions were forecast. This is further supported by statistical analysis of the pavement condition and friction data.[10]

5.3 DATA AND RESULTS FROM LIQUID APPLICATION SITES

Data and results from the experimental sites in Nevada, Wisconsin, New Hampshire, Colorado, California, and Iowa are presented here. At each site a chemical solution was used on the test section. Magnesium chloride solution was used in Nevada, Colorado, and California; sodium chloride solution in Wisconsin and Iowa; and potassium acetate solution in New Hampshire. Rock salt and abrasives were also used on the test sections and on the control sections.

Table 27 lists the storm data sets presented and discussed in this section. More extensive analyses and interpretations of the data sets are presented in the corresponding site reports.

5.3.1 Data and Results From Nevada

The Nevada site is in Reno. Operations were conducted out of the Nevada Department of Transportation (NDOT) Reno maintenance station, which is located within 1 km (1/2 mi) of the site. The test and control sections were 10-km (6-mi) sections of U.S. 395 from mileposts 25 to 31. For most of this length the highway has two travel lanes in each direction. A short distance between two interchanges contains three lanes each way. The pavement surface course is portland cement concrete. The northbound lanes were the test section, and the southbound lanes were the control section. Each section covered approximately 19 lane-km (12 lane-mi).

Measurements and observations of effectiveness were made on the outside driving lanes. There is an increase in elevation of about 215 m (700 ft) over the length of the section, from 1370 m (4500 ft) in the south to 1585 m (5200 ft) in the north. To minimize the effect that the highway grades of the elevation change has on friction measurements, the measurements were made at relatively flat locations along the section. Statistical analysis of baseline friction measurements of the sections when the pavement was wet indicates that the effect is not significant.

Table 27. Storm data sets showing operations using liquid applications.

Site	Storm Dates	Storm ID
Nevada	December 14-15, 1994	NV412C
Nevada	January 6-7, 1995	NV501B
Nevada	February 13-14, 1995	NV502A
Nevada	March 22-23, 1995	NV503B
Wisconsin	January 19-20, 1995	WI501B
Wisconsin	February 14-15, 1995	WI502A
Wisconsin	March 4-5, 1995	WI503A
Wisconsin	January 10, 1994	WI0194C
New Hampshire	January 6-7, 1995	NH501B
New Hampshire	January 11-13, 1995	NH501C
New Hampshire	February 4-5, 1995	NH502A
New Hampshire	February 15-16, 1995	NH502B
New Hampshire	February 27-28, 1995	NH502C
New Hampshire	December 19, 1993	NH1293B
New Hampshire	December 21, 1993	NH1293C
New Hampshire	December 29-30, 1993	NH1293D
New Hampshire	January 7-8, 1994	NH0194B
Colorado	December 15-16, 1994	CO412C
Colorado	January 11-12, 1995	CO501B
California	December 5-7, 1994	CA412A
California	December 13-14, 1994	CA412C
Iowa	December 14-15, 1994	IA412B
Iowa	March 4-5, 1995	IA503A

The site is the location of experiments conducted for the previous SHRP project H-208.[2] NDOT has road weather information system and traffic data installations at the site. The RWIS installation is at approximately 1542 m (5060 ft) elevation. Wintertime average daily traffic is approximately 40000.

Analyses of 14 representative Nevada storm data sets from the 1994/1995 season, and six sets from the 1993/1994 season, are presented in detail in the site report.[13] The data histories and operations summaries for four of the 1994/1995 storms are presented in figures 24 through 27 and table 28. Additional results are included in table 29, figure 28, and table 30. Summary points and conclusions regarding the operations and their effectiveness over the course of the 1994/1995 season are presented below.

5.3.1.1 Precipitation and pavement temperature

Light snow and snow dominated the 1994/1995 precipitation at the site. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) and > 0°C (> 32°F) categories. About 6 percent of the temperatures were in the -6.7°C to -3.3°C (20°F to 26°F) category. Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

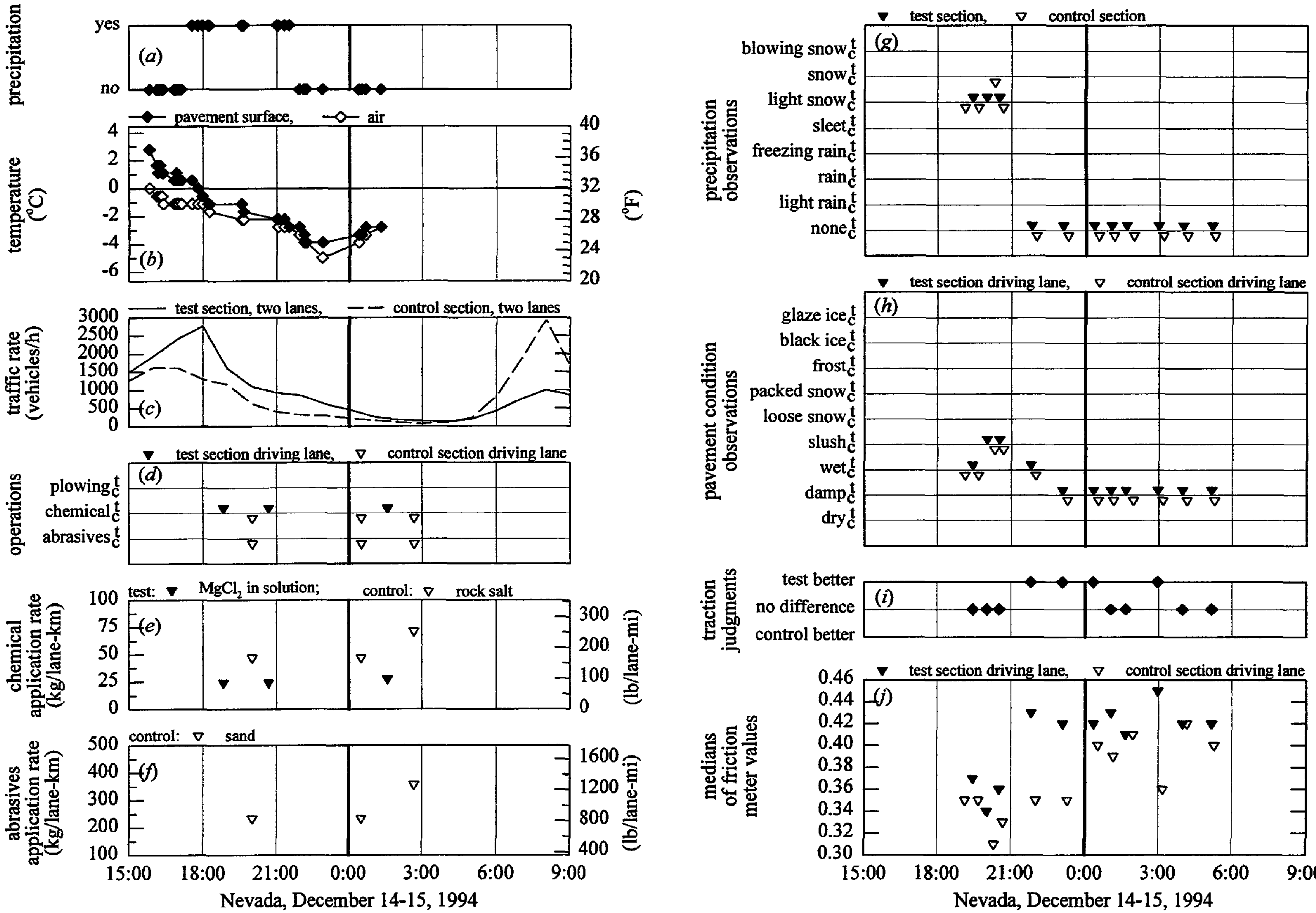


Figure 24. Nevada, storm NV412C, December 14-15, 1994, data histories.

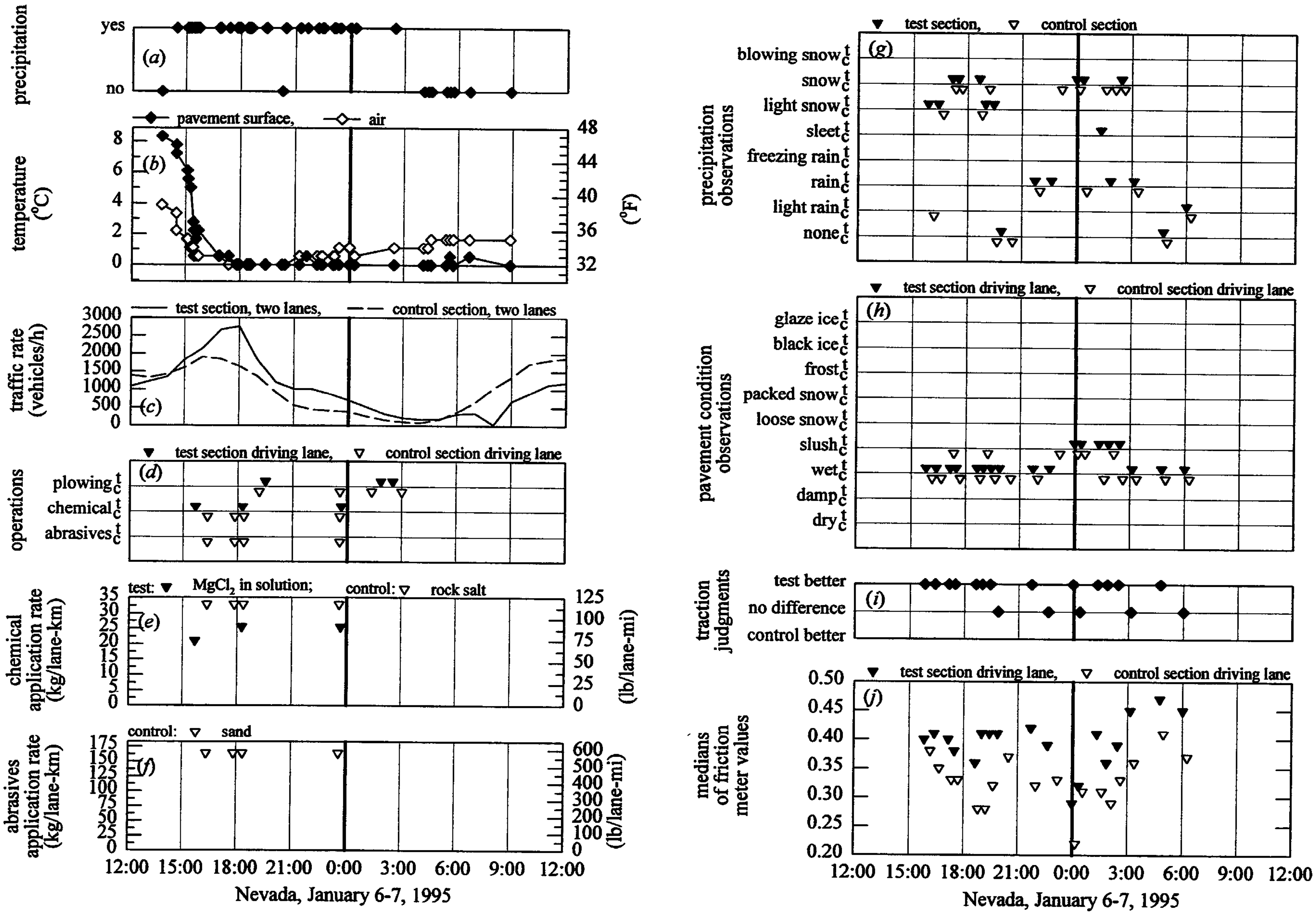


Figure 25. Nevada, storm NV501B, January 6-7, 1995, data histories.

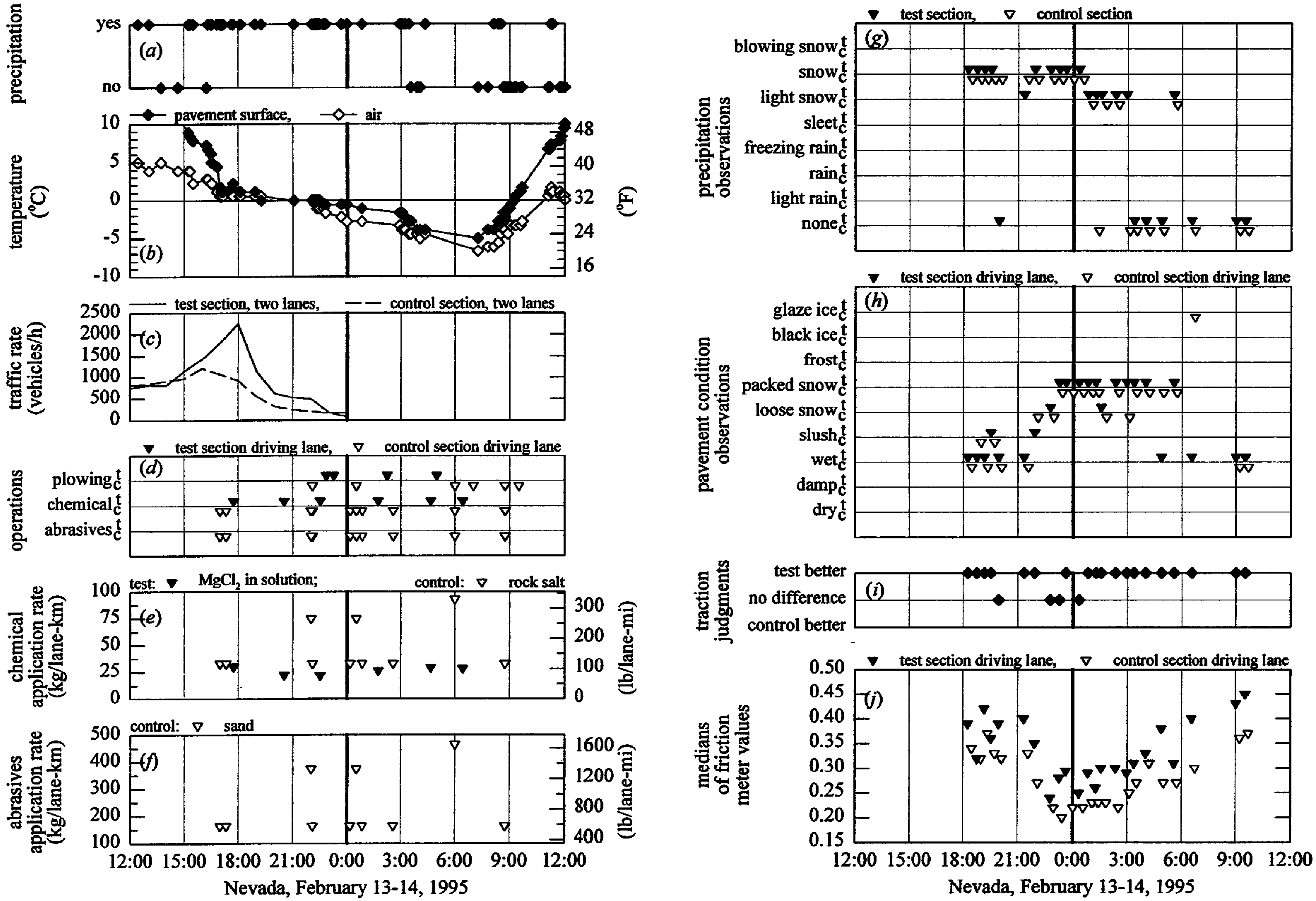


Figure 26. Nevada, storm NV502A, February 13-14, 1995, data histories.

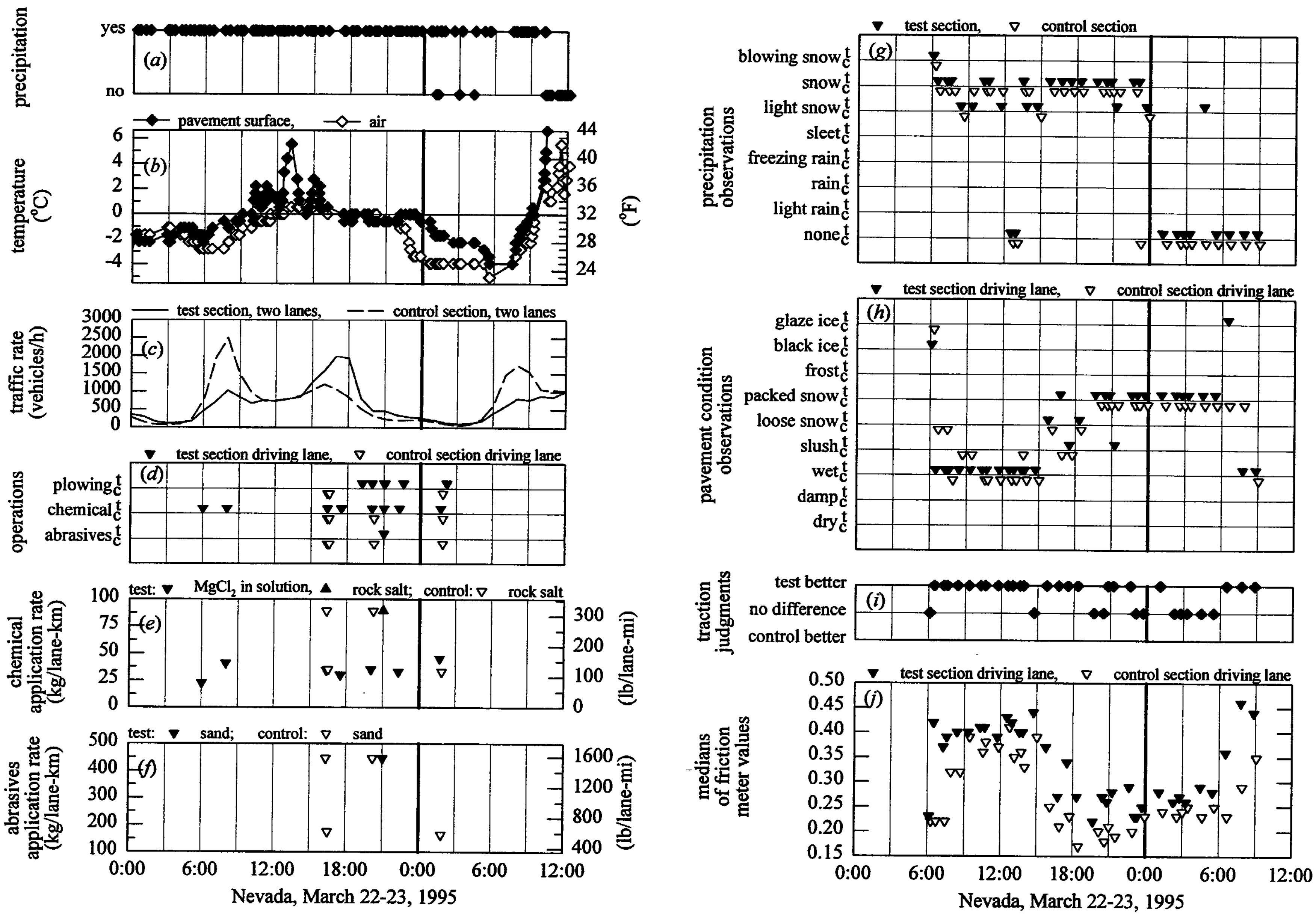


Figure 27. Nevada, storm NV503B, March 22-23, 1995, data histories.

Table 28. Nevada, storms NV412C, NV501B, NV502A, and NV503B. Summary of documented driving lane operations on test and control sections.

	NV412C December 14-15, 1994		**NV501B** January 6-7, 1995		**NV502A** February 13-14, 1995		**NV503B** March 22-23, 1995	
	test section	**control section**	**test section**	**control section**	**test section**	**control section**	**test section**	**control section**
total number of passes	3	3	6	7	11	12	15	4
number of passes with plowing	0	0	3	4	5	6	9	3
number of passes with application of magnesium chloride-based solution	3	0	3	0	6	0	7	0
total $MgCl_2$ application kg/lane-km	76		72		159		242	
(lb/lane-mi)	(271)		(257)		(565)		(857)	
number of passes with rock salt application	0	3	0	4	0	10	1	4
total application kg/lane-km		165		132		474	89	247
(lb/lane-mi)		(587)		(468)		(1682)	(317)	(875)
number of passes with abrasives application	0	3	0	4	0	10	1	4
total application kg/lane-km		827		657		2367	446	1231
(lb/lane-mi)		(2933)		(2332)		(8398)	(1583)	(4369)

Table 29. Nevada, winter 1994/1995. Summary of documented driving lane operations.

	test section	**control section**
total number of passes	64	58
number of passes with plowing	24	18
number of passes with application of magnesium chloride-based solution	41	0
total $MgCl_2$ application kg/lane-km	1137	
(lb/lane-mi)	(4033)	
number of passes with rock salt application	4	52
total application kg/lane-km	188	2484
(lb/lane-mi)	(668)	(8812)
number of passes with abrasives application	4	52
total application kg/lane-km	939	12407
(lb/lane-mi)	(3332)	(44020)

Note: Data from storms NV411A, NV411B, NV412A, NV412B, NV412C, NV501A, NV501B, NV501C, NV501D, NV501F, NV501G, NV502A, NV503A, and NV503B.

5.3.1.2 Operations

The operations summary for the 1994/1995 season is shown in table 29. The test section chemical operations were mostly applications of the magnesium chloride solution, yet applications of rock salt in a 1:5 mix with abrasives were applied as well. Chemical operations on the control section were applications of rock salt in the 1:5 mix with abrasives. During the 14 1994/1995 storms that were analyzed, nearly twice as much rock salt was applied on the control section driving lane than the amount of magnesium chloride and rock salt applied on the test section driving lane. Over 13 times as much sand was applied on the control section driving lane than on the test section driving lane.

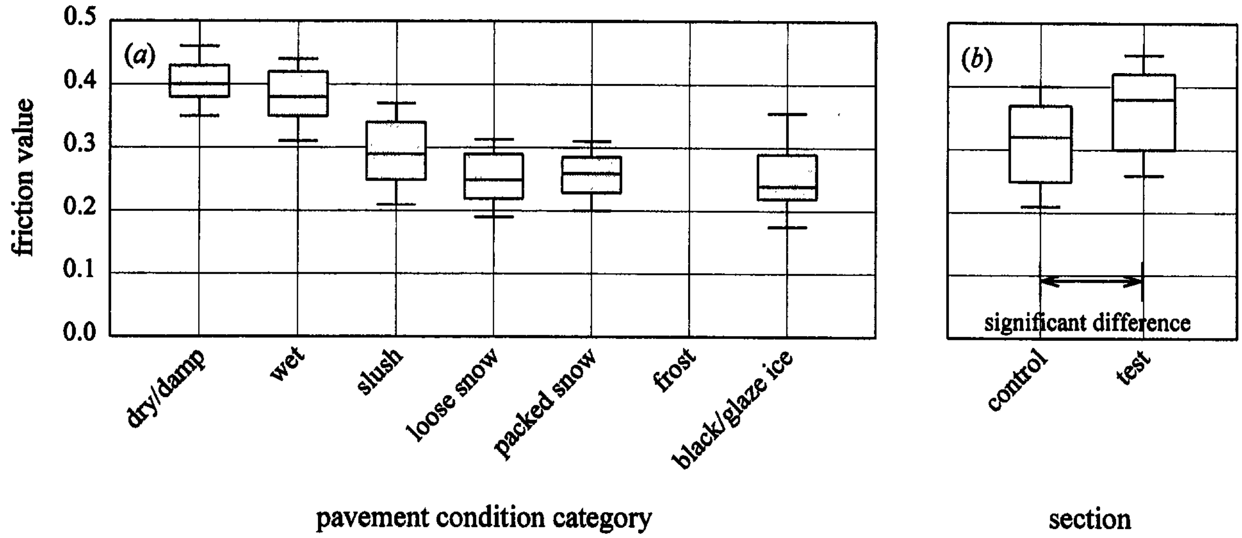


Figure 28. Nevada friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 30. Statistics of Nevada friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	452	0	0.400	0.380	0.430
wet	1000	2	0.380	0.350	0.420
slush	466	0	0.290	0.250	0.340
loose snow	152	0	0.250	0.220	0.290
packed snow	449	1	0.260	0.230	0.285
black/glaze ice	57	7	0.240	0.220	0.290

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	1288	2	0.320	0.250	0.370
test	1288	8	0.380	0.300	0.420

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

The initial magnesium chloride applications were generally placed when snowfall had just begun and/or when the pavement temperature was dropping toward freezing, and when the pavement condition was wet. None of the applications were made well in advance of a storm, which demonstrates that in the case of a chemical solution pretreatment, the practice is not always as simple as applying the solution onto dry pavement before the time at which precipitation starts, although it sometimes may be. In particular, in storms that begin with rain or snow falling on a pavement with above-freezing temperatures, pretreatments long before pavement temperatures drop to freezing should be avoided because of the excessive dilution of the chemical that will occur. On two occasions, including storm NV503B shown in figure 27, the initial $MgCl_2$ solution application was made after the precipitation had begun and with an observed icy pavement condition. The result of both applications was to improve the pavement condition to wet and increase the friction. In each event the snow began unexpectedly early, and pavement temperatures were slightly lower than expected. These prompt and successful responses to earlier-than-expected storm conditions demonstrate how effective anti-icing readiness can be in the early stages of snow and ice control operations, and how the preventive nature of an anti-icing strategy can readily accommodate early and prompt responses to rapidly changing conditions.

Subsequent application passes were generally made only as needed and in prompt response to worsening or changing conditions. During times when magnesium chloride applications were suspended, plowing operations were utilized effectively to help break up the packed snow.

Overall both the initial and subsequent test section operations reflect intelligent use of weather and pavement temperature forecast information, real-time pavement temperature and other RWIS data such as chemical concentration indicators, friction measurement data, and observational data including operator observations. The test section operations provide an example of the evolving use and the benefits of modern technology in anti-icing operations, demonstrate an efficient use of chemicals, and demonstrate effective anti-icing operations with few abrasives applications.

5.3.1.3 Pavement condition

Pavement condition observation data are listed in tables 56 and 57, which are presented later in section 5.5, and in the table immediately below. Wet was the most common test section pavement condition observation, followed by dry/damp, slush, packed snow, loose snow, and black/glaze ice. Wet was also the most common control section observation, followed by slush, packed snow, dry/damp, loose snow, and black/glaze ice. The difference between the test and control observations is significant, and favors the test section.(13) Whereas there were more wet observations on the test section, there were more slush, packed snow, and loose snow observations on the control section.

1994/1995 Nevada pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	18	17
wet	34	43
slush	19	17
loose snow	7	5
packed snow	19	16
black/glaze ice	3	2

Packed snow conditions on the test section driving lane occurred during three 1994/1995 storms that included heavier and prolonged snowfall, including the storms NV502A and NV503B, whose data histories are shown in figures 26 and 27. Pack was observed for several hours in each case, which suggests optimal moisture in the snow and sufficient traffic action to create the pack, and a strong bond to sustain it. The results indicate that the application rates of the magnesium chloride were too low, or the number of passes prior to the development of the packed snow too few, to prevent a bonded snowpack with the snowfall, temperature, snow moisture, and traffic conditions of the storms. Plowing ahead of liquid applications appears essential when it is snowing hard and with conditions of loose snow on the pavement.

During the three storms in which sustained packed snow conditions occurred, the test section operations generally resulted in less packed snow, more wet, and fewer loose snow or slush observations, and the traction judgment and friction effectiveness measures indicate a considerably higher degree of operational success on the test section compared to the control. Further, the pack broke up 1 to 2 h earlier on the test section than on the control section.

In storm NV502A, during the period of packed snow on both sections, much more chemical was used on the control section driving lane than on the test section driving lane, and a large quantity of sand was placed on the control section driving lane. The greater chemical amounts and the use of abrasives did not lead to better friction, traction, or an earlier breakup of the pack. Regular plowing operations, moderate applications of the $MgCl_2$ solution, and precipitation changing from snow to light snow to none, led to the test section break *prior* to rush hour traffic. The later breakup of the control section snowpack coincided with a rise in pavement temperature and rush hour traffic.

In storm NV503B, the packed snow remained on both the test and control sections 6 to 8 h after the end of the snowfall, but broke sooner on the test section. Friction increased sooner on the test section as well, even though higher traffic rates acted on the control section during the period of the breakup of the pack. Whereas the test section pack broke *before* rush hour traffic, sunny skies, and pavement temperature increase, the later breakup of the control section snowpack coincided with sunshine, a rise in pavement temperature, and the rush hour traffic. No operations were conducted during the 4 h immediately before the breakup of the test section pack, and in the 6 h before the breakup of the control section pack.

These events with packed snow conditions demonstrate a great benefit of anti-icing operations under the climatic conditions and moderate pavement temperatures encountered. Early, regular, and moderate chemical applications, without abrasives applications, can lead to a considerably higher degree of operational success throughout a storm, and when dangerous packed snow conditions develop, to a weaker bond between the pavement and snowpack and an earlier breakup of the pack that is attributable solely to the preceding operations.

5.3.1.4 Friction measurements and traction judgments

Tukey box plots of the test and control section friction data are shown in figure 28 (b); corresponding data are given in table 30. The comparison shows that the median friction value for the season, and the box plot friction distribution, were higher for the test section, and the difference between test and control section median friction was significant.

The test section had a high overall median friction for the season, equal to the median of all friction values when the observed pavement condition was wet (figure 28 (a)). The control section also had a high overall median friction for the season, falling between the 50 and 75 percentiles of all friction values when the observed pavement condition was slush. These results indicate an overall operational success on both the test and control section, but they indicate a higher degree of success on the test section.

Except for a single pass during the entire season, the measurement vehicle operator's judgments always were that the test section was better in terms of traction than the control section or that there was no difference.

From the point of view of reduced chemical and abrasive use, and based upon the pavement condition observation, friction, and traction judgment effectiveness measures, the overall operational success of the test section was considerably higher than that of the control section.

5.3.1.5 Application rates

As evidenced by a number of storm data sets of the 1994/1995 season, such as storm NV412C shown in figure 24, the test section strategy, application timing, and rates are well suited to storm events that include light snowfall of short duration and pavement temperatures dropping toward and slightly below freezing. In each of these events, the test section anti-icing operations with magnesium chloride solution application rates close to 28 kg/lane-km (100 lb/lane-mi) were successful in preventing packed snow or sustained icing conditions, while maintaining higher friction than the control section with considerably less material use. In the longer duration storm NV501B (figure 25), which was characterized by snow, rain, and light snow and pavement temperatures at the freezing level, the magnesium chloride application timing and rates—between 20 and 28 kg/lane-km (75 and 100 lb/lane-mi)—appear to be appropriate. However, in storms where snow was combined with pavement temperatures just a few degrees below freezing, such as NV502A (figure 26) and NV503B (figure 27), excessive reductions in friction and packed snow conditions resulted. The test section applications were generally well timed in these storms, illustrating the excellent decision-making process at the site, and usually were coordinated with plowing operations when necessary. But, as suggested above, the application rate of the magnesium chloride (approximately 28 kg/lane-km (100 lb/lane-mi)) was too low, or the number of passes prior to the development of the packed snow were too few, to prevent these conditions with the snowfall, temperature, snow moisture, and traffic conditions of the storms.

5.3.2 Data and Results From Wisconsin

The Wisconsin site is in the Green Bay metropolitan area. Operations were conducted by the Brown County Highway Department out of the Brown County Highway shop located approximately 13-km (8-mi) from the site. Data were collected by Wisconsin Department of Transportation (WDOT) personnel working out of the District 3 office, also approximately 13 km (8 mi) from the site.

The test and control sections were 13-km (8-mi) sections of Interstate 43 with two travel lanes in each direction. The southbound lanes were the test section, and the northbound lanes were the control section. Measurements and observations of effectiveness were made on the outside driving lanes. The pavement surface course is continuously reinforced portland cement concrete pavement. WDOT has road weather information system and traffic data installations at the site. Wintertime average daily traffic is approximately 10,000.

Analyses of four Wisconsin storm data sets from the 1994/1995 season, and four sets from the 1993/1994 season, are presented in detail in the site report.[18] The data histories and operations summaries for four of the 1994/1995 storms are presented in figure 29 through figure 32 and table 31. Additional results are included in table 32 through table 34 and figure 33. Summary points and conclusions regarding the operations and their effectiveness over the course of the 1994/1995 and 1993/1994 seasons are presented below.

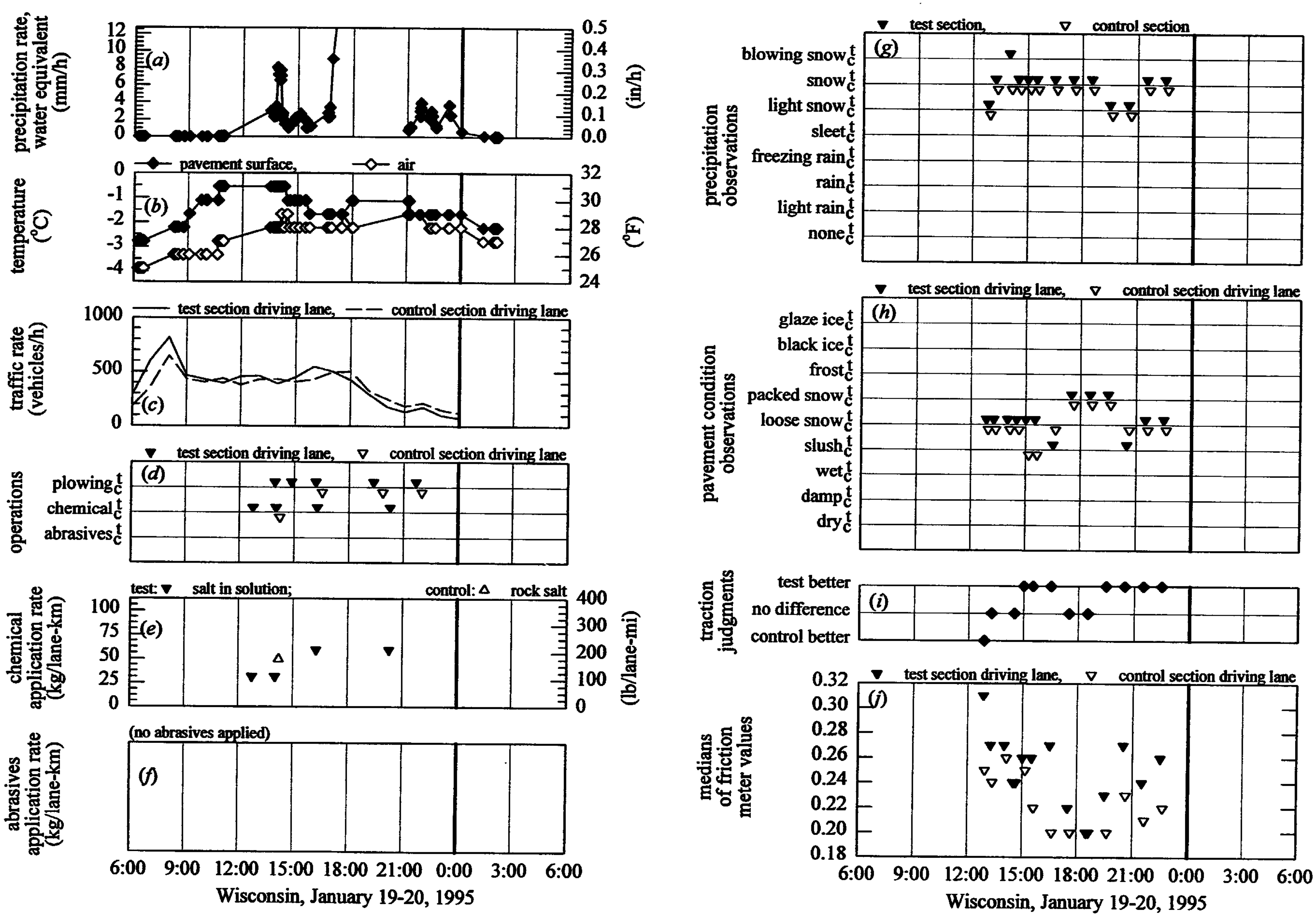


Figure 29. Wisconsin, storm WI501B, January 19-20, 1995, data histories.

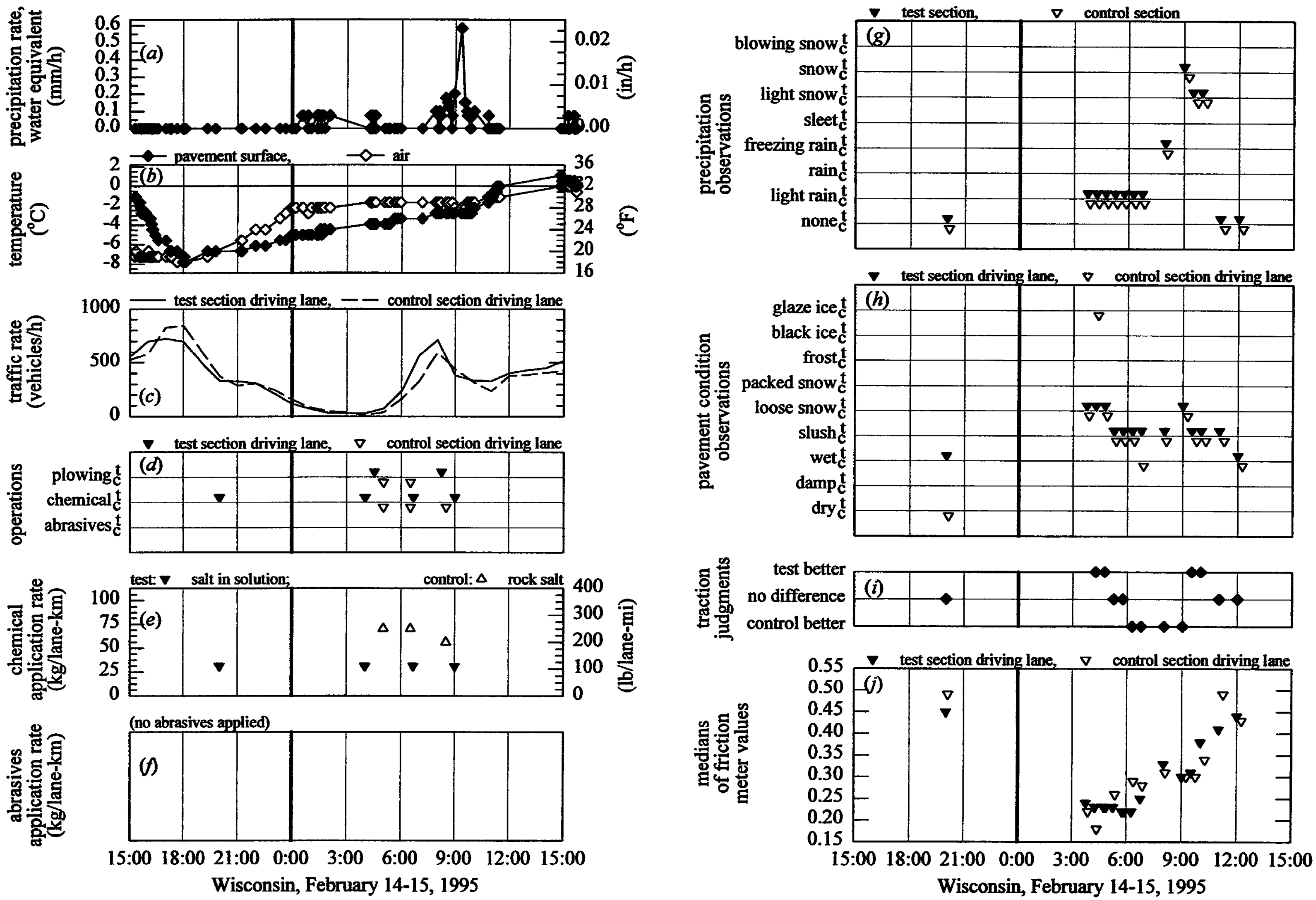


Figure 30. Wisconsin, storm WI502A, February 14-15, 1995, data histories.

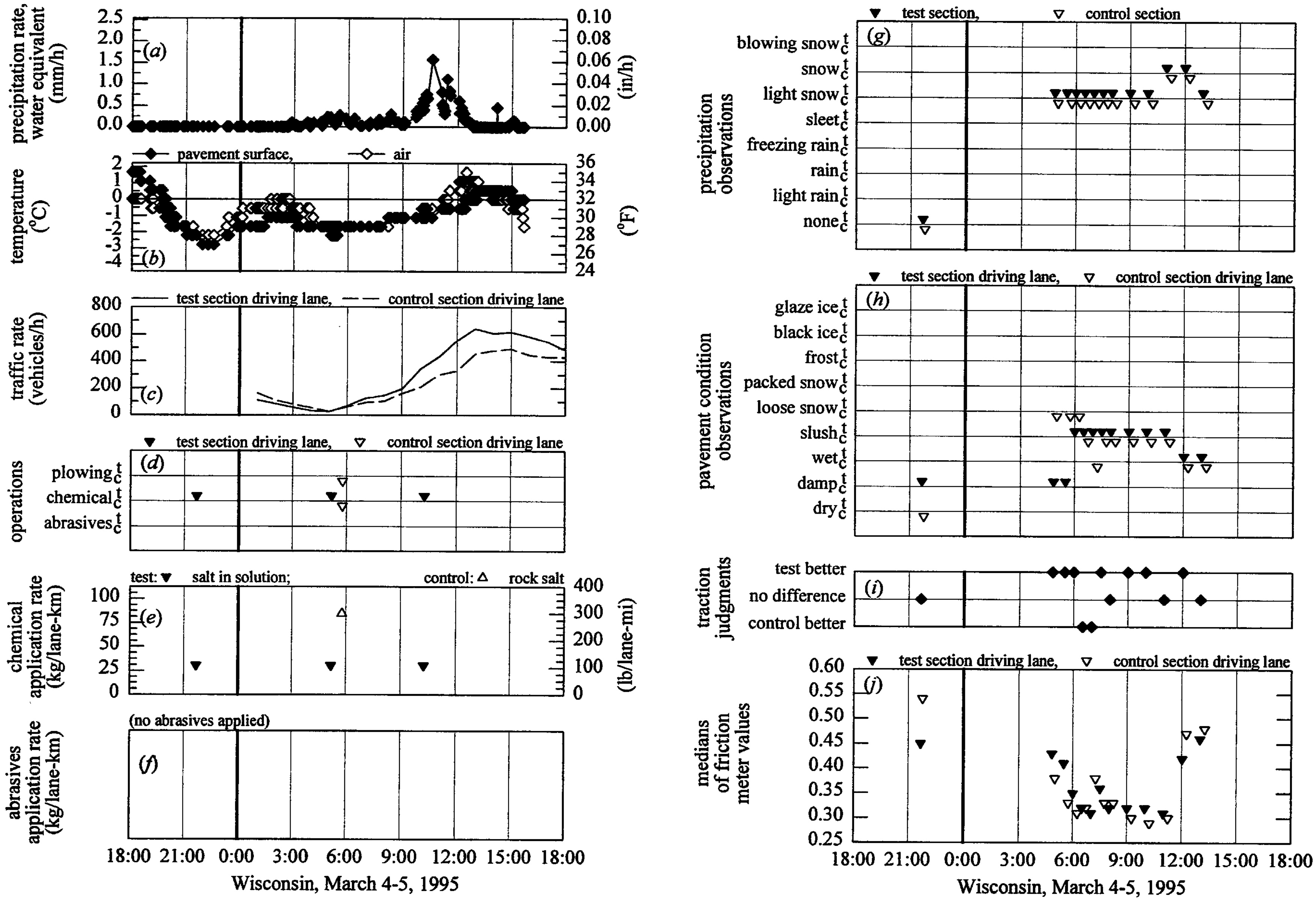


Figure 31. Wisconsin, storm WI503A, March 4-5, 1995, data histories.

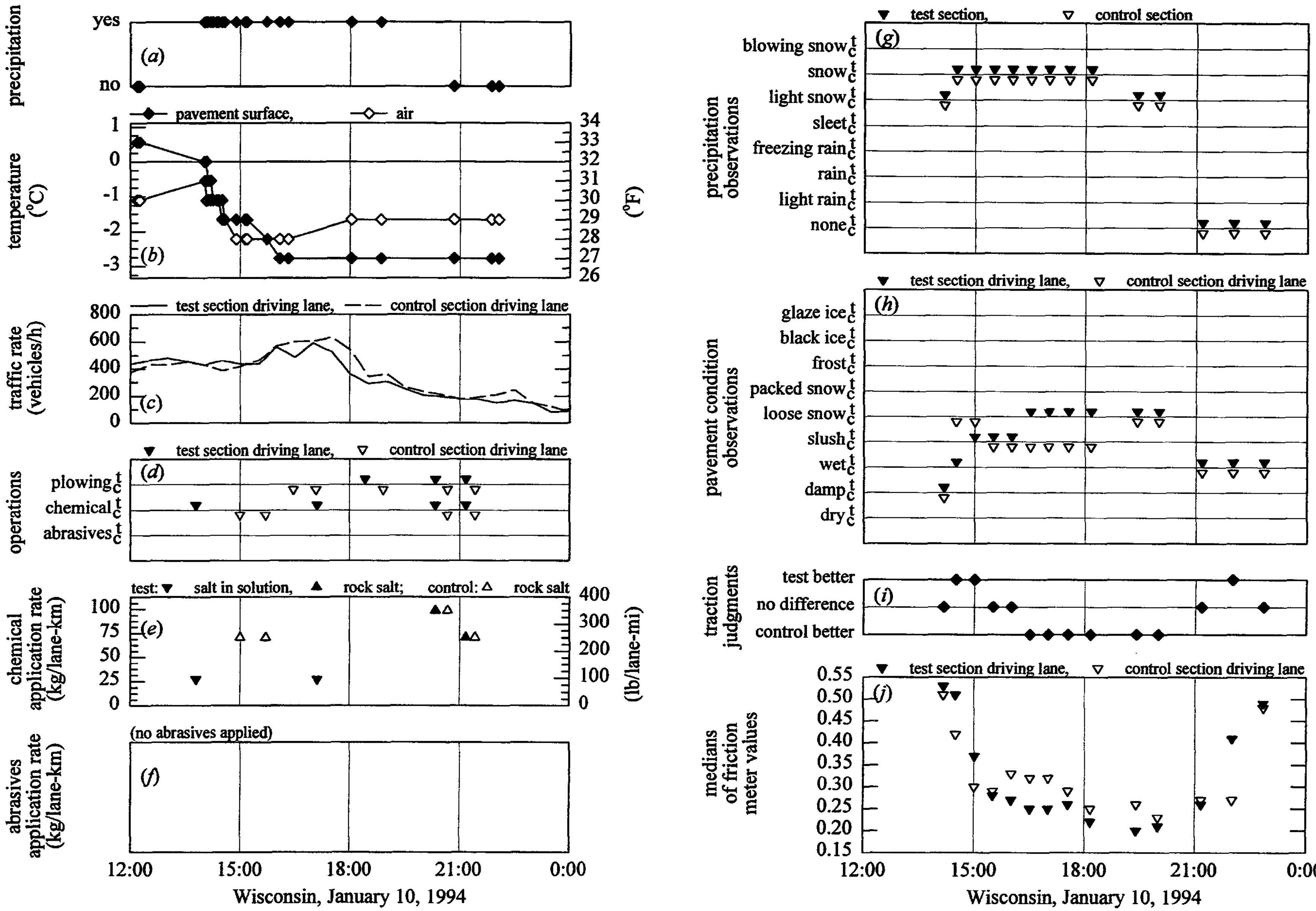


Figure 32. Wisconsin, storm WI0194C, January 10, 1994, data histories.

Table 31. Wisconsin, storms WI501B, WI502A, WI503A, and WI0194C. Summary of documented driving lane operations on test and control sections.

	WI501B January 19-20, 1995		WI502A February 14-15, 1995		WI503A March 4-5, 1995		WI0194C January 10, 1994	
	test section	control section	test section	control section	test section	control section	test section	control section
total number of passes	9	4	6	3	3	1	5	7
number of passes with plowing	5	3	2	2	0	1	3	5
number of passes with NaCl salt brine application	4	0	4	0	3	0	2	0
total NaCl application kg/lane-km	182		125		92		55	
(lb/lane-mi)	(646)		(443)		(328)		(193)	
number of passes with rock salt application[1,2]	0	1	0	3	0	1	2	4
total application kg/lane-km		49		197		85	169	310
(lb/lane-mi)		(175)		(700)		(300)	(600)	(1100)

Notes:
[1]Does not include spot applications on control section during storm WI501B.
[2]Does not include spot applications on test and control sections during storm WI503A.

Table 32. Wisconsin, winter 1994/1995. Summary of documented driving lane operations.

	test section	control section
total number of passes	20	8
number of passes with plowing	7	6
number of passes with NaCl salt brine application	13	0
total NaCl application kg/lane-km	463	
(lb/lane-mi)	(1641)	
number of passes with rock salt application[1,2]	0	5
total application kg/lane-km		331
(lb/lane-mi)		(1175)

Notes:
Data from storms WI501A, W501B, WI502A, WI503A.
[1]Does not include spot applications on control section during storms WI501A and WI501B.
[2]Does not include spot applications on test and control sections during storm WI503A.

Table 33. Wisconsin, winter 1993/1994. Summary of documented driving lane operations.

	test section	control section
total number of passes	13	11
number of passes with plowing[1]	6	6
number of passes with NaCl salt brine application	6	0
total NaCl application kg/lane-km	164	
(lb/lane-mi)	(580)	
number of passes with rock salt application[2,3]	4	7
total application kg/lane-km	328	431
(lb/lane-mi)	(1163)	(1530)

Notes:
Data from storms WI1293A, WI0194A, WI0194B, and WI0194C.
[1]Does not include complete plowing operations on test and control sections during storm WI0194B.
[2]Does not include spot applications on test and control sections during storm WI1293A.
[3]Does not include spot applications on control section during storm WI0194C.

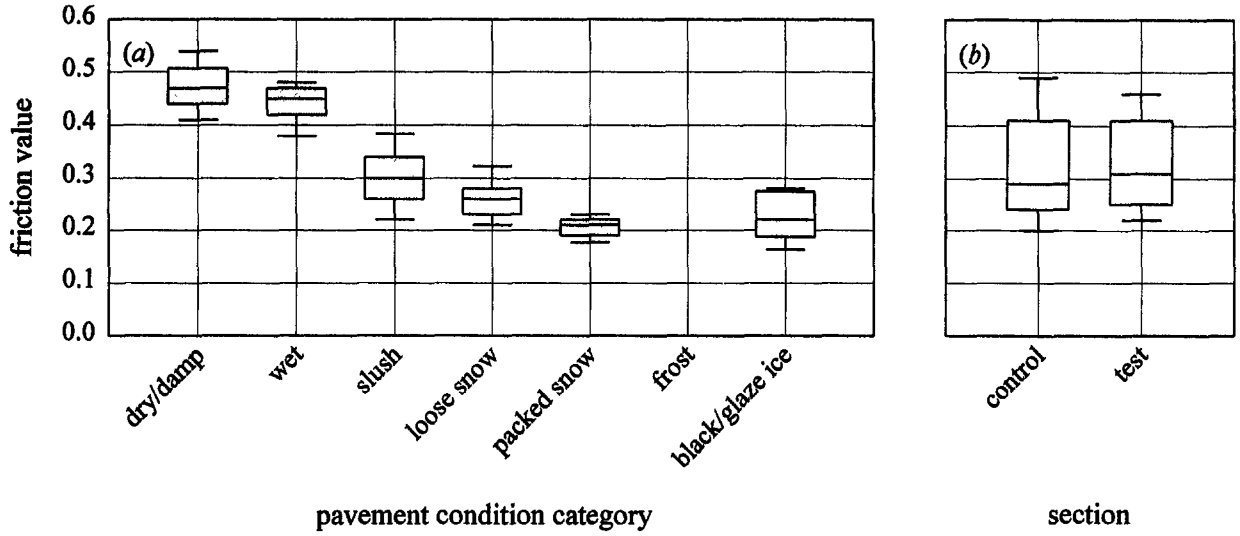


Figure 33. Wisconsin friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 34. Statistics of Wisconsin friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	63	0	0.470	0.440	0.508
wet	105	0	0.450	0.420	0.470
slush	231	0	0.300	0.260	0.340
loose snow	183	0	0.260	0.230	0.280
packed snow	42	0	0.210	0.190	0.220
black/glaze ice	7	0	0.220	0.188	0.275

Mann-Whitney Rank Sum Test of Friction Values as a Function of Section

Group	N	Missing	Median	25%	75%
control	316	0	0.290	0.240	0.410
test	315	0	0.310	0.250	0.410

The differences in the median values among the two groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50^{th}, 25^{th}, and 75^{th} percentiles of the friction measurements in the group.

5.3.2.1 Precipitation and pavement temperature

Light snow, snow, and rain dominated the 1994/1995 precipitation at the site, while snow and light snow dominated the 1993/1994 precipitation. In 1994/1995, pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) and -6.7°C to -3.3°C (20°F to 26°F) categories. About 4 percent of the temperatures were in the category -10°C to -6.7°C (14°F to 20°F). In 1993/1994, the pavement temperatures were mostly in the 3.3°C to 0°C (26°F to 32°F) and -10°C to -6.7°C (14°F to 20°F) categories. About 9 percent of the temperatures were in the -6.7°C to -3.3°C (20°F to 26°F) category and 7 percent in the -13.3°C to -10°C (8°F to 14°F) category. Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

5.3.2.2 Operations

Anti-icing is included in the *Wisconsin State Highway Maintenance Manual* as an appropriate use of chemical for preventing bonded snow or ice and keeping snow accumulation plowable. Deicing is included as an appropriate use as well, either after a storm or after anti-icing has failed. At the site, conventional chemical operations are generally used to support plowing operations, i.e., to keep snow in plowable conditions during storms or to facilitate the cleanup after a storm, and as deicing treatments. These include applications of straight rock salt, salt prewet with calcium chloride solution, or, in extremely cold conditions, salt treated with solid calcium chloride. Salt-treated sand may also be applied. In snowstorms, if the snow appears to be a packing type, initial treatments are generally made early as an anti-icing treatment to prevent bonding.

Operations summaries for the 1994/1995 and 1993/1994 seasons are shown in tables 32 and 33, respectively. The test section chemical operations included applications of sodium chloride (salt) solution and rock salt. Chemical operations on the control section were applications of rock salt. Spot applications of rock salt were used on both sections, but were most common on the control section.

As indicated in figure 29 through figure 32, the initial salt solution applications were placed either well in advance of precipitation (e.g., storms WI502A, figure 30, and WI503A, figure 31), just in advance of precipitation (e.g., storm WI0194C, figure 32), or when snowfall had just begun (e.g., storm WI501B, figure 29). Particular attention was paid to weather and pavement temperature forecasts, radar images, local weather observations, and RWIS pavement temperature data, for deciding on the timing of the initial operation. Subsequent application passes were generally made in response to worsening or changing conditions, and usually at the discretion of the measurement vehicle operator. Chemical concentration information was not available for test section operational decisions since the RWIS concentration sensors were located in the control section. Overall, both the initial and subsequent test section operations reflect intelligent use of decision-making tools. The availability of the chemical concentration indicators for the test section operations would have enhanced the decision making regarding reapplications of the salt solution.

The data histories of storms WI503A (figure 31) and WI0194C (figure 32) show evidence of the advantages of salt solution applications in advance of precipitation. Although the benefit is short lived, higher friction, better pavement conditions, and favorable traction judgments are the apparent result of the pretreatment in both cases. Pavement temperatures were slightly below freezing in the early parts of both storms, and the precipitation was light snow changing to snow. In storm WI503A, a second application was made just after the second pass of the measurement vehicle because it had been almost 3 h since the pretreatment was made. Although the two applications combined did not prevent a drop in friction, the pavement condition deteriorated to a slush condition at worst. Of interest in this storm is the control section refreeze temperature data from the RWIS sensors (not shown on figure 31) at the beginning of the precipitation. The refreeze temperature dropped as low as -2°C (29°F), likely due to residual chemical from previous storm operations. Even though this apparent residual produced a measurable drop in the refreeze temperature, it was not as effective as the test section pretreatment. With later additional moisture from the light snowfall, the refreeze temperature increased sharply toward 0°C (32°F), suggesting that the residual was easily dissipated.

The initial salt solution application in storm WI501B (figure 29) was made onto loose snow. The snowfall began without warning, which precluded the pretreatment that WDOT desired. However, the early applications resulted in higher test section friction early in the storm, when pavement temperature was at -0.5°C (31°F), compared to the control section for which there was minimal salting performed because of high winds and blowing snow. Early salt solution applications in storm WI502A (figure 30) show a benefit as well. In this storm, the light rain with pavement and air temperatures between -4°C and -1°C (the mid and upper 20s °F), caused glaze ice and slightly lower friction on the control section early in the storm.

Subsequent salt solution applications were generally coordinated with plowing when necessary. In storm WI0194A (figure 32), an application made without plowing during a snowfall period apparently led to a slight reduction in friction rather than an increase. That plowing should have been conducted prior to this application is suggested because plowing operations were ongoing on the control section at the time. This decrease in friction is opposite from the effect of reapplications in storm WI501B, which were coordinated with plowing.

5.3.2.3 Pavement condition

Pavement condition observation data are listed in tables 56 and 57, which are presented later in section 5.5, and for the 1994/1995 season in the table immediately below. As indicated in the table, slush was the most common test section pavement condition observation, followed by loose snow, wet, dry/damp, and packed snow. Slush was the most common control section observation as well, followed by loose snow, wet, dry/damp, packed snow, and black/glaze ice. The difference between the test and control observations is significant and slightly favors the test section.[18]

1994/1995 Wisconsin pavement condition observations

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	9	11
wet	18	16
slush	33	40
loose snow	31	27
packed snow	7	7
black/glaze ice	2	0

Packed snow conditions on the test section driving lane occurred during the storm WI501B (figure 29), which included heavy and prolonged snowfall and a sharp increase in snow intensity just before the pack developed. The pack was observed for 3 h beginning in the afternoon rush traffic period, and reflects optimal moisture in the snow and sufficient traffic action to create pack. The results indicate that the application rates of the salt solution were too low or the number of passes prior to the development of the packed snow too few to prevent a bonded snowpack with the increase in snowfall intensity that occurred, even though the application rate was appropriately increased in an attempt to counteract the increasing snowfall rate. Comparison with the control section effectiveness measures does show that the salt solution applications resulted in higher friction before, during, and after the packed snow observations, which is consistent with the pavement condition observations and traction judgments. Control section operations at the time consisted only of plowing operations, as it was conventional practice to minimize salt applications in blowing snow conditions.

5.3.2.4 Friction

Tukey box plots of the 1994/1995 test and control section friction data are shown in figure 33 (b); corresponding data are given in table 34. Although the test section friction had a slightly higher median, the difference is not significant. Both the test and control median values were consistent with the pavement condition category slush (figure 33 (a)).

5.3.2.5 Application rates

As evidenced by the benefit of the salt solution applications made in advance of the storm, the pretreatment applications at rates close to 28 kg/lane-km (100 lb/lane-mi) appear suited to the conditions and operations of the Wisconsin site. The practice of WDOT in the storms WI502A (figure 30) and WI503A (figure 31) was to use the pretreatments for their short-lived benefit early in the storm, and not to expect a long-term benefit from the application. This practice appears to be appropriate.

Subsequent applications in snow, as suggested by the applications in storm WI501B (figure 29), should be regular and frequent, coordinated with plowing, and timed to coincide with increases in snowfall intensity. During storm WI501B, a 60 kg/lane-km (210 lb/lane-mi) application at the beginning of the most intense snowfall was not successful in *preventing* packed snow or friction decreases. However, this application together with earlier applications at approximately 28 kg/lane-km (100 lb/lane-mi) was successful in *mitigating* the effects of the heavy snow. Overall the salt solution applications caused delays in the reduction in friction, provided higher friction and better traction throughout the periods of heavier snow, and caused faster recovery from the snowpack, relative to the conventional operations, which were plowing and rock salt applications using fewer passes and less chemical due to blowing snow conditions. The timing of the 60 kg/lane-km (210 lb/lane-mi) application just at the beginning of the intense snowfall likely contributed to the better condition of the road.

Applications at approximately 28 kg/lane-km (100 lb/lane-mi) in storm WI502A appear to have contributed to a steady increase in friction. Increases in pavement temperature toward the freezing point were occurring simultaneously, however, obscuring the effect of the chemical application.

5.3.3 Data and Results From New Hampshire

The New Hampshire experiments were conducted in the towns of Hanover and Lyme on a 16-km (10-mi) length of New Hampshire Route 10. At the site Rt. 10 is an undivided highway with one travel lane in each direction. The test section was the northbound and southbound lanes of the southernmost 8 km (5 mi), and the control section comprised both lanes of the northernmost 8 km (5 mi). Measurements and observations of effectiveness were made in both directions. The pavement surface is asphalt concrete.

New Hampshire Department of Transportation (NHDOT) has traffic data installations at the site. Wintertime average daily traffic is approximately 8,000 within the test section and 4,000 within the control section. A weather station equipped with pavement temperature sensors was placed at the site for the experiments. For the project, NHDOT contracted with a local meteorological consultant for site-specific forecast information. The consultant used in part the site weather station data to prepare forecasts. Pavement temperature forecasts were not made, although pavement temperatures could be monitored by the consultant and by NHDOT.

Analyses of six New Hampshire storm data sets from the 1994/1995 season, and nine sets from the 1993/1994 season, are presented in detail in the site report.[14] The data histories and operations summaries for nine of the storms are presented in figures 34 through 42, and tables 35 and 36. Additional results are included in tables 37 through 41 and figures 43 through 45. Summary points and conclusions regarding the operations and their effectiveness are presented below.

5.3.3.1 Precipitation and pavement temperature

Light snow, snow, and freezing rain dominated the 1994/1995 precipitation at the site, while light snow and snow dominated the 1993/1994 precipitation. In 1994/1995, pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -6.7°C to -3.3°C (20°F to 26°F) and -3.3°C to 0°C (26°F to 32°F) categories. About 22 percent of the temperatures were in the -10°C to -6.7°C (14°F to 20°F) category.

In 1993/1994, the pavement temperatures were mostly in the -10°C to -6.7°C (14°F to 20°F), -13.3°C to -10°C (8°F to 14°F), and > 0°C (> 32°F) categories.

Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

5.3.3.2 Operations

NHDOT's policy has been for many years to provide bare and dry pavements as soon as practical after a storm, but not to provide bare pavement during a storm. However, the policy does state that chemical can be used to prevent snow and ice build-up on the pavement as well as to aid removal of any build-up that occurs, which is a preventive approach consistent with anti-icing. Operations summaries for the 1994/1995 and 1993/1994 seasons are shown in tables 37 and 38, respectively. The test section chemical operations included applications of potassium acetate solution and rock salt. Chemical operations on the control section were applications of rock salt. Abrasives were used on both sections, but were most commonly used on the control section.

The initial potassium acetate solution applications were usually placed either well in advance of precipitation (e.g., storms NH501B, NH501C, NH502A, and NH502B; see figures 34 through 37), or when light snowfall had just begun (e.g., storms NH502C, NH1293B, NH1293C, and NH1293D; see figures 38 through 41). Details and results of these example applications are given in table 42. Particular attention was paid to weather contractor forecasts and weather observations for deciding on the timing of the initial operation, which was highly successful for the pre-storm treatment strategy. As indicated in table 42, only during storm NH1293B (figure 39), with light snow with pavement temperatures around -1°C (30°F), were the applications successful relative to no operations on the control section. Generally, the control section response to the early storm precipitation was very similar to the test section response, even though no operations had been conducted on the control section. This is in contrast to the short-lived effectiveness of the initial salt solution applications in Wisconsin, not only during a light snow event but also in storms with precipitation changing from light snow to snow and pavement temperatures in the range -4°C to -1°C (upper 20s °F).

As a consequence of the effort to evaluate the liquid pre-storm treatments and the usual rapid deterioration of conditions, and because expectations of the effectiveness of the treatments were high, subsequent test section chemical application passes were initiated well after the conditions had deteriorated. The frequency and timing of the subsequent applications, when multiple applications were conducted, were consistent with the frequency and timing of the conventional operations at the site. Usually the second test section application pass came after the initial control section chemical pass, but

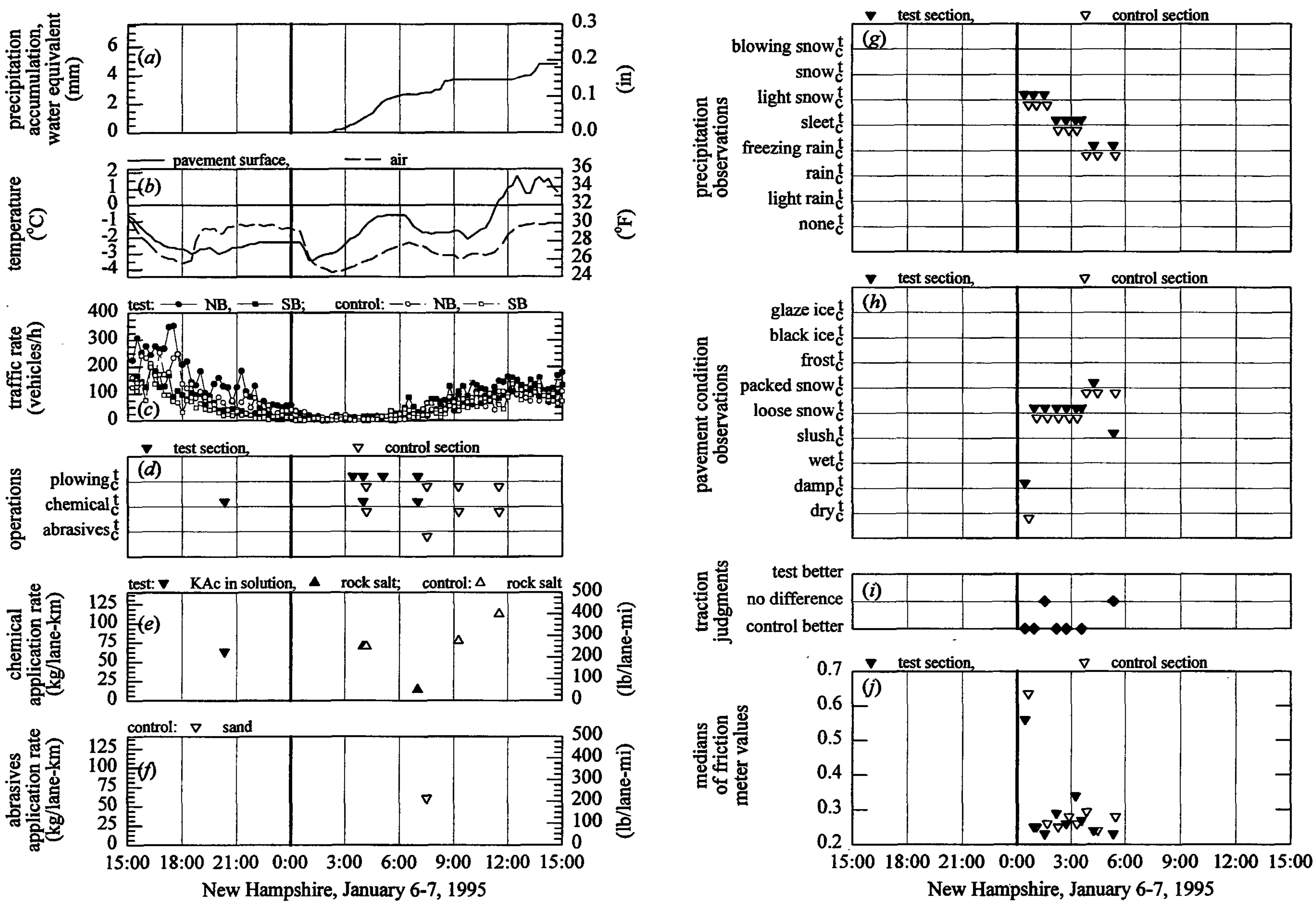


Figure 34. New Hampshire, storm NH501B, January 6-7, 1995, data histories.

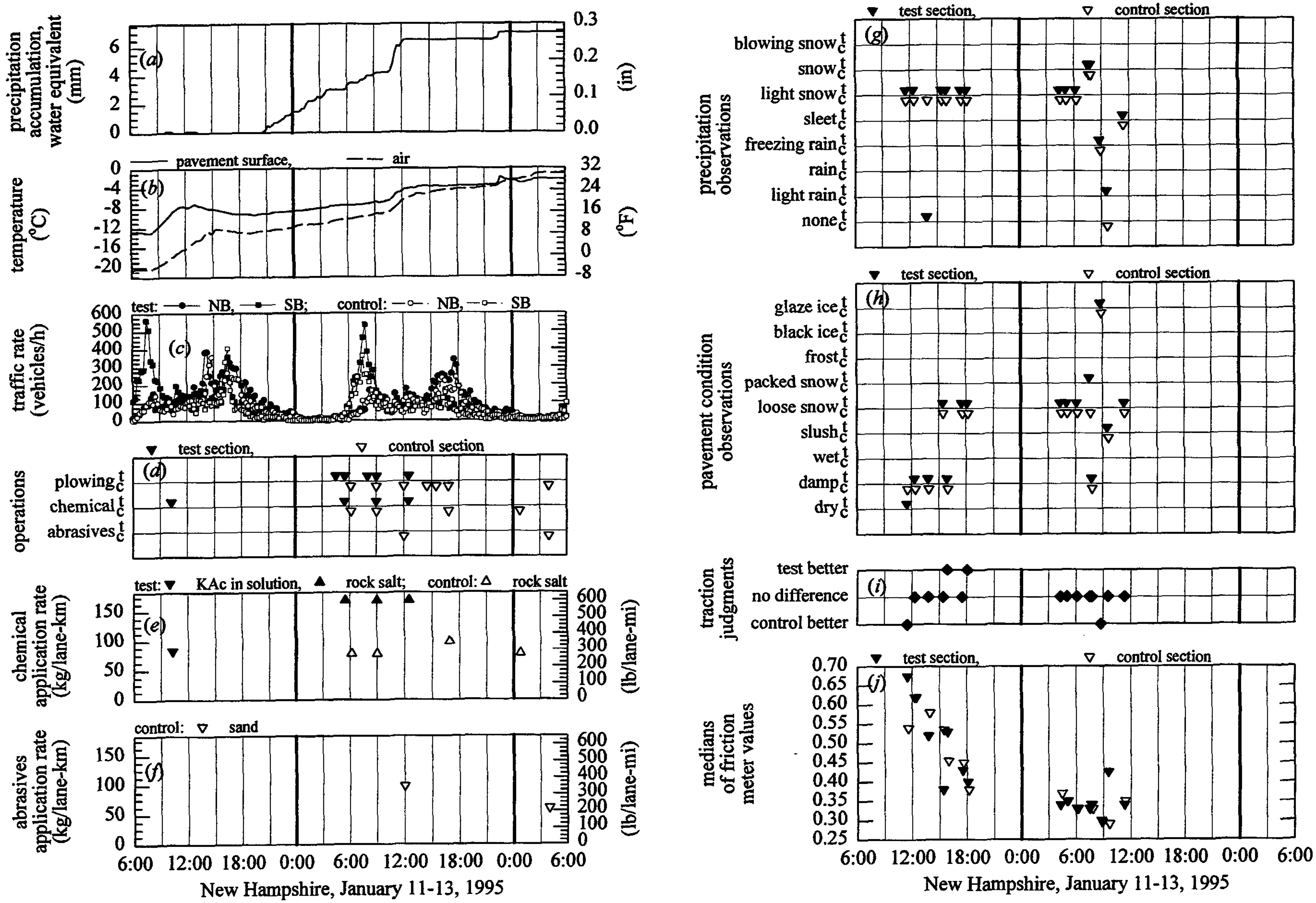


Figure 35. New Hampshire, storm NH501C, January 11-13, 1995, data histories.

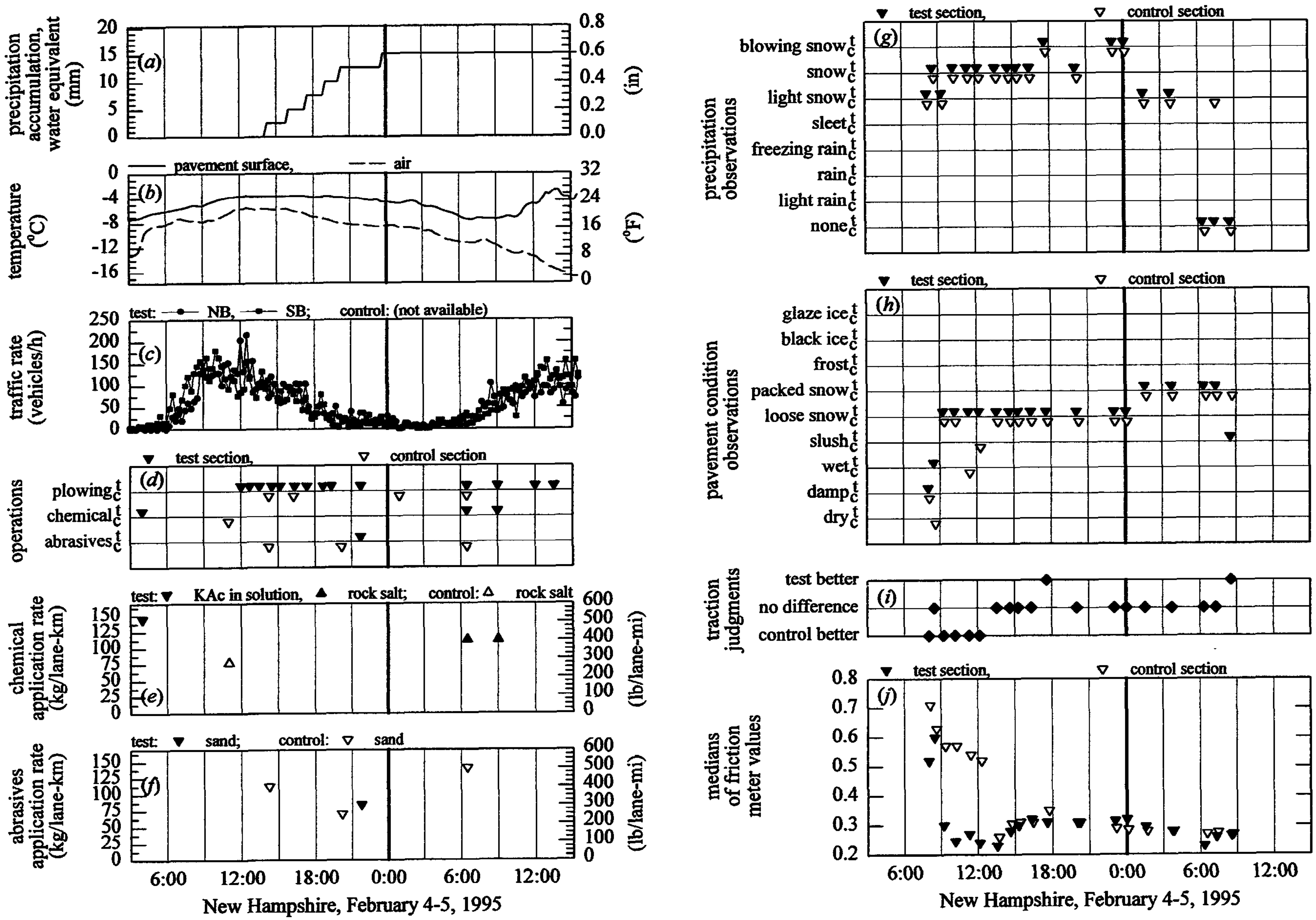


Figure 36. New Hampshire, storm NH502A, February 4-5, 1995, data histories.

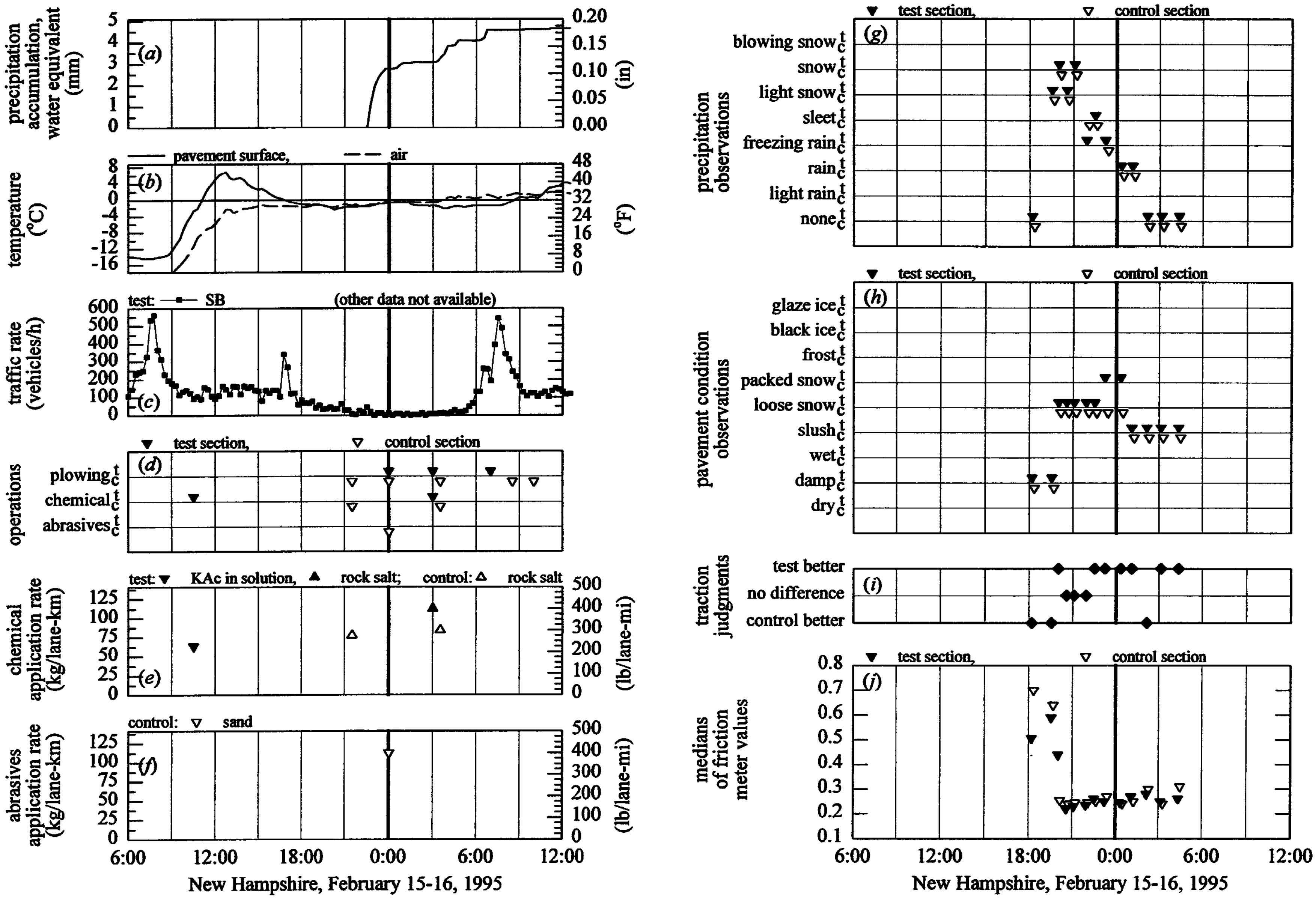


Figure 37. New Hampshire, storm NH502B, February 15-16, 1995, data histories.

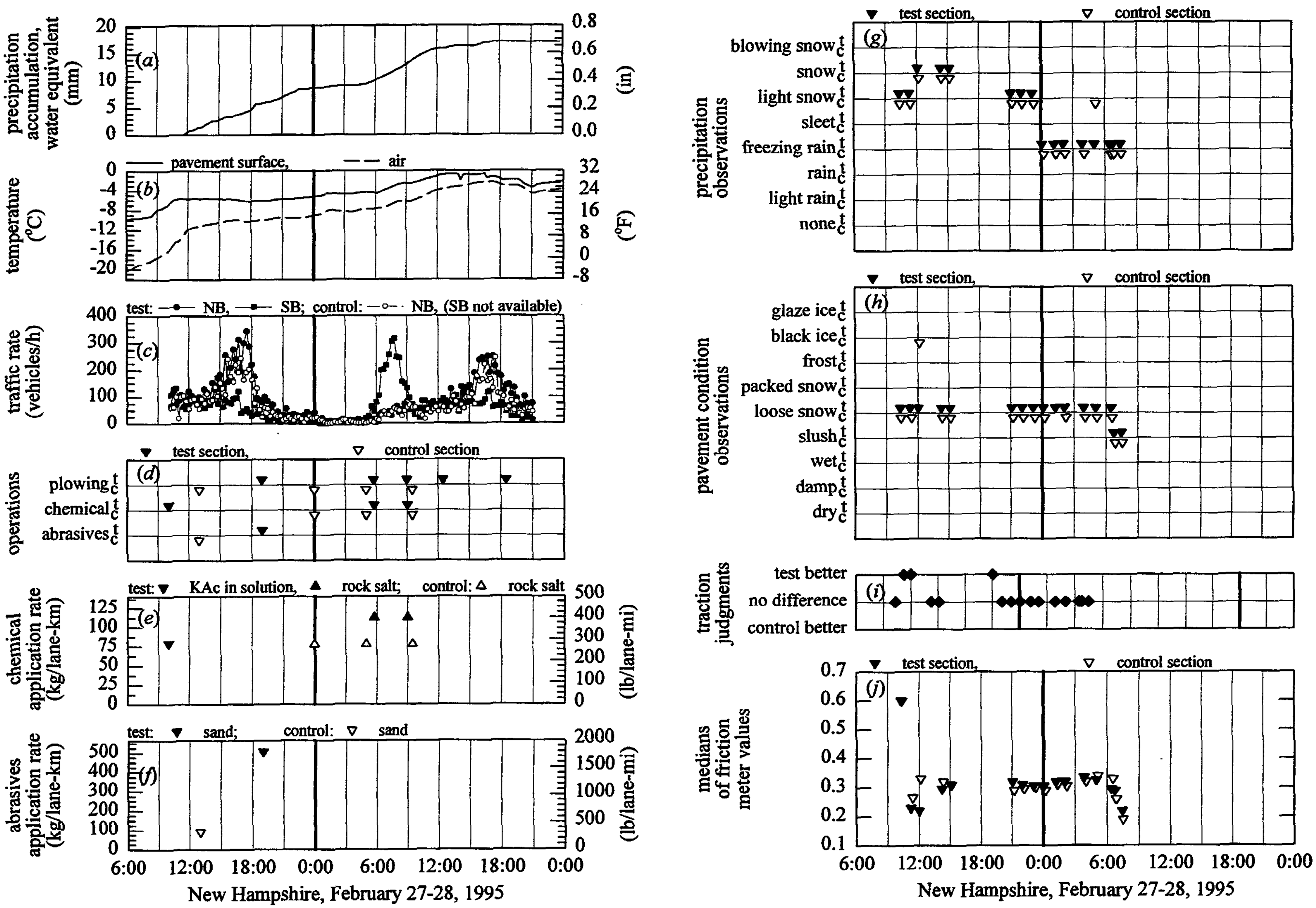


Figure 38. New Hampshire, storm NH502C, February 27-28, 1995, data histories.

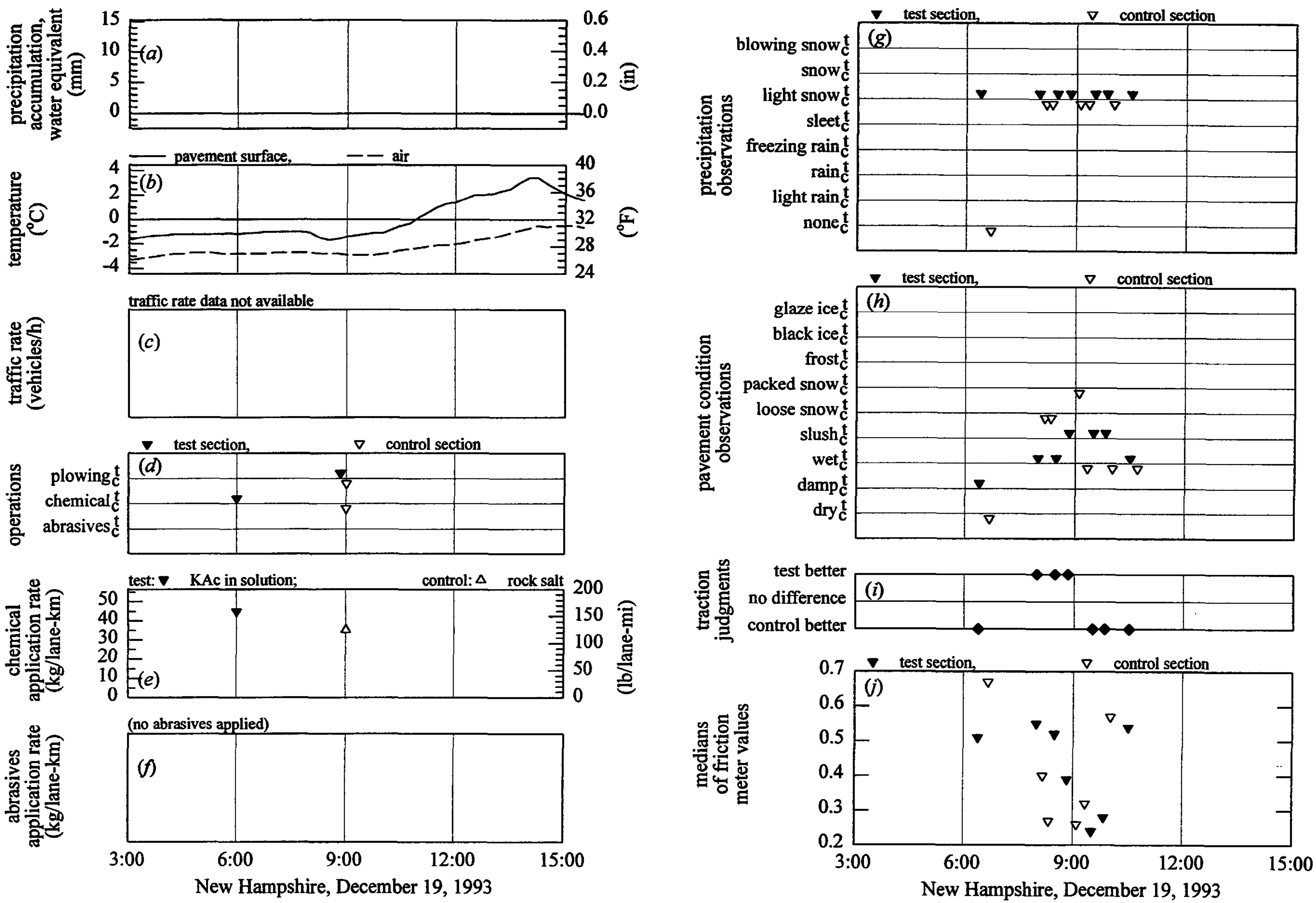


Figure 39. New Hampshire, storm NH1293B, December 19, 1993, data histories.

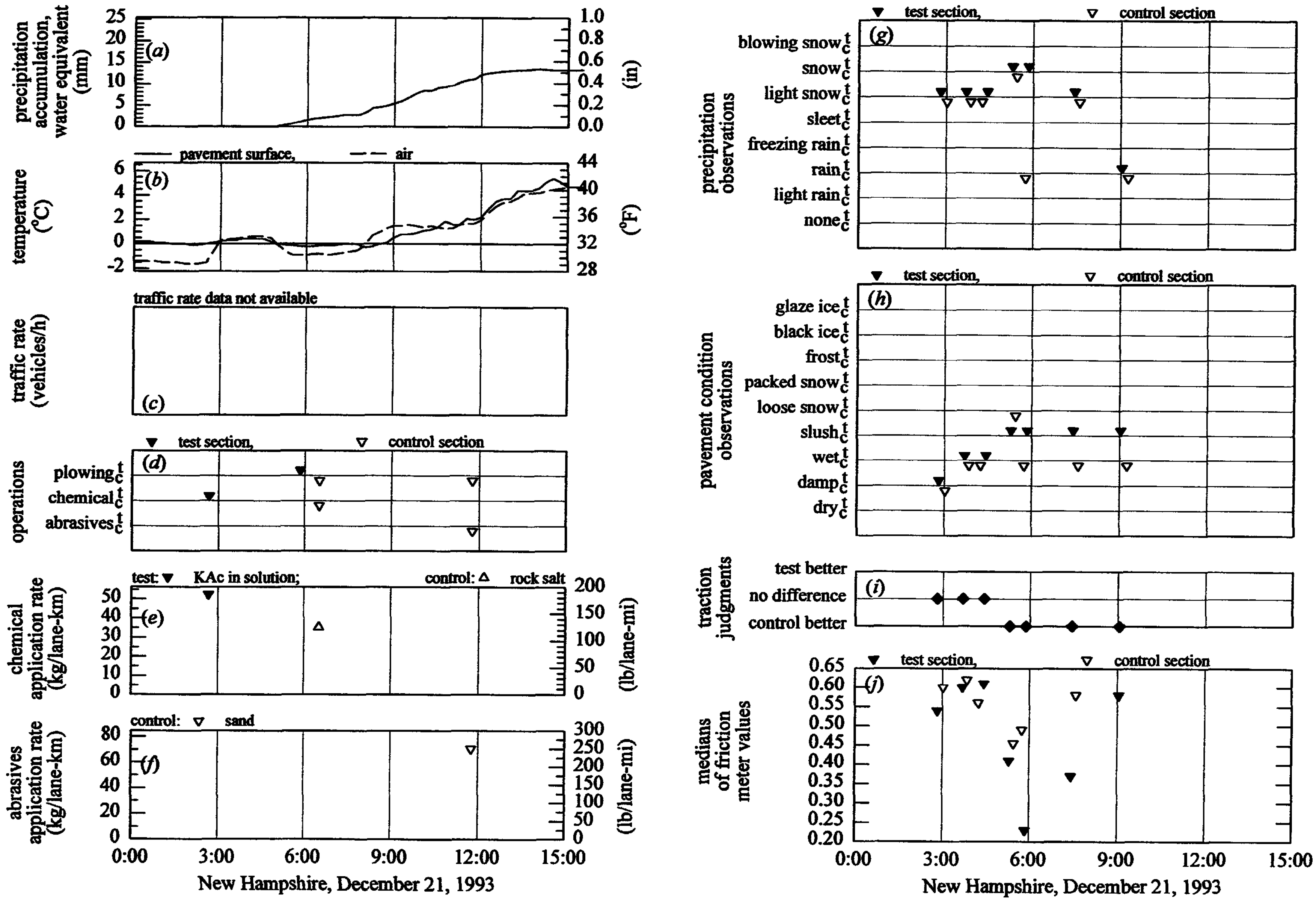


Figure 40. New Hampshire, storm NH1293C, December 21, 1993, data histories.

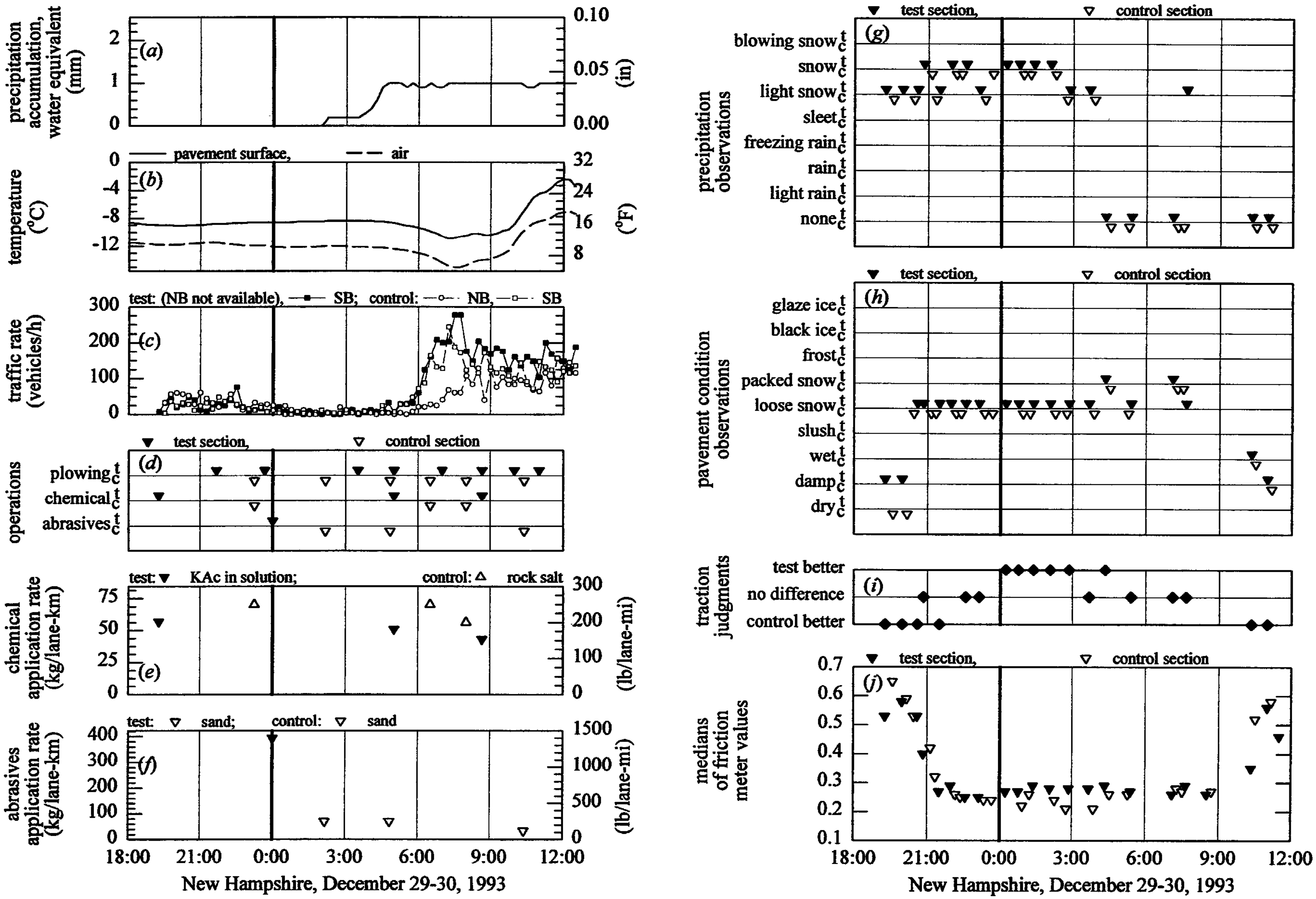


Figure 41. New Hampshire, storm NH1293D, December 29-30, 1993, data histories.

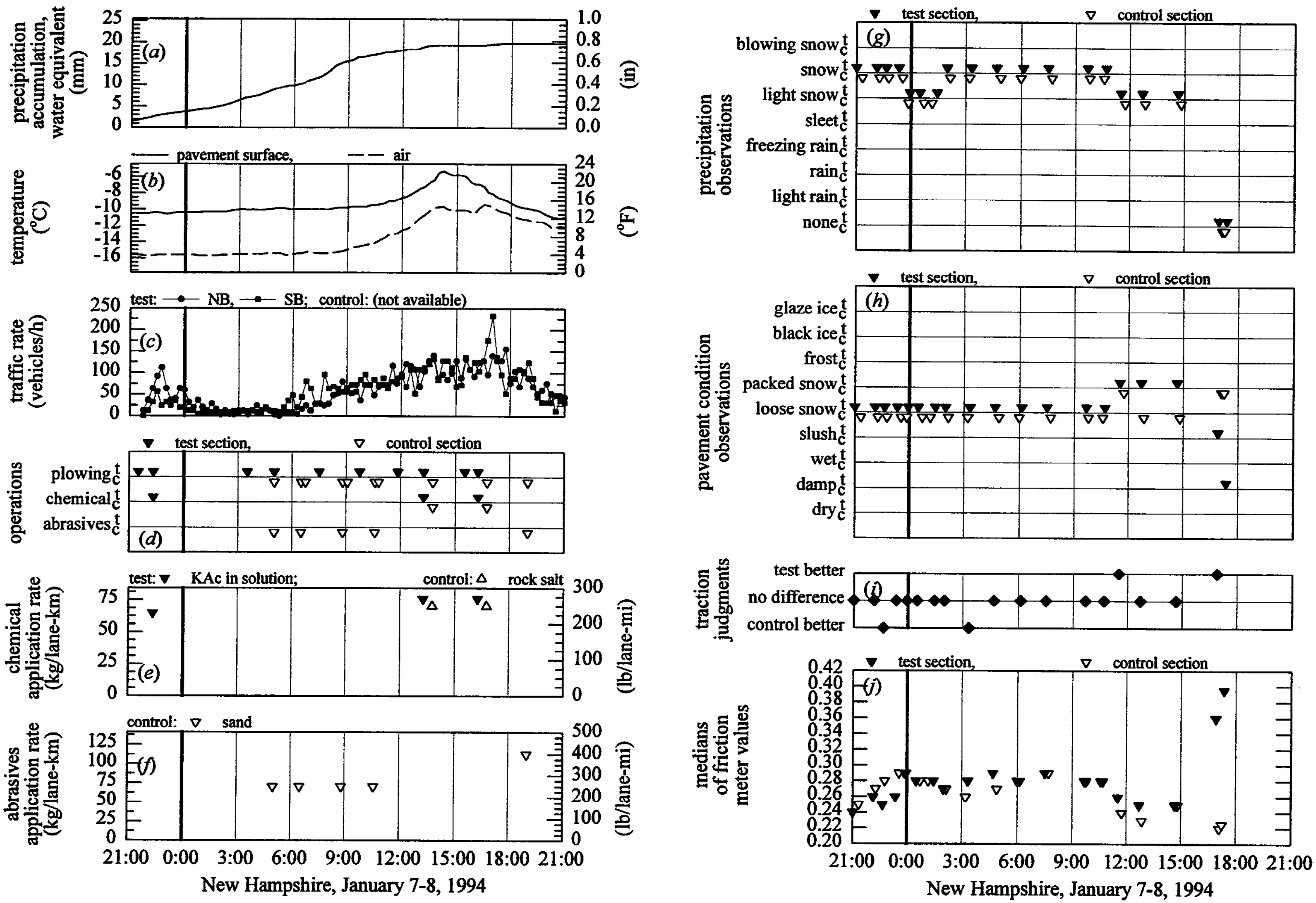


Figure 42. New Hampshire, storm NH0194B, January 7-8, 1994, data histories.

Table 35. New Hampshire, storms NH501B, NH501C, NH502A, and NH502B. Summary of documented operations on test and control sections.

	NH501B January 6-7, 1995		NH501C January 11-13, 1995		NH502A February 4-5, 1995		NH502B February 15-16, 1995	
	test section	**control section**	**test section**	**control section**	**test section**	**control section**	**test section**	**control section**
total number of passes	5	4	6	8	15	5	4	5
number of passes with plowing	4	4	5	7	14	4	3	5
number of passes with application of potassium acetate-based solution	1	0	1	0	1	0	1	0
total KAc application kg/lane-km	64		83		146		64	
(lb/lane-mi)	(227)		(296)		(517)		(227)	
number of passes with rock salt application	2	3	3	4	2	1	1	2
total application kg/lane-km	141	261	507	331	225	78	113	162
(lb/lane-mi)	(500)	(925)	(1800)	(1175)	(800)	(275)	(400)	(575)
number of passes with abrasives application	0	1	0	2	1	3	0	1
total application kg/lane-km		61		159	85	324		113
(lb/lane-mi)		(215)		(565)	(300)	(1150)		(400)

Table 36. New Hampshire, storms NH502C, NH1293B, and NH0194B. Summary of documented operations on test and control sections.

	NH502C February 27-28, 1995		NH1293B December 19, 1993		NH0194B January 7-8, 1994	
	test section	**control section**	**test section**	**control section**	**test section**	**control section**
total number of passes	6	4	2	1	10	10
number of passes with plowing	5	4	1	1	10	10
number of passes with application of potassium acetate-based solution	1	0	1	0	3	0
total KAc application kg/lane-km	80		45		217	
(lb/lane-mi)	(282)		(159)		(770)	
number of passes with rock salt application	2	3	0	1	0	2
total application kg/lane-km	225	233		35		141
(lb/lane-mi)	(800)	(825)		(125)		(500)
number of passes with abrasives application	1	1	0	0	0	5
total application kg/lane-km	507	92				395
(lb/lane-mi)	(1800)	(325)				(1400)

Table 37. New Hampshire, winter 1994/1995. Summary of documented operations.

	test section	control section
total number of passes	41	29
number of passes with plowing	35	26
number of passes with application of potassium acetate-based solution	6	0
total KAc application kg/lane-km	501	0
(lb/lane-mi)	(1776)	(0)
number of passes with rock salt application	11	15
total application kg/lane-km	1282	1219
(lb/lane-mi)	(4550)	(4325)
number of passes with abrasives application	2	9
total application kg/lane-km	592	960
(lb/lane-mi)	(2100)	(3405)

Note: Data from storms NH501A, NH501B, NH501C, NH502A, NH502B, and NH502C.

Table 38. New Hampshire, winter 1993/1994. Summary of documented operations.

	test section	control section
total number of passes	64	46
number of passes with plowing	52	45
number of passes with application of potassium acetate-based solution	18	0
total KAc application kg/lane-km	1101	0
(lb/lane-mi)	(3905)	(0)
number of passes with rock salt application	2	20
total application kg/lane-km	211	1238
(lb/lane-mi)	(750)	(4394)
number of passes with abrasives application	4	21
total application kg/lane-km	617	1409
(lb/lane-mi)	(2190)	(5000)

Note: Data from storms NH1293B, NH1293C, NH1293D, NH0194A, NH0194B, NH0194C, NH0194D, NH0394A, and NH0394B.

occasionally slightly before. Chemical concentration information was not available for operational decisions since the weather station did not contain concentration sensors. The availability of the chemical concentration indicators for the test section operations likely could have enhanced decision making regarding reapplications of the potassium acetate solution and subsequent rock salt applications, although the service level of the highway did not necessarily warrant more frequent applications. During the 1993/1994 season, the liquid retreatments were always coordinated with plowing because the liquid application truck was a plow truck. The potassium acetate solution was not used in retreatment applications during the 1994/1995 season.

Of the storm data sets presented here, only storms NH1293D and NH0194B include measurement and observation data showing the return to higher friction and bare pavement conditions. In the cold storm NH1293D (figure 41) the improvement occurred 6 h after the end of snowfall. It followed chemical and plowing operations on both test and control sections, and coincided with pavement temperatures increasing to -4°C (24°F) and above from approximately -10°C (14°F). The data histories of storm

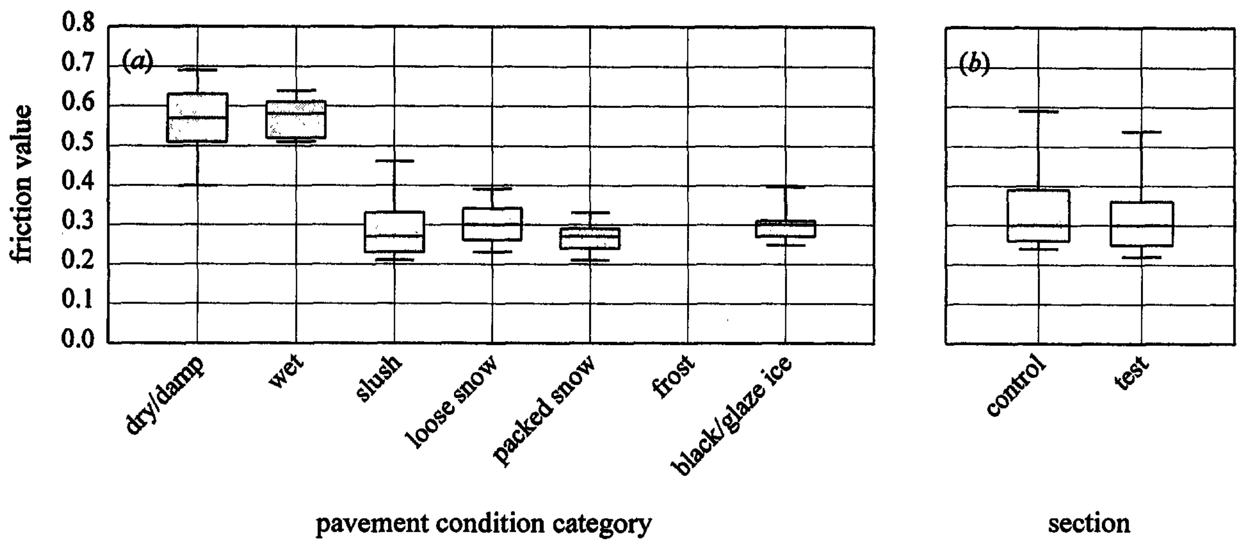


Figure 43. New Hampshire friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 39. Statistics of New Hampshire friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	154	0	0.570	0.510	0.630
wet	36	0	0.580	0.520	0.610
slush	132	0	0.270	0.230	0.330
loose snow	729	0	0.300	0.260	0.340
packed snow	118	0	0.270	0.240	0.290
black/glaze ice	23	0	0.300	0.270	0.310

Mann-Whitney Rank Sum Test of Friction Values

Group	N	Missing	Median	25%	75%
control	589	0	0.300	0.260	0.390
test	603	0	0.300	0.250	0.360

There is no difference in median values.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

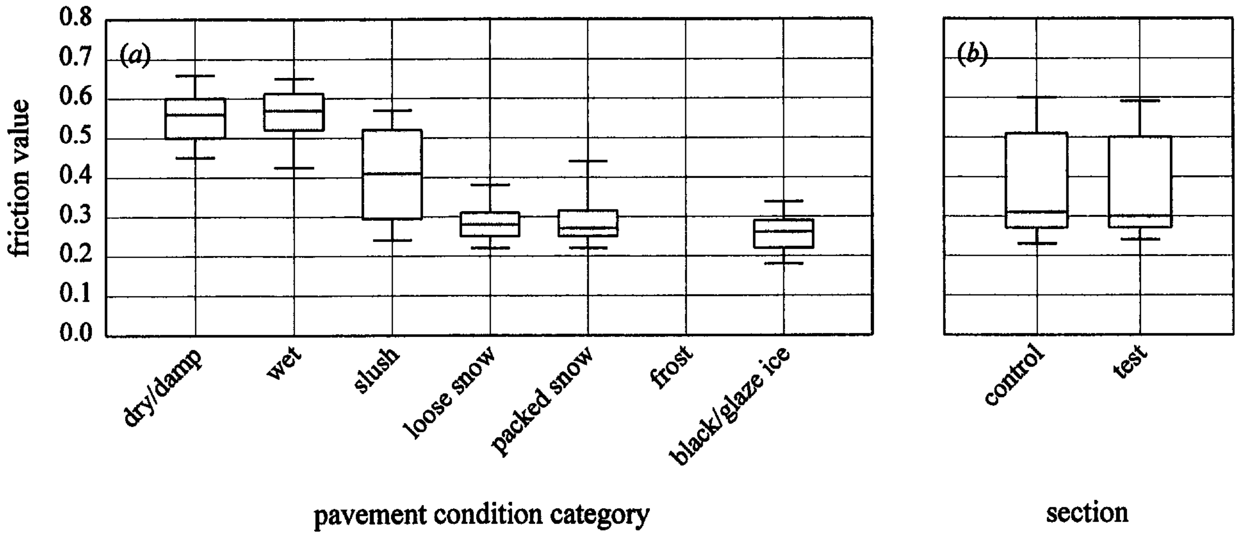


Figure 44. New Hampshire friction measurement data, winter 1993/1994. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 40. Statistics of New Hampshire friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1993/1994.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	226	0	0.560	0.500	0.600
wet	265	16	0.570	0.520	0.613
slush	236	0	0.410	0.295	0.520
loose snow	859	1	0.280	0.250	0.310
packed snow	205	1	0.270	0.250	0.315
black/glaze ice	39	0	0.260	0.220	0.290

Mann-Whitney Rank Sum Test of Friction Values

Group	N	Missing	Median	25%	75%
test	803	15	0.300	0.270	0.500
control	790	16	0.310	0.270	0.510

The differences in the median values among the two groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

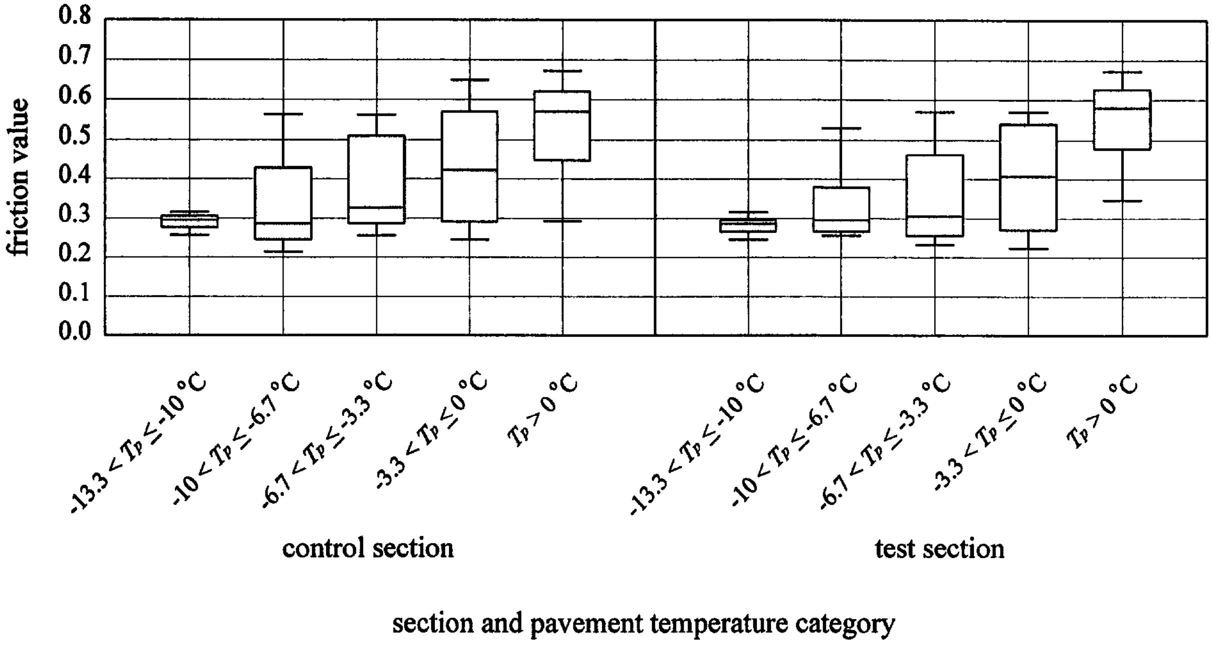


Figure 45. New Hampshire friction data, winter 1993/1994. Tukey box plot of friction data statistics as a function of section and pavement temperature category.

Table 41. Statistics of New Hampshire friction data, winter 1993/1994, grouped according to section and pavement temperature category.

Group	N	Missing	Median	25%	75%
Control Section, -13.3 °C < T_p ≤ -10 °C	166	0	0.30	0.27	0.31
Control Section, -10 °C < T_p ≤ -6.7 °C	262	0	0.28	0.24	0.43
Control Section, -6.7 °C < T_p ≤ -3.3 °C	113	0	0.33	0.28	0.51
Control Section, -3.3 °C < T_p ≤ 0 °C	85	9	0.42	0.29	0.57
Control Section, T_p > 0 °C	164	7	0.57	0.45	0.62
Test Section, -13.3 °C < T_p ≤ -10 °C	182	0	0.28	0.26	0.30
Test Section, -10 °C < T_p ≤ -6.7 °C	262	1	0.30	0.26	0.38
Test Section, -6.7 °C < T_p ≤ -3.3 °C	113	0	0.31	0.25	0.46
Test Section, -3.3 °C < T_p ≤ 0 °C	83	7	0.41	0.27	0.54
Test Section, T_p > 0 °C	163	7	0.58	0.48	0.63

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

NH0194B (figure 42), also a cold storm, show that subsequent potassium acetate applications during and following a midday rise of pavement temperatures toward -5°C (into the lower 20s °F), during a period of packed snow observations, were more effective than rock salt applications at slightly lower rates. The result was a faster return to higher pavement friction. Of interest in the control section operations is the apparent lack of benefit of the four control section abrasives applications during a prolonged period of low friction. Other end-of-storm data included in the site report, with higher pavement temperatures, show rapid improvement in test section conditions following the end of snowfall and operations.

Table 42. Initial potassium acetate solution applications and results.

Storm	Pavement temperature and variation at beginning of precipitation	Precipitation type at beginning of storm	Approximate period between initial application and beginning of precipitation	Approximate application rate	Result	Comments on control section operation and result
NH501B	-2°C (28°F); dropping slightly to -3.5°C (26°F)	Light snow	3-4 h	60 kg/lane-km (225 lb/lane-mi)	Sharp drop in friction within an hour, condition changing from damp to loose snow	Before any control operations, control showed similar variations in friction and conditions
NH501C	-8°C (18°F) and remaining fairly steady	Light snow	1 h	80 kg/lane-km (300 lb/lane-mi)	Steady drop in friction over 6 h, condition changing from dry to damp to loose snow	Before any control operations, control showed similar variations in friction and conditions
NH502A	-5°C (23°F) and rising slightly	Light snow changing immediately to snow	4 h	140 kg/lane-km (500 lb/lane-mi)	Sharp drop in friction within an hour, condition changing from damp to wet to loose snow	Rock salt at 77 kg/lane-km (275 lb/lane-mi) applied soon after snowfall increase; arrested drop in friction
NH502B	-1 to -2°C (approx. 30°F) and steady	Light snow changing immediately to snow	8 h	60 kg/lane-km (225 lb/lane-mi)	Sharp drop in friction within an hour, condition changing from damp to loose snow	Before any control operations, control showed similar variations in friction and conditions
NH502C	-5°C (22°F) and steady	Light snow changing to snow	0 h	75 kg/lane-km (275 lb/lane-mi)	Sharp drop in friction within an hour	Before any control operations, control showed similar variations in friction
NH1293B	-1°C (30°F) and steady	Light snow	0 h	45 kg/lane-km (160 lb/lane-mi)	Friction steady, road damp or wet, then deteriorating 2 h later	Before any control operations, control showed lower friction and worse conditions than test section
NH1293C	0 to 0.5°C (32 to 33°F) and steady	Light snow turning 2 h later to snow	0 h	50 kg/lane-km (190 lb/lane-mi)	Friction steady and road wet in light snow, then deteriorating with snow to lower friction and slush	Before any control operations, control showed variations in friction and conditions similar to test section
NH1293D	-9°C (16°F) and steady	Light snow turning 2 h later to snow	0 h	55 kg/lane-km (200 lb/lane-mi)	Friction steady and road damp in light snow, then deteriorating with snow to lower friction and loose snow	Before any control operations, control showed variations in friction and conditions nearly identical to test section
NH0194B	-11°C (13°F) and steady	Mostly snow	After 25 mm (1 in) of dry snow had fallen and blown off wheel tracks	65 kg/lane-km (230 lb/lane-mi)	Mostly low friction and loose snow, but slight friction increase after application/plowing	Before any control operations, control showed friction and conditions similar to test section

5.3.3.3 Pavement condition

Pavement condition observation data are listed in tables 56 and 57, which are presented later in section 5.5, and in the table immediately below. For the 1994/1995 season, loose snow was the most common test section pavement condition observation, followed by dry/damp, slush, packed snow, wet, and black/glaze ice. Loose snow was the most common test section observation, followed by dry/damp, slush, packed snow, wet, and black/glaze ice. The difference between the test and control observations is not significant.[14]

1994/1995 New Hampshire pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	14	12
wet	3	3
slush	12	11
loose snow	60	63
packed snow	10	10
black/glaze ice	2	1

For the colder 1993/1994 season, loose snow was the most common test section pavement condition observation, followed by wet, slush, dry/damp, packed snow, and no observation recorded. Loose snow was the most common test section pavement condition observation, followed by wet, slush, dry/damp, packed snow, no observation recorded, and black/glaze ice. The difference between the test and control observations is significant but small.[14]

1993/1994 New Hampshire pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	10	12
wet	16	15
slush	13	15
loose snow	46	45
packed snow	9	7
black/glaze ice	1	0
no observation	5	6

5.3.3.4 Friction

Tukey box plots of the 1994/1995 test and control section friction data are shown in figure 43 (b); corresponding data are given in table 39. Although the test section and control section friction had identical medians, the distribution of the control section data is toward higher values. As indicated in figure 43, both the test and control median values were consistent with the pavement condition categories slush and loose snow.

Box plots of the 1993/1994 data are shown in figure 44 (b), and corresponding data are given in table 40. The difference between the test and control section friction is not significant. Both the test and control median values were low. They were consistent with the pavement condition categories loose snow and packed snow (figure 44 (a)).

A further graph of data from the 1993/1994 season, showing friction box plots vs. section and pavement temperature category, is included as figure 45. Corresponding data are presented in table 41. The graph and table reveal that the friction medians for all categories below freezing, except -13.3°C to -10°C (8°F to 14°F), were slightly higher on the control section. This result is in contrast with the expectation of NHDOT that the pretreatments with the potassium acetate solution would provide generally better lower temperature effectiveness than conventional rock salt treatments.

5.3.3.5 Application rates

In general, the pretreatment applications on the test section were no more effective than no operations on the control section. As table 42 indicates, the rates varied from approximately 45 to 140 kg/lane-km (160 to 500 lb/lane-mi).

5.3.4 Data and Results From Colorado

Analyses of 10 Colorado storm data sets from the 1994/1995 season are presented in the site report.[8] The data histories and operations summaries for two of the storms, CO412C and CO501B, are presented in figure 46, figure 47, and table 43. A short description of the Colorado site and these storms is presented here. Information regarding the full-season analysis is not discussed here but is included in section 5.5.

The Colorado experiments were conducted on Interstate 70 in Garfield County, on highway sections in the western end of Glenwood Canyon just east of Glenwood Springs. Operations were conducted out of the Colorado Department of Transportation (CDOT) maintenance station in Glenwood Springs.

The test section was a 5-km (3-mi) stretch of westbound I-70 from milepost 116 to milepost 119. The control section was the parallel highway in the eastbound direction. The highway at this location has two travel lanes in each direction. The test and control sections each covered approximately 10 lane-km (6 lane-mi). The pavement surface course is asphalt concrete.

CDOT has an elaborate road weather information system (RWIS) installation at the site in the canyon, as well as a traffic data installation. These are monitored along with other highway information at the canyon's Hanging Lake Tunnel control room. Wintertime average daily traffic (ADT) varies from 8,000 to 10,000. CDOT's initial use of the RWIS and associated weather and pavement temperature forecasting capabilities was during the first season of this project.

5.3.4.1 Precipitation and pavement temperature

Snow and light snow dominated the precipitation in storm CO412C (figure 46). Pavement temperatures were above -5°C (23°F) throughout the snowfall, but fell to lower values after the precipitation ended. The storm CO501B (figure 47) was a brief light snow event that ended soon after chemical was applied on the test section. Pavement temperatures were close to -0.5°C (31°F).

5.3.4.2 Operations

At the site, conventional CDOT operations on the control section call for applications of sand treated with salt at 8 percent by volume. Operators apply the mix at various rates, which are not always known because of the lack of metering capability. The operations strategy on the test section called for applications of a magnesium chloride-based solution at concentrations from 26 to 30 percent. Conventional applications of the sand and salt mix were to be used when the temperature was too low for liquid chemical applications, although a goal of CDOT for the project was to reduce the amount of the mix used in the canyon.

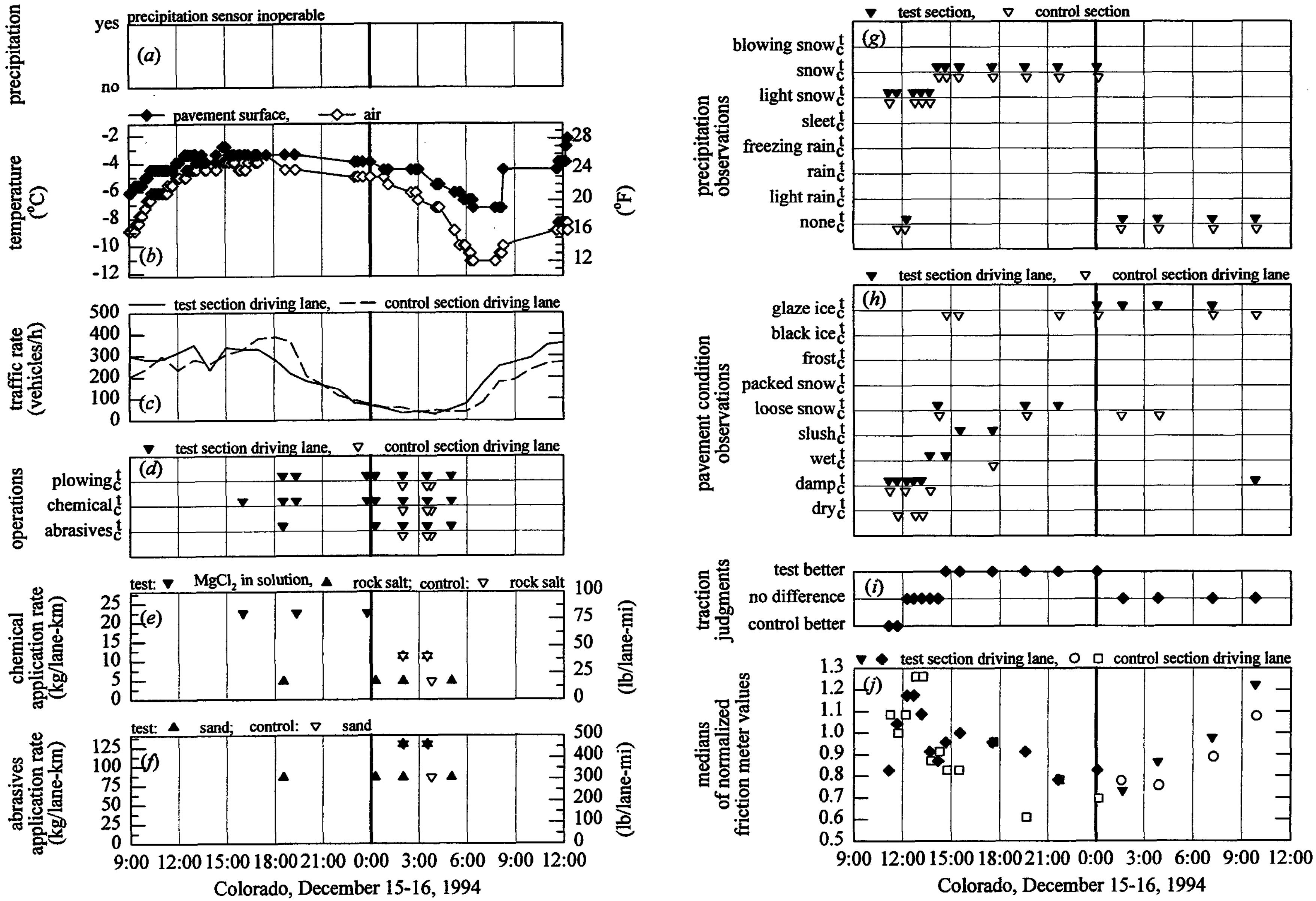


Figure 46. Colorado, storm CO412C, December 15-16, 1994, data histories.

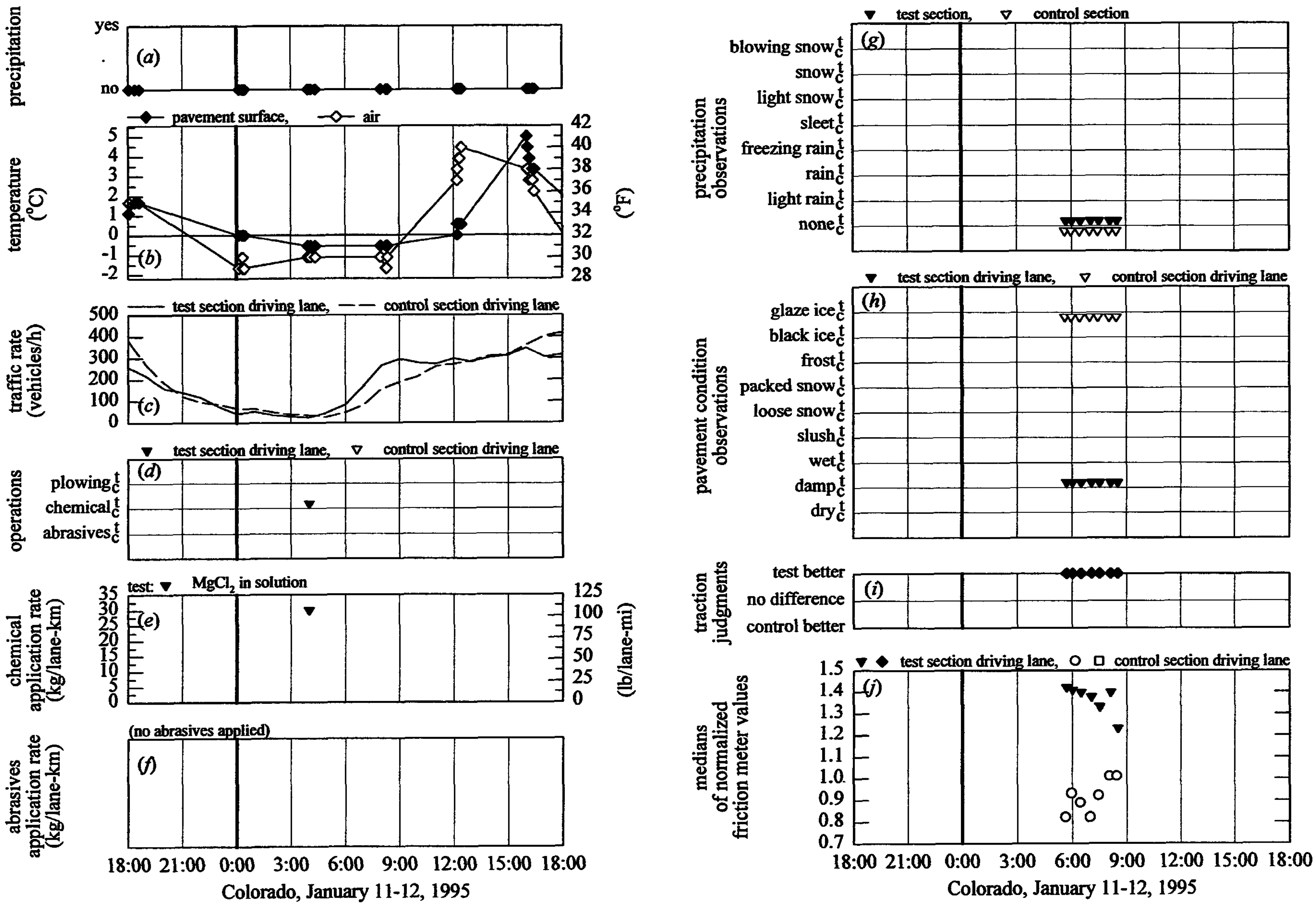


Figure 47. Colorado, storm CO501B, January 11-12, 1995, data histories.

Table 43. Colorado, storms CO412C and CO501B. Summary of documented driving lane operations on test and control sections.

	CO412C December 15-16, 1994 test section	CO412C control section	CO501B January 11-12, 1995 test section	CO501B control section
total number of passes	9	3	1	0
number of passes with plowing	8	3	0	0
number of passes with application of magnesium chloride-based solution	3	0	1	0
total $MgCl_2$ application kg/lane-km	68		30	
(lb/lane-mi)	(241)		(107)	
number of passes with rock salt application	6	3	0	0
total application kg/lane-km	42	27		
(lb/lane-mi)	(148)	(97)		
number of passes with abrasives application	6	3	0	0
total application kg/lane-km	604	346		
(lb/lane-mi)	(2144)	(1226)		

For storm CO412C, as indicated in figure 46, slight applications of the magnesium chloride-based solution were initiated several hours after snowfall, but before conditions deteriorated. The initial control section operation came much later, according to the storm documentation. The test section $MgCl_2$ applications were supplemented by applications of the sand and salt mix during the early part of the storm. However, after three driving lane $MgCl_2$ treatments, the liquid application equipment failed, and the sand and salt mix was the only material used. For storm CO501B, as indicated in figure 47, only a single moderate $MgCl_2$ treatment was made on the test section driving lane. There were no control section operations.

5.3.4.3 Pavement condition, traction judgments, and friction measurements

Because two measurement vehicles were used to test for friction, and because the vehicles did not provide comparable friction values in like conditions, special analysis was required to handle the data.[8] This consisted of analyzing the friction data separately, and combining the data for plotting and further analysis only after both data sets were normalized. The normalization consisted of dividing the data of each vehicle for the whole season by the median of all friction values in that data set when the pavement condition observed was "wet." The results of this normalizing technique indicated that, indeed, the data from the two vehicles could be combined into a single data set for the full-season analysis. It is normalized friction data that is presented (for both vehicles) in figures 46 and 47.

Based on the pavement condition, traction and friction results, both storms illustrate the benefits of a preventive, rather than reactive, practice. For storm CO412C (figure 46) the traction judgments clearly favor the test section during the period of snowfall. Ice was common on the control section during this period, yet not on the test section. During one pass of the measurement vehicle, the friction was far higher on the test section. These results indicate that the operations on the test section during the snowfall, relative to no operations on the control section, were beneficial. Later after the snowfall ended, however, there was ice reported on the test section, although the friction values were steadily increasing on both sections. For the storm CO501B (figure 47), the pavement condition observations, traction judgments, and friction values all indicate a clear benefit of the test section operations—over a 3-h period subsequent to the single $MgCl_2$ application—relative to no operations on the control section. The test section showed higher friction and damp pavement in the short 3-h period, while the control section had low friction and icing.

5.3.5 Data and Results From California

The California site is on Interstate 5 in Siskiyou County, near Mt. Shasta and the town of the same name. Operations were conducted out of the California Department of Transportation (Caltrans) Mt. Shasta maintenance station, which is located within 6 km (4 mi) of the site.

The test and control sections were 3.2-km (2-mi) sections of Interstate 5 from mileposts 9.5 to 11.5. For this length, the highway has two travel lanes in each direction. The highway was resurfaced in 1994 and now has a surface course of gap-graded rubberized asphalt. The northbound lanes were the test section, and the southbound lanes were the control section. Each section covered approximately 6.4 lane-km (4 lane-mi). The sections are on a nearly level stretch of highway at 790-m (2600-ft) elevation.

Measurements and observations of effectiveness were made on the outside driving lanes. Caltrans has traffic data installations at the site and a road weather information system (RWIS) installation approximately 3.2 km (2 mi) north of the site, on Black Butte Summit. Annual average daily traffic (ADT) is approximately 22,000.

Analyses of five representative California storm data sets from the 1994/1995 season, and two sets from the 1993/1994 season, are presented in detail in the site report.[7] The data histories and operations summaries for two of the 1994/1995 storms are presented in figure 48, figure 49, and table 44. Additional results are included in table 45, figure 50, and table 46. Summary points and conclusions regarding the operations and their effectiveness over the course of the 1994/1995 season are presented below.

5.3.5.1 Precipitation and pavement temperature

Light snow and snow dominated the 1994/1995 precipitation observations. All recorded pavement temperatures at the times of the measurements and observations were above -7°C (20°F). Ninety percent of the pavement temperatures at the times of the measurements and observations were above -3.3°C (26°F). Tables 53 and 54 in section 5.5 provide further detail of the precipitation observations and pavement temperatures at the times of the friction measurements.

5.3.5.2 Operations

The operations summary for the 1994/1995 season is shown in table 45. Conventional Caltrans operations call for applications of abrasives and rock salt, and mixtures of both. The abrasives used are volcanic cinders. For snow events, plowing is conducted nearly continuously, approximately every 30 min. As indicated in the note of table 45, however, plowing operations were not fully documented at the site. The chemical operations on the test section were primarily applications of a magnesium chloride-based solution.

The 1994/1995 material application operations on both test and control can be characterized primarily as abrasives operations with minimal chemical operations. The frequency of the abrasives operations was far greater than the frequency of the chemical operations. Slightly more chemical and abrasives were applied on the control section driving lane compared to the test section driving lane.

The test section operations at the site generally began with cinder applications, and were most often followed with $MgCl_2$ solution applications at approximately 20 kg/lane-km (75 lb/lane-mi). The pavement condition at the time of the initial chemical application was in one storm icy, but when

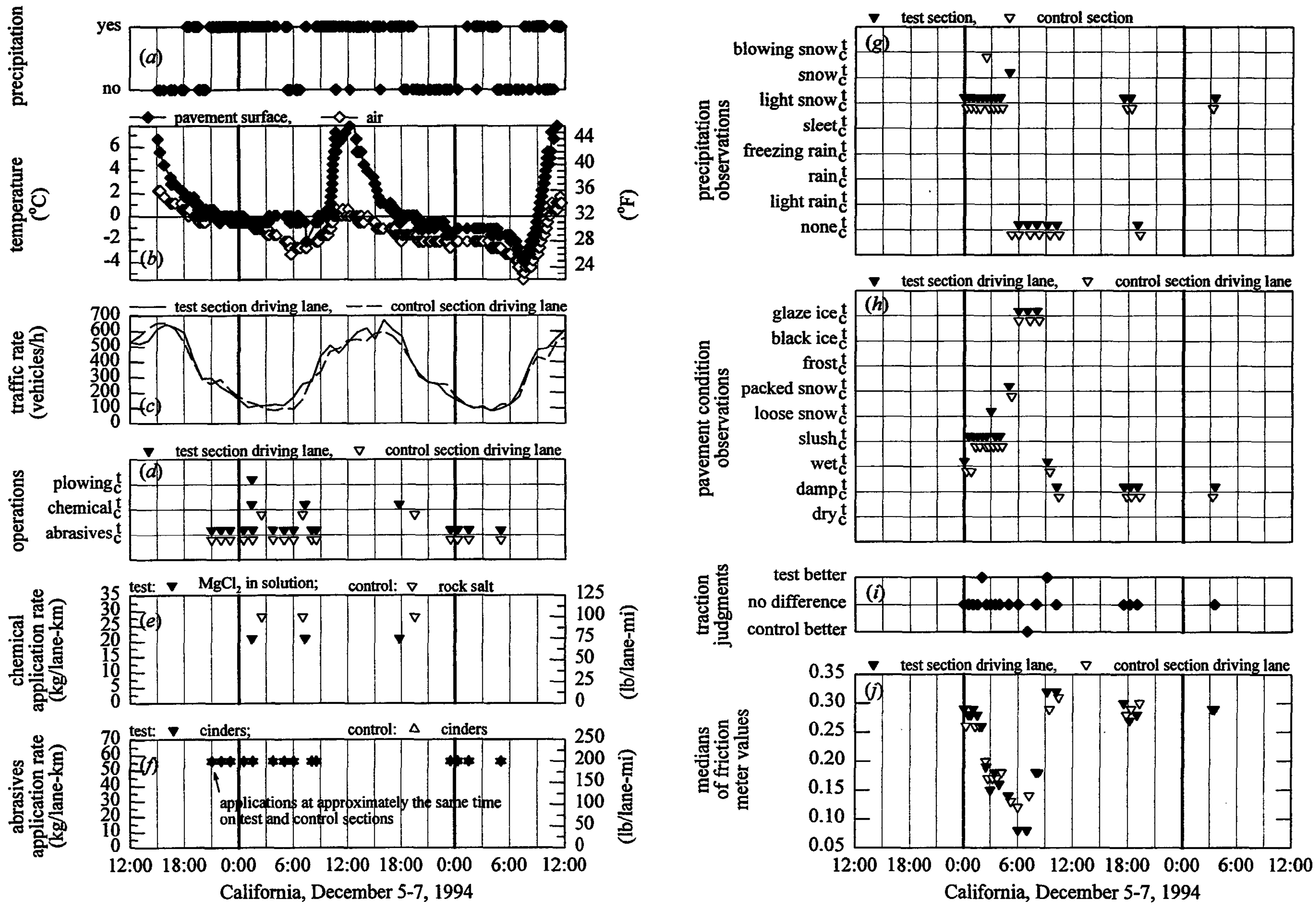


Figure 48. California, storm CA412A, December 5-7, 1994, data histories.

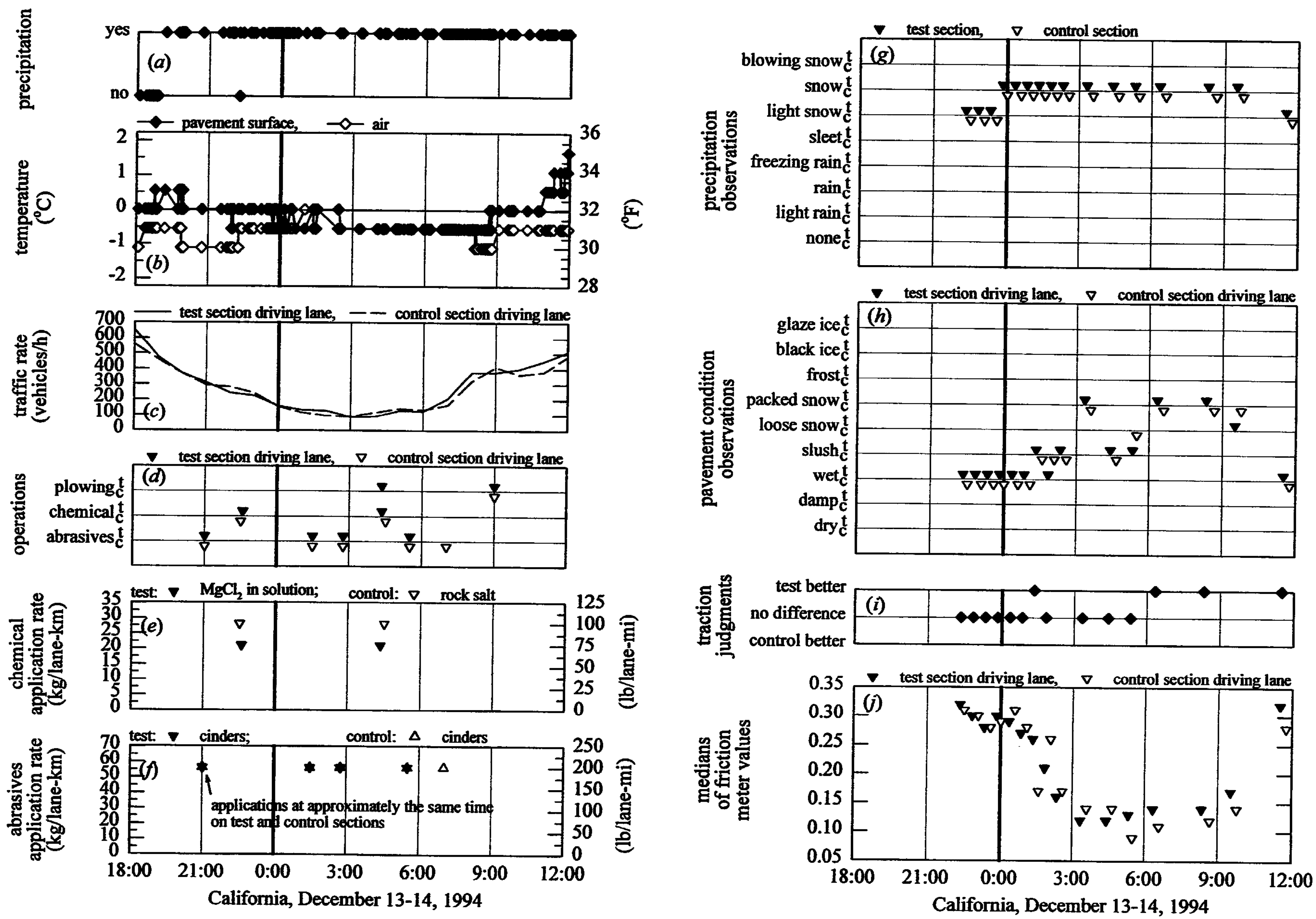


Figure 49. California, storm CA412C, December 13-14, 1994, data histories.

Table 44. California, storms CA412A and CA412C. Summary of documented driving lane operations on test and control sections.

	CA412A December 5-7, 1994		CA412C December 13-14, 1994	
	test section	**control section**	**test section**	**control section**
total number of passes[1]	17	17	7	8
number of passes with plowing[1]	1	0	2	1
number of passes with application of magnesium chloride-based solution	3	0	2	0
total $MgCl_2$ application kg/lane-km	63		42	
(lb/lane-mi)	(225)		(150)	
number of passes with rock salt application	0	3	0	2
total application kg/lane-km		85		56
(lb/lane-mi)		(300)		(200)
number of passes with abrasives application	14	14	4	5
total application kg/lane-km	789	789	225	282
(lb/lane-mi)	(2800)	(2800)	(800)	(1000)

Note: Plowing operations not fully documented.

Table 45. California, winter 1994/1995. Summary of documented operations.

	test section	**control section**
total number of passes[1]	51	53
number of passes with plowing[1]	8	5
number of passes with application of magnesium chloride-based solution	9	0
total $MgCl_2$ application kg/lane-km	191	
(lb/lane-mi)	(679)	
number of passes with rock salt application	2	11
total application kg/lane-km	56	310
(lb/lane-mi)	(200)	(1100)
number of passes with abrasives application	37	39
total application kg/lane-km	2086	2198
(lb/lane-mi)	(7400)	(7800)

Notes:
Data from storms CA412A, CA412B, CA412C, CA501B, and CA503A.
Plowing operations not fully documented.

reported for other storms was wet or slush. In storm CA412A, as shown in figure 48, the initial treatments on test and control were cinder applications at 9 p.m., just as the pavement temperature at nearby Black Butte Summit dropped to freezing. Several cinder applications were made throughout the event. The initial $MgCl_2$ solution application was made on the test section just prior to 1:30 a.m., after a few hours of snowfall, because the RWIS chemical concentration indicators had dropped to low readings. Subsequent $MgCl_2$ applications were made because of re-freeze conditions later in the morning and because of low chemical concentration in the evening. In storm CA412C (figure 49), the initial treatments on test and control were also cinder applications at 9 p.m. The initial $MgCl_2$ solution

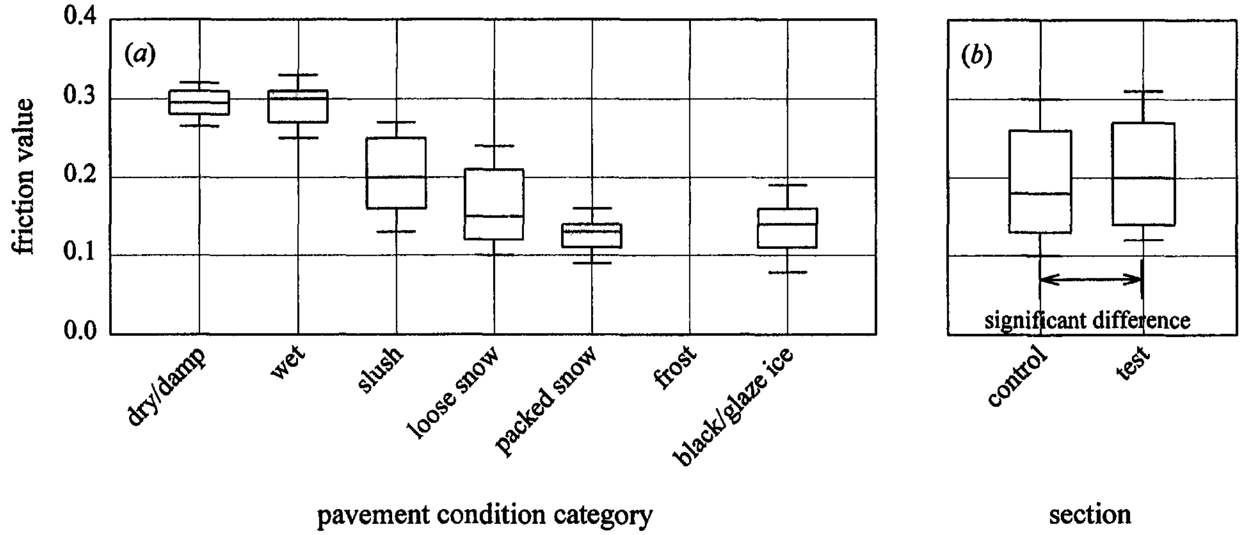


Figure 50. California friction measurement data, winter 1994/1995. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 46. Statistics of California friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1994/1995.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	**N**	**Missing**	**Median**	**25%**	**75%**
dry/damp	70	0	0.295	0.280	0.310
wet	221	0	0.300	0.270	0.310
slush	368	1	0.200	0.160	0.250
loose snow	293	0	0.150	0.120	0.210
packed snow	182	0	0.130	0.110	0.140
black/glaze ice	84	0	0.140	0.110	0.160

Mann-Whitney Rank Sum Test of Friction Values

Group	**N**	**Missing**	**Median**	**25%**	**75%**
control	610	1	0.180	0.130	0.260
test	608	0	0.200	0.140	0.270

The differences in the median values among the two groups are greater than would be expected by chance; there is a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

application was made on the test section soon after, at approximately 10:30 p.m., because of the light snowfall and falling pavement temperatures. A subsequent $MgCl_2$ application were made around 4:30 a.m. because of low friction. In both storms the timing of rock salt applications on the control section was similar, while slightly smaller amounts of chemical and cinders were used on the test section driving lane compared to the control section driving lane (table 44). This is consistent with the season's totals (table 45).

5.3.5.3 Pavement condition, friction measurements, and traction judgments

Pavement condition observation data are listed in tables 56 and 57, which are presented later in section 5.5, and in the table immediately below. On both test and control, slush was the most common pavement condition observation, followed by loose snow, wet, packed snow, black/glaze ice, and dry/damp. There was no significant difference between the test and control, but the control section observations included more packed snow reports than did the test section observations.

1994/1995 California pavement condition observations.

Pavement Condition Category	Percent of all control section observations	Percent of all test section observations
dry/damp	6	6
wet	18	18
slush	30	30
loose snow	22	26
packed snow	17	13
black/glaze ice	7	7

Tukey box plots of the test and control section friction data are shown in figure 50 (b); corresponding data are given in table 46. The comparison shows that the median friction value for the season and the box plot friction distribution were higher for the test section, and the difference between test and control section median friction was significant. The test section had a median friction for the season equal to the median of all friction values when the observed pavement condition was slush (figure 50 (b)). The lower control section value fell between the 25 and 50 percentiles of all friction values when the observed condition was slush.

In storm CA412A (figure 48), the $MgCl_2$ solution application at 1:30 a.m. on December 6 appears to have had no positive effect on friction and pavement conditions during a period of light snowfall. As indicated by the subsequent excessive friction drop and the observations of packed snow and icing around 6 a.m., the $MgCl_2$ solution did not have any lasting effect that carried into the early morning traffic increase. The cinders also appear to have been ineffective in these conditions. On the control section the observed pavement conditions were similar to the test section, but the friction did not drop as low as on the test section. The operator judged the control section to have better traction around 7 a.m. as well. In the period from 7 a.m. to noon, increases in friction and improvements in pavement condition occurred on both sections. These are perhaps attributable to chemical applications, increasing traffic, and, later in the period, increasing pavement temperature.

In storm CA412C (figure 49), the $MgCl_2$ solution and rock salt applications at 10:30 p.m. did not prevent a drop in friction during the subsequent heavier snow period. Nor did the cinder applications. The drop in friction on the test section corresponded primarily to changes in the pavement condition from wet to slush and packed snow conditions. On the control section, the changes were similar, although packed snow was observed earlier than on the test section. Low friction was measured approximately 6 h beyond the initial decrease, and packed snow was observed for much of this period. Also, during much of this period and during the subsequent recovery period, the test section friction was slightly higher than the control section friction. The recovery was slightly earlier on the test section, as indicated by the pavement condition observations showing a breakup of packed snow one pass before the control section breakup. Traction judgments favored the test section as well. These better test section conditions appear to be attributable to the $MgCl_2$ application around 4:30 a.m. and the simultaneous plowing. On both test and control, the final increases in friction and the improvements in pavement conditions at the end of the event occurred following plowing operations, with decreasing snowfall intensity and increasing pavement temperatures. They do not appear attributable primarily to previous chemical applications.

The response from all storms suggests in general that the operational success of the test section was only slightly higher than that of the control section. Some mitigation of the effect of poor pavement conditions was evidenced, although not to the extent that bare pavement was restored. Only in storm CA412C did the breakup of packed snow occur before the control section breakup. In no case did an $MgCl_2$ solution application have a lasting effect and prevent a drop in friction relative to the control section. This is perhaps because of the primary reliance on abrasives rather than chemicals in the operations. Yet in no case did the application of abrasives provide a large friction increase, like that associated with improving conditions to wet pavement. Friction increases due to abrasives applications were not distinctly evident in the data histories.

5.3.5.4 Application rates

The 1994/1995 average chemical application rates on the test section driving lane were approximately 20 kg/lane-km (75 lb/lane-mi) of magnesium chloride and 28 kg/lane-km (100 lb/lane-mi) of rock salt. The control section driving lane average was also 28 kg/lane-km (100 lb/lane-mi) of rock salt. On both sections, the average abrasives application rate was 56 kg/lane-km (200 lb/lane-mi). On both test and control sections in moderate or heavy snow conditions, the results indicate that the chemical application rates were too low to prevent bonded snowpack with the precipitation, temperature, snow moisture, and traffic conditions of the storms.

The frequency and rates of the $MgCl_2$ solution applications on the test section appear to have been geared more for mildly mitigating the effects of bonded snow or ice, rather than for preventing the formation of bonded snow or ice and maintaining bare pavement throughout a storm. The strategy therefore provides an illustrative example of non-urban Interstate snow and ice control for the project, with operations deviating only slightly from conventional operations.

5.3.6 Data and Results From Iowa

Analyses of six Iowa storm data sets from the 1994/1995 season are presented in the site report.[9] The data histories and operations summaries for two of the storms, IA412B and IA503A, are presented in figure 51, figure 52, and table 47. A short description of the Iowa site and these storms is presented here. Information regarding the full-season analysis is not discussed here, but is included in section 5.5.

The Iowa experiments were conducted on a 6.4-km (4-mi) section of Interstate 35 in West Des Moines, between Iowa Highway 5 and the I-35/I 80/I 235 interchange. Operations were conducted out of the Iowa Department of Transportation (IDOT) maintenance station in Clive, which is located within 3 km (2 mi) of the site.

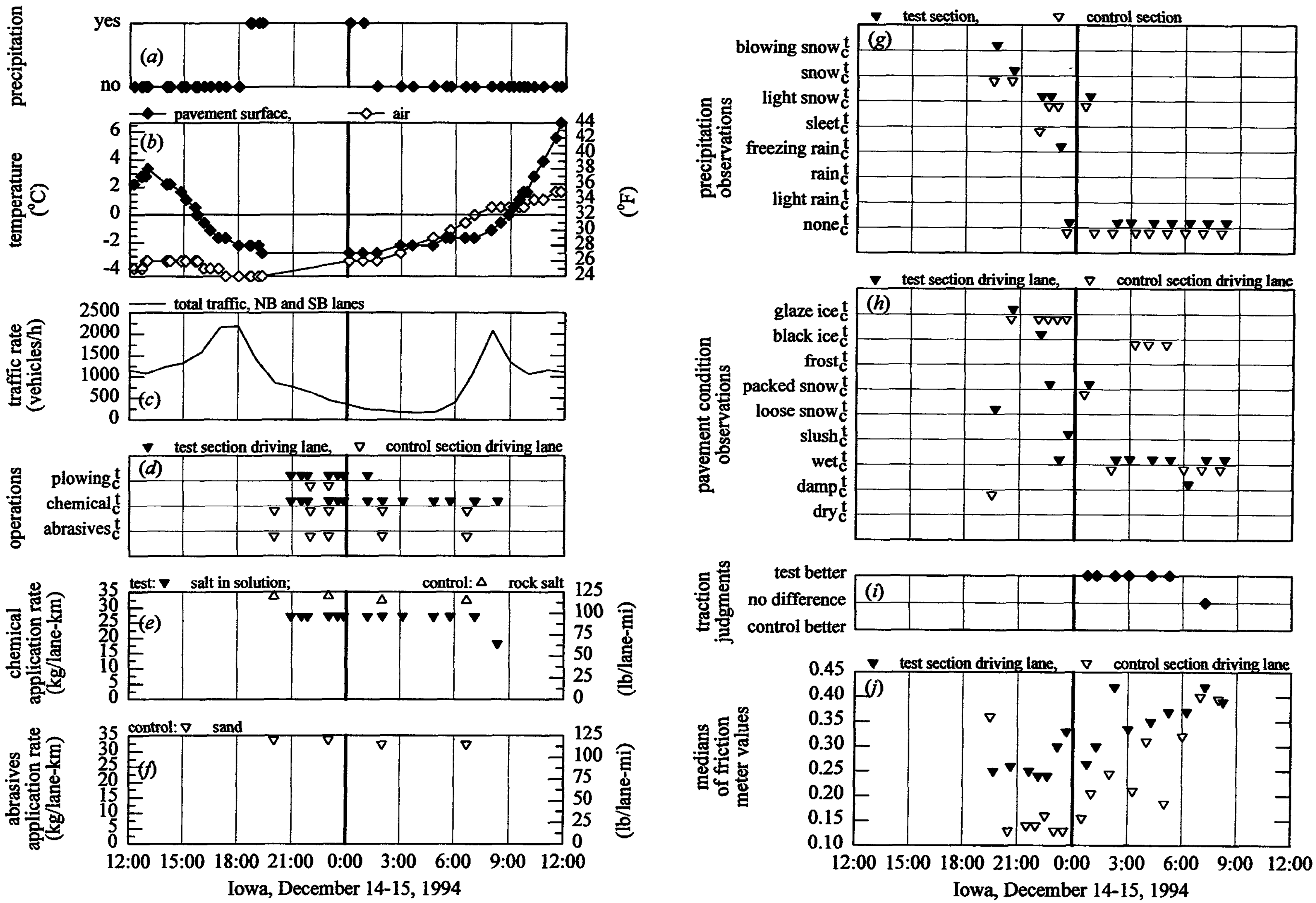


Figure 51. Iowa, storm IA412B, December 14-15, 1994, data histories.

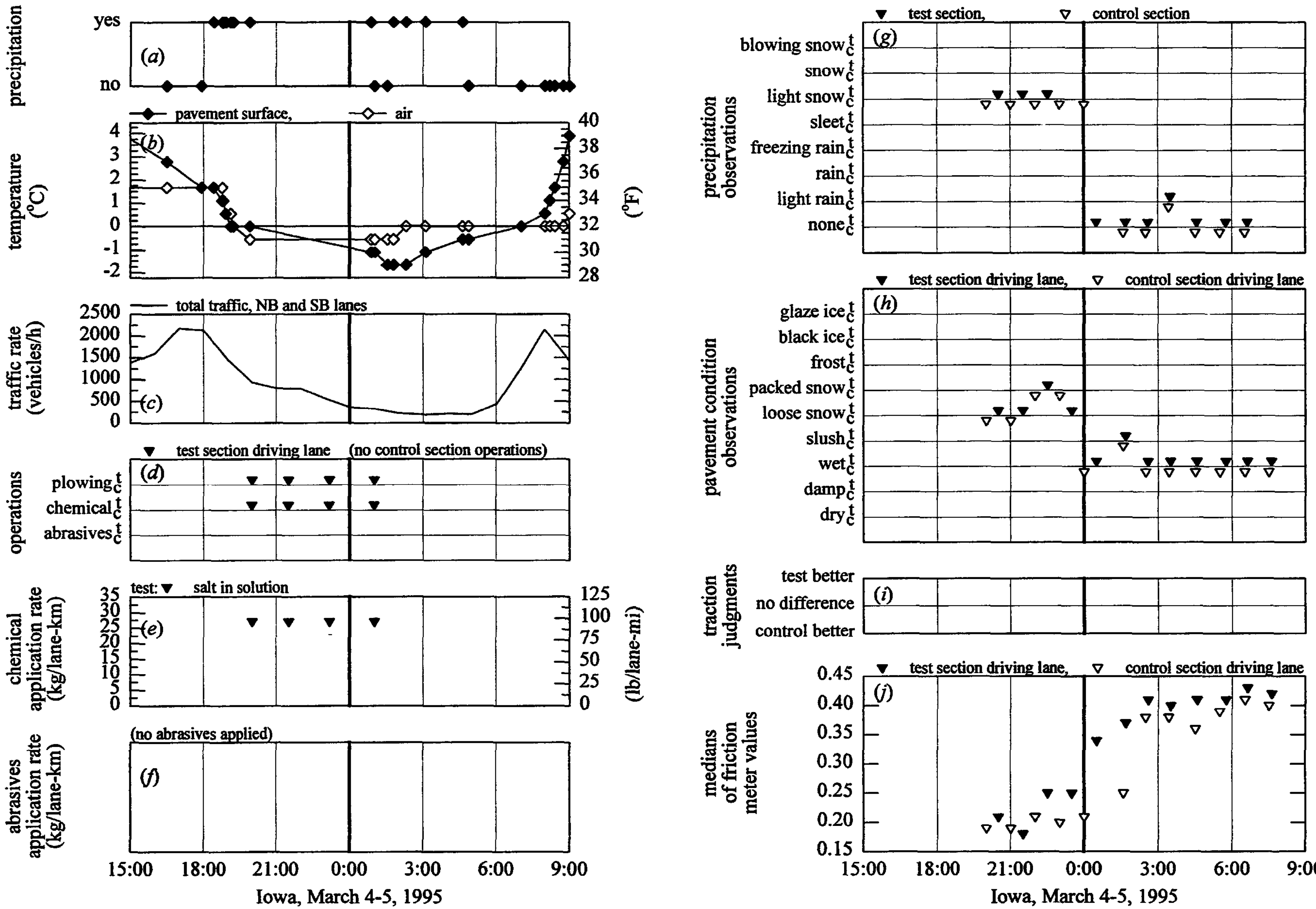


Figure 52. Iowa, storm IA503A, March 4-5, 1995, data histories.

Table 47. Iowa, storms IA412B and IA503A. Summary of documented driving lane operations on test and control sections.

	IA412B December 14-15, 1994		IA503A March 4-5, 1995	
	test section	**control section**	**test section**	**control section**
total number of passes	13	5	4	0
number of passes with plowing	7	2	4	0
number of passes with NaCl salt brine application	13	0	4	0
total NaCl application kg/lane-km	345		109	
(lb/lane-mi)	(1225)		(387)	
number of passes with rock salt application	0	5	0	0
total application kg/lane-km		166		
(lb/lane-mi)		(590)		
number of passes with abrasives application	0	5	0	0
total application kg/lane-km		166		
(lb/lane-mi)		(590)		

The test section was the two northbound lanes from milepost 68.13 to milepost 72.2. The control section was the parallel southbound lanes. The test and control sections each covered approximately 13 lane-km (8 lane-mi). The pavement surface course is asphalt concrete. IDOT has a RWIS installation at the intersection of IA 5 and I-35, and a traffic data installation on I-35 at milepost 70. Annual average daily traffic is approximately 22,000. The RWIS was in use by IDOT prior to the project.

5.3.6.1 Precipitation and pavement temperature

Snow and light snow dominated the precipitation in storm IA412B (figure 51). Pavement temperatures were close to -3°C (27°F) throughout the snowfall, increasing only slightly until after daylight on December 15. The storm IA503A (figure 52) was a light snow event. Pavement temperatures were between freezing and -1°C (30°F).

5.3.6.2 Operations

Conventional IDOT operations at the site are applications of sand and salt in a 1:1 mix. This was the case for the control section in storm IA412B. In storm IA503A, no control section operations were reported.

The operations strategy on the test section called for applications of a sodium chloride solution (salt brine). In storms IA412B and IA503A, the salt brine was nearly always placed at 28 kg/lane-km (100 lb/lane-mi). In storm IA412B, over twice as much chemical was placed on the test section driving lane compared to the control section (table 47), although no abrasives were applied.

In all of the storms at the site presented in the site report, the test section operations generally began with salt brine applications, most often after snowfall had begun. Pretreatments ahead of precipitation were not reported. The pavement condition at the time of the initial liquid application was not always reported, but varied from icy to loose snow conditions. When the conditions required, simultaneous plowing was done. In storm IA412B, the initial driving lane application was after 2-3 h of snow or blowing snow onto an icy surface, although the initial passing lane application was made 1½ h earlier. In storm IA503A, the initial application was made after the beginning of light snow and after the pavement temperature had dropped to freezing.

5.3.6.3 Pavement condition, traction judgments, and friction measurements

In storm IA412B, the test section driving lane remained icy or snowpacked with fairly low friction following the initial salt brine application, although the friction preceding and following the application was considerably higher than on the control section. As a whole, the early brine applications on the test section driving lane (six in total prior to midnight) had the combined effect of returning pavement to acceptable conditions and higher friction much sooner than the control operations. The later brine applications after midnight and into the following day apparently prevented refreezing like that which occurred on the control section and provided better traction. Overall in this storm there was higher friction throughout on the test section, indicating that the greater chemical use on the test section and the overall operations approach was clearly more effective. The control section operations with the abrasives in the salt-sand mix did not provide friction or traction as good as did the test section operations.

In storm IA503A, in which there were no reported control section operations, loose snow and low friction were reported on the test section after the initial brine application. While packed snow was reported later on both sections, it was observed for a longer period on the control section. The test section recovered sooner than the control section, but both sections recovered after snowfall ended and by morning rush traffic. There was higher friction throughout the storm on the test section, indicating again that the test section operations were effective in providing better road conditions, although in this case relative to no operations.

5.4 DATA AND RESULTS FROM SALT/ABRASIVES MIX APPLICATION SITES

Data and results from the experimental sites in Missouri and Maryland are presented here. At the Missouri site a mixture of conventional sodium chloride rock salt and cinders was used on both the test and control sections. Calcium chloride in solution was used as a prewetting liquid during all test section applications and some of the control section applications. At the Maryland site, both the test and control section operations included rock salt/abrasives mix applications and straight abrasives applications. Previous results of salt/abrasives mix operations that were shown in the Ohio I-71 and Nevada control section presentations above are briefly discussed here as well.

Table 48 lists the storm data sets discussed in this section and presented either in this or a previous section. More extensive analyses and interpretations of the data sets are presented in the corresponding site reports listed in the references.

Table 48. Storm data sets showing operations using salt/abrasives mix applications.

Site	Storm Dates	Storm ID
Missouri	December 31, 1994 - January 1, 1995	MO412A
Missouri	January 5-6, 1995	MO501A
Maryland	December 20-22, 1993	MD1293D
Maryland	December 24-27, 1993	MD1293F
Ohio I-71	January 6-7, 1995	O1501A
Ohio I-71	February 3-4, 1995	O1502B
Nevada	December 13-14, 1994	NV412C
Nevada	January 6-7, 1995	NV501B
Nevada	February 13-14, 1995	NV502A
Nevada	March 22-23, 1995	NV503B

5.4.1 Data and Results From Missouri

The Missouri experiments were conducted in Cass County on an 8-km (5-mi) length of U.S. 71, a divided highway with two travel lanes in each direction. The test section was the northbound lanes and the control section was the southbound lanes. Measurements and observations of effectiveness were made on the outside driving lanes. The pavement surface is an overlay of asphalt concrete. The site is the location of experiments conducted for the previous SHRP project H-208.(2) MODOT has road weather information system and traffic data installations at the site. Wintertime average daily traffic is approximately 6,000.

Analyses of two Missouri storms from the 1994/1995 season, MO412A and MO501A, are presented in detail in the site report.(12) Their data histories and operations summaries are presented in figure 53, figure 54, and table 49. Summary points and conclusions regarding the operations and their effectiveness are presented below.

5.4.1.1 Precipitation and pavement temperature

Snow and light snow dominated the precipitation in the two storms. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the -3.3°C to 0°C (26°F to 32°F) category.

5.4.1.2 Operations

The test section operations included rock salt/abrasives mix applications that were prewetted with a 32 percent calcium chloride solution, at a nominal rate of 21 L/t (5 gal/ton) of mix. The abrasives were cinders and the mix with rock salt was at a 1:1 ratio by weight. The mix was applied at 56 kg/lane-km (200 lb/lane-mi). As at the Ohio I-70 site, the control operations were conducted using the same vehicle as, and sequentially to, the test operations. The mix was applied at 112 kg/lane-km (400 lb/lane-mi) on the control section. During storm MO412A, the control section mix was not prewet with the calcium chloride solution, but during storm MO501A it was.

During both storms the initial salt/abrasives application was placed when the pavement was wet and very soon after the beginning of light snow that quickly turned to snow. At the beginning of storm MO412A (figure 53) the pavement temperature was just above freezing. It would not reach 0°C (32°F) until over an hour after the beginning of snowfall, but was slowly dropping toward below-freezing values. At the beginning of storm MO501A (figure 54), the pavement temperature was at 0°C (32°F) and also dropping toward below-freezing values. Subsequent applications were made regularly in both storms, but after packed snow developed during storm MO501A, back-to-back operations were conducted with plowing in an attempt to break the pack.

5.4.1.3 Pavement condition and friction

During storm MO412A, wet was the most common pavement condition on both sections, reflecting successful anti-icing operations and the slightly warmer pavement when compared to storm MO501A. In storm MO501A, packed snow was the most common pavement condition on both sections. Packed snow was observed more often on the control section, however.

In neither storm was there a significant difference between test and control section friction. Considering that double the amount of material was applied on the control section, the test section operations would be preferable because of the apparent lack of a benefit of higher application rates. However, in storm MO501A, neither operation was able to prevent reductions in friction with increases in snowfall intensity that preceded pack development. In addition, there appeared to be slightly higher yet short-lived increases in control section friction following some of the mix applications.

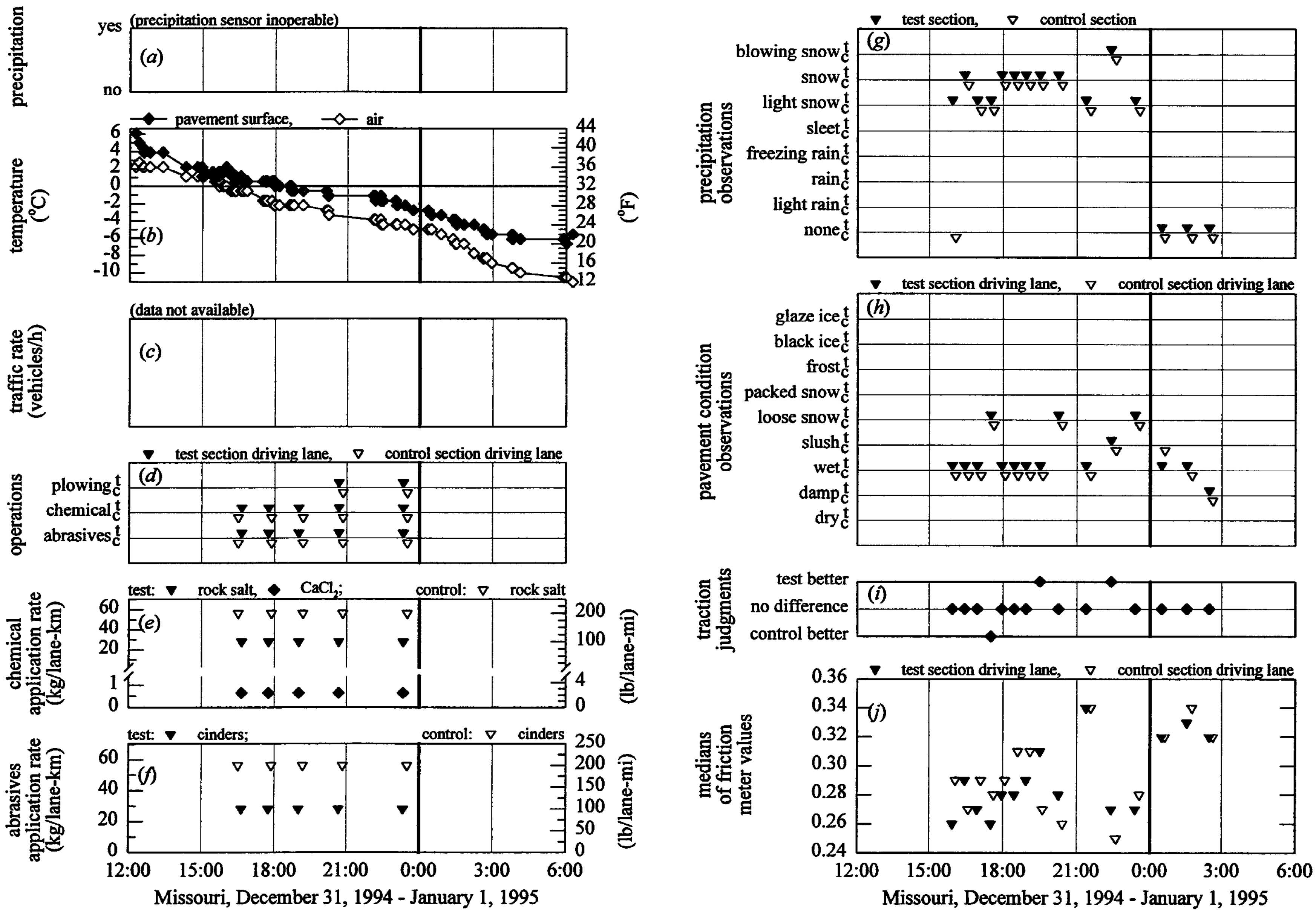


Figure 53. Missouri, storm MO412A, December 31, 1994 - January 1, 1995, data histories.

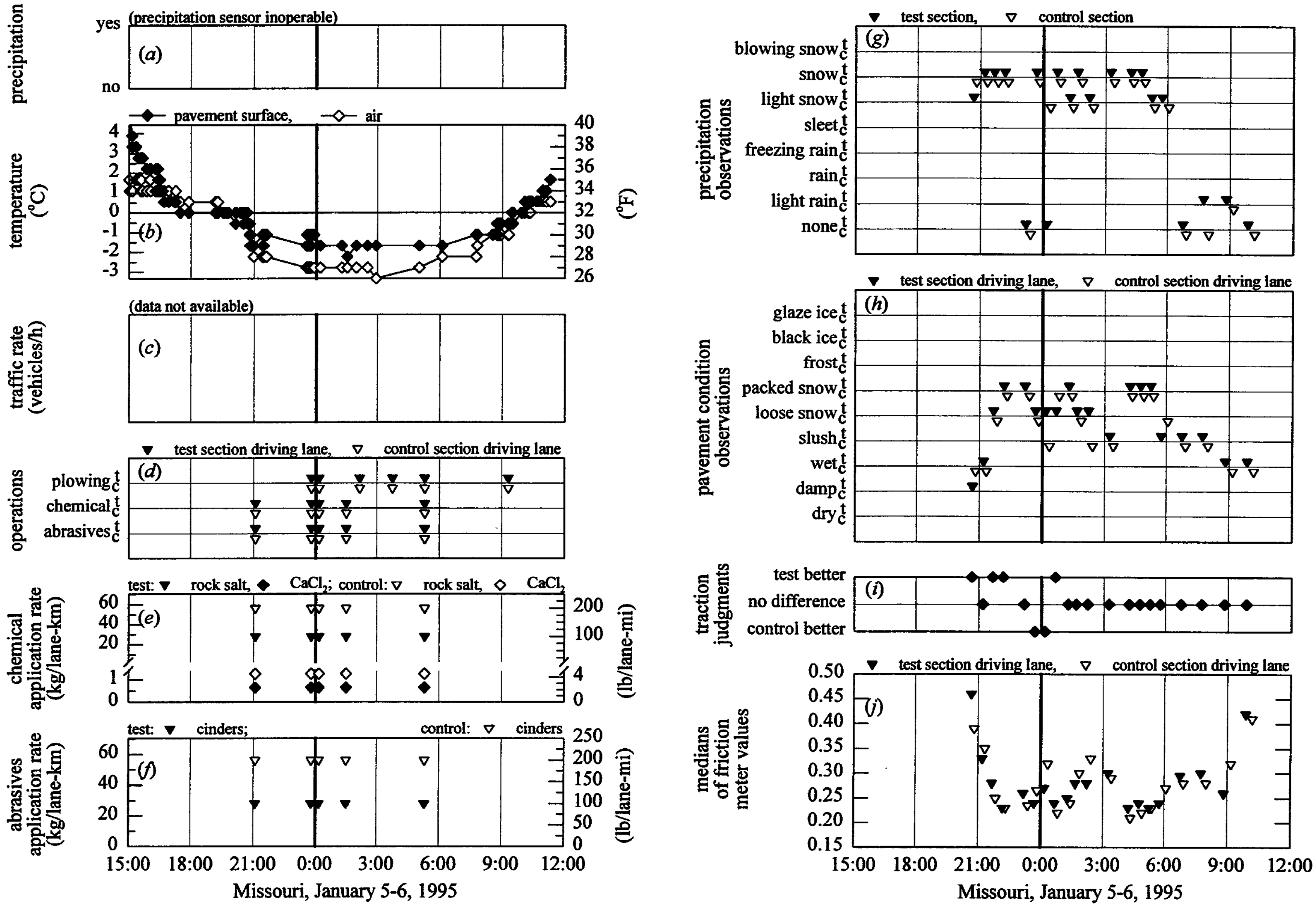


Figure 54. Missouri, storm MO501A, January 5-6, 1995, data histories.

Table 49. Missouri, storms MO412A and MO501A. Summary of documented driving lane operations on test and control sections.

	MO412A December 31, 1994 - January 1, 1995		MO501A January 5-6, 1995	
	test section	**control section**	**test section**	**control section**
total number of passes	5	5	8	8
number of passes with plowing	2	2	6	6
number of passes with rock salt application	5	5	5	5
total application kg/lane-km	141	282	141	282
(lb/lane-mi)	(500)	(1000)	(500)	(1000)
number of passes with $CaCl_2$ prewetting solution	5	0	5	5
total $CaCl_2$ application kg/lane-km	3		3	6
(lb/lane-mi)	(12)		(12)	(23)
number of passes with abrasives application	5	5	5	5
total application kg/lane-km	141	282	141	282
(lb/lane-mi)	(500)	(1000)	(500)	(1000)

5.4.2 Data and Results From Maryland

The Maryland experiments were conducted in Garrett County on a 16-km (10-mi) length of U.S. 219. At the site, U.S. 219 is an undivided highway with one travel lane in each direction. The test section was the northbound and southbound lanes of the northernmost 8 km (5 mi), and the control section was the lanes of the southernmost 8 km (5 mi). Measurements and observations of effectiveness were made in both directions. The pavement surface is asphalt concrete.

MDDOT has traffic data installations at the site. Wintertime average daily traffic is approximately 3,000. There were no road weather information systems at the site, which is the location of experiments conducted for the previous SHRP project H-208.[2]

Analyses of seven Maryland storm data sets from the 1993/1994 season are presented in the site report.[11] The data histories and operations summaries for two of these storms are presented in figure 55, figure 56, and table 50. Additional results are included in table 51, figure 57, and table 52. Summary points and conclusions regarding the operations and their effectiveness are presented below.

5.4.2.1 Precipitation and pavement temperature

Snow (including blowing snow) dominated the precipitation at the site. Pavement temperatures at the times of the friction measurements and pavement condition observations were mostly in the categories -6.7°C to -3.3°C (20°F to 26°F) and -3.3°C to 0°C (26°F to 32°F), but 32 percent of the readings were made when the temperatures were -6.7°C (20°F) and lower.

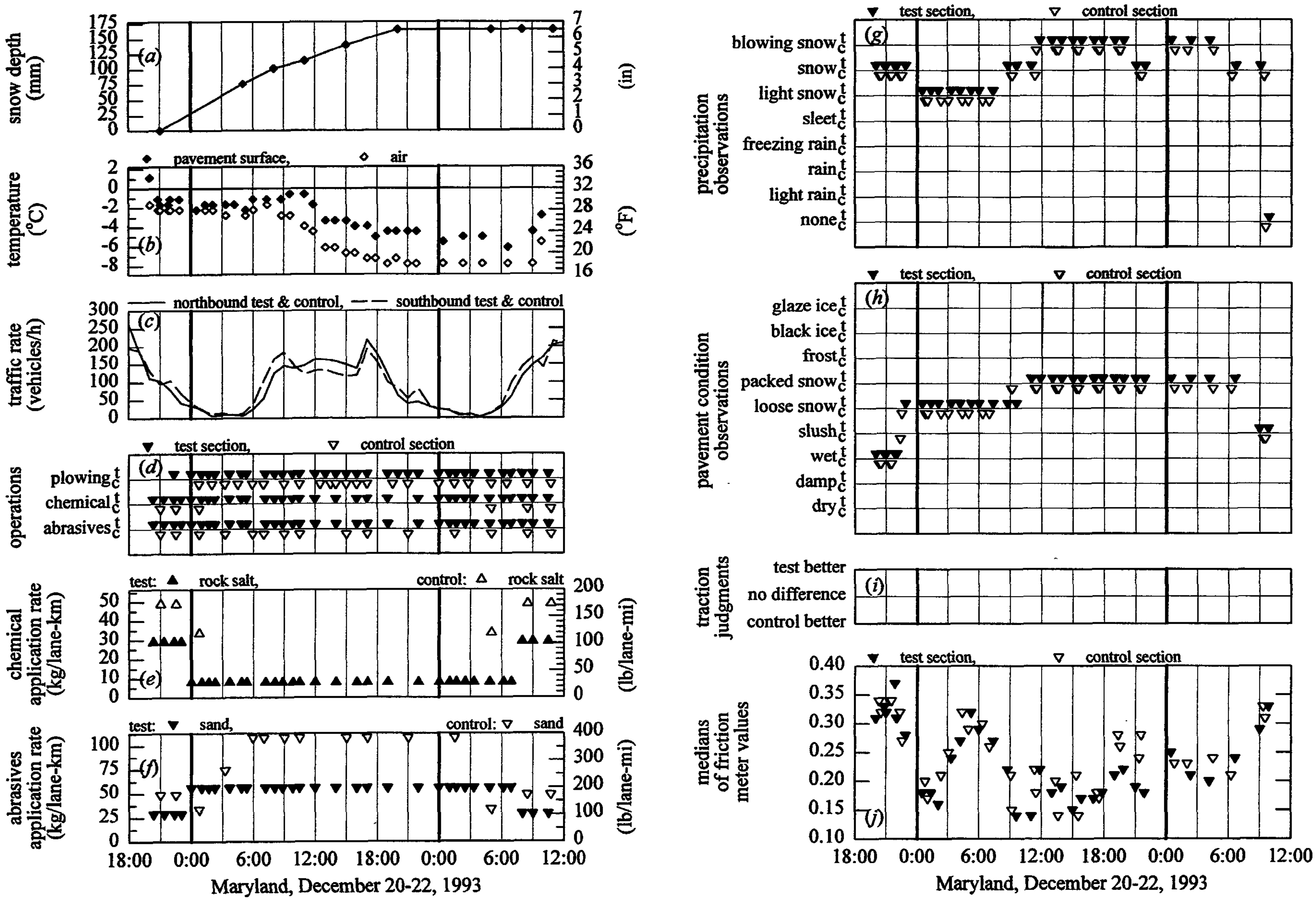


Figure 55. Maryland, storm MD1293D, December 20-22, 1993, data histories.

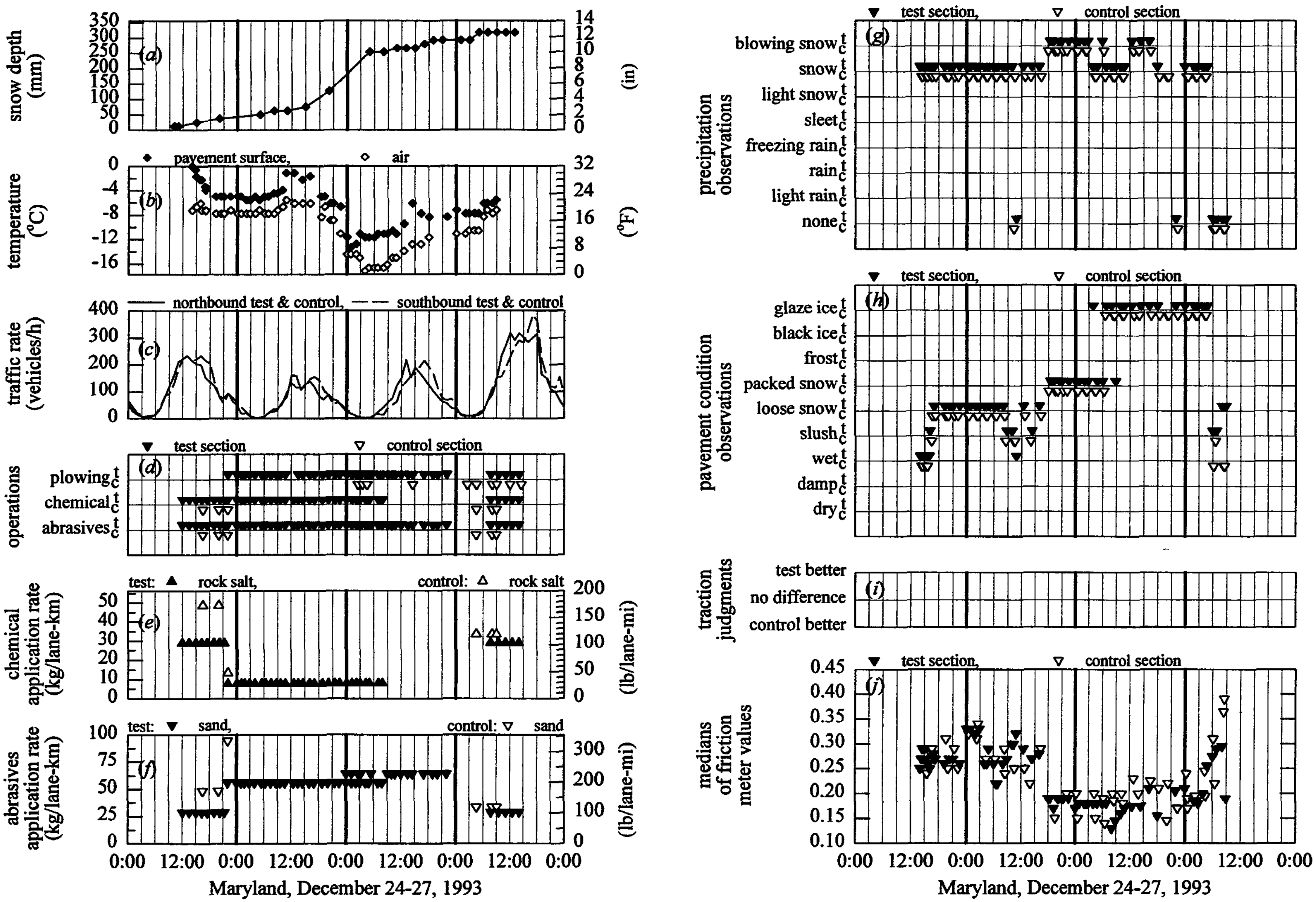


Figure 56. Maryland, storm MD1293F, December 24-27, 1993, data histories.

Table 50. Maryland, storms MD1293D and MD1293F. Summary of documented operations on test and control sections.

	MD1293D December 20-22, 1993 test	MD1293D December 20-22, 1993 control	MD1293F December 24-27, 1993 test	MD1293F December 24-27, 1993 control
total number of passes	37	25	57	13
number of passes with plowing	34	23	48	10
number of passes with rock salt application	33	6	42	6
total application kg/lane-km	408	262	606	212
(lb/lane-mi)	(1449)	(930)	(2151)	(751)
number of passes with abrasives application	33	15	57	6
total application kg/lane-km	1662	1202	2968	293
(lb/lane-mi)	(5895)	(4266)	(10530)	(1039)

Table 51. Maryland, winter 1993/1994. Summary of documented operations.

	test section	control section
total number of passes	214	98
number of passes with plowing	193	84
number of passes with rock salt application	162	29
total application kg/lane-km	3504	1087
(lb/lane-mi)	(12432)	(3857)
number of passes with abrasives application	209	64
total application kg/lane-km	9223	4997
(lb/lane-mi)	(32724)	(17729)

Note: Data from storms MD1293B, MD1293C, MD1293D, MD1293F, MD1293G, MD0194A, and MD0194D.

5.4.2.2 Operations

The test and control section operations included rock salt/abrasives mix applications and straight abrasives applications. The abrasives were sand and the mix with rock salt was at various ratios. The operations summary for the seven storms of the 1993/1994 season is shown in table 51. As indicated, the test section operations were far more intensive than the control section operations, much more salt and sand was used on the test section, and far more test section plowing passes were made. These figures are reflective of MDDOT's experimental goal of achieving a bare pavement level of effectiveness with the salt/sand mixes, and their attempt within this project to do so irrespective of the excessive frequency of the operations beyond the frequency of their conventional operations. This experimental approach is in contrast to the operations in New Hampshire, another site in this project with a relatively low ADT, where operational frequencies on the test section were more typical of their conventional operations.

The test section applications were usually placed near the time of the beginning of precipitation. Subsequent applications were made regularly and frequently. As there was no road weather information system at the site, chemical concentration information was not available for operational decisions. The availability of the chemical concentration indicators for the test section operations likely could have enhanced decision making regarding reapplications of the rock salt/abrasives mixes.

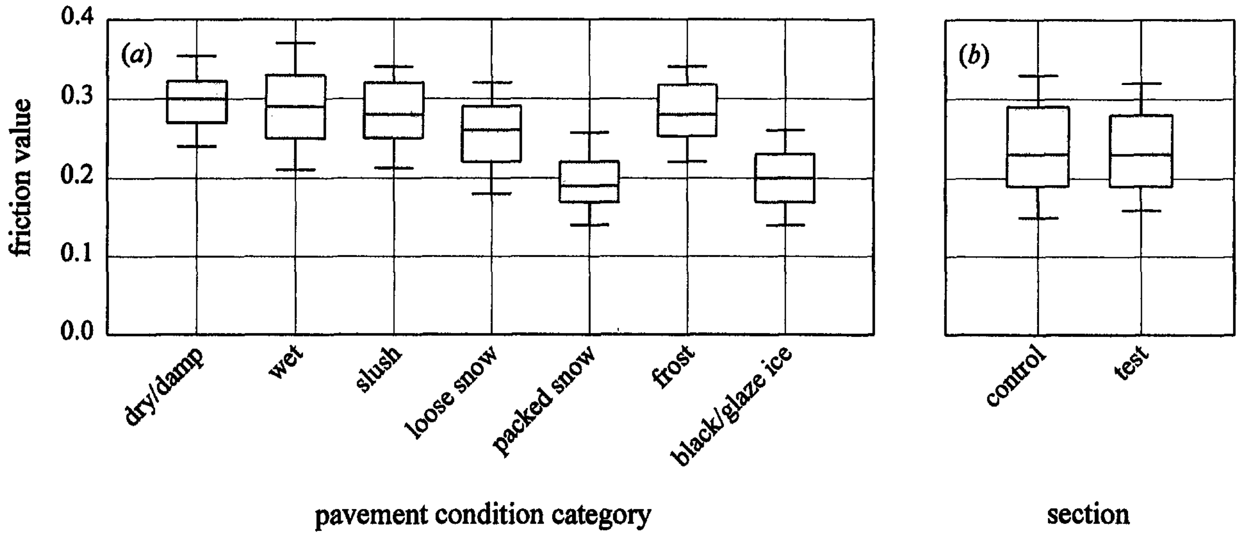


Figure 57. Maryland friction measurement data, winter 1993/1994. Tukey box plots of friction data statistics as a function of (a) pavement condition category, and (b) section.

Table 52. Statistics of Maryland friction measurement data as a function of pavement condition category, and results of Mann-Whitney rank sum test of friction as a function of section, winter 1993/1994.

Statistics of Friction Values as a Function of Pavement Condition Category

Group	N	Missing	Median	25%	75%
dry/damp	61	0	0.300	0.270	0.323
wet	469	0	0.290	0.250	0.330
slush	297	0	0.280	0.250	0.320
loose snow	609	0	0.260	0.220	0.290
packed snow	858	0	0.190	0.170	0.220
frost	35	0	0.280	0.253	0.318
black/glaze ice	566	0	0.200	0.170	0.230

Mann-Whitney Rank Sum Test of Friction Values

Group	N	Missing	Median	25%	75%
test	1440	0	0.230	0.190	0.280
control	1455	0	0.230	0.190	0.290

The differences in the median values among the two groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

Notes: N is the total number of observations or measurements in a group. The "Missing" column gives the number of times observations were made without a friction measurement. The remaining columns give the 50th, 25th, and 75th percentiles of the friction measurements in the group.

5.4.2.3 Pavement condition

Pavement condition observation data are listed in tables 56 and 57, which are presented later in section 5.5, and for the 1994/1995 season in the table immediately below. Packed snow was the most common test section pavement condition observation, followed by black/glaze ice, loose snow, wet, slush, and dry/damp. Packed snow was also the most common control section observation, followed by black/glaze ice, loose snow, wet, slush, frost, and dry/damp. The difference between the test and control observations is significant and slightly favors the test section.[11] The difference appears to result primarily from more wet and less slush observations on the test section relative to the control section.

1993/1994 Maryland pavement condition observations

Pavement Condition Category	**Percent of all control section observations**	**Percent of all test section observations**
dry/damp	2	2
wet	14	18
slush	12	8
loose snow	21	21
packed snow	29	30
frost	2	0
black/glaze ice	19	20

5.4.2.4 Friction

Tukey box plots of the 1993/1994 test and control section friction data are shown in figure 57 (b); corresponding data are given in table 52. The test section and control section friction had identical medians, and the distributions were similar. The difference is not significant. As indicated by figure 57, both the test and control median values were low, falling between the median friction values for the pavement condition categories loose snow and packed snow.

5.4.2.5 Application rates

Relative to the conventional operations, the much higher chemical and material use on the test section did not lead to corresponding improvements in friction or conditions during the seven storms: it led to slightly worse conditions and nearly the same overall friction. Nor did it lead to a faster improvement in pavement conditions toward and at the end of storms. The clear indication is that for lower ADT sites, like the Maryland site, with conditions like those experienced in the Maryland storms, applications of excessive amounts of a salt/abrasives mix does not result in either higher levels of effectiveness or faster improvement in pavement conditions.

The data sets of storms MD1293D and MD1293F support the above statements. The histories of storm MD1293D show early operations during snow using a 1:1 ratio salt/abrasives mix on both test and control. The control applications were at a higher rate, but fewer passes were made. The friction drop was similar in both cases. Later friction and pavement condition variations appear to be in response to changes in precipitation from snow to light snow to snow and blowing snow, and in response to reductions in pavement temperature. The variations do not appear to be in response to heavy applications of abrasives on either the test or control section. Snowpack developed following a period of increasing snowfall intensity, fairly high traffic rates, and pavement temperatures slightly below freezing. Regular abrasives applications and plowing on both sections did not prevent the development of pack.

Early operations during storm MD1293F were again performed in snow. The 1:1 ratio salt/abrasives mix was used on both test and control. Again the control applications were at a higher rate, but in this storm far fewer passes were made. The friction was already low at the beginning of measurements, but the change in pavement condition was similar in both cases. Also as in the previous storm, later friction and pavement condition variations appear to be in response to changes in precipitation from snow to none to snow and blowing snow, and in response to fluctuations in pavement temperature. The variations do not appear to be in response to heavy applications of abrasives on the test section. Snowpack developed during a period of decreasing pavement temperatures and blowing snow. Regular abrasives applications and plowing on the test section did not prevent the development of pack. The operational effort on the test section was much higher than on the control section, but without any apparent benefit.

5.4.3 Data and Results From Ohio I-71 and Nevada

As described previously in sections 5.2.3 and 5.3.1, control section operations in Ohio at the I-71 site and in Nevada included applications of salt/abrasives mixes. The timing of the initial control operations at the sites was not very different from the initial test operations, and subsequent operations were performed regularly at intervals similar to those on the test section. (Kansas control operations included salt/abrasives mixes as well, but there are no examples with operational timing similar to the test operations.) However, the much higher chemical and material use at the Ohio I-71 site did not lead to corresponding improvements in friction or conditions. Further, during the 1994/1995 season, the use of nearly twice as much chemical overall and 13 times as much salt/abrasives mix on the Nevada control section, compared to the test section, resulted not in better conditions or higher friction, but in significantly different conditions and significantly different friction that clearly favor the test section. The overall indication is that it takes far greater amounts of chemical in a mix with abrasives, than chemical alone, to adequately maintain a road during storms like those of the Ohio I-71 and Nevada 1994/1995 seasons.

5.5 SUMMARIZING DATA AND RESULTS

Summary tables and figures are presented here. The tables and figures provide a broad overview of the results, and include data from 17 full-season data sets. Individual storms from these sets have been presented and discussed above in the preceding sections of this chapter.

Table 53 lists results of precipitation observation data. The table shows the number and percentage of observations in each precipitation observation category, for combined test and control section data of each of the 17 data sets. As in the following two tables (tables 54 and 55), part (a) of table 53 indicates the numbers of observations by category, and part (b) indicates corresponding percentages. The bottom rows show totals that further combine the data of the 17 sets. As indicated, over 35,000 observations were made during the included storms. Overall the data indicate the predominance of "snow" and "light snow" observations, which make up 36 and 34 percent of the total, respectively. The category "none" made up 22 percent of the observations, but no other category had as high as 5 percent of the total. These results indicate that the evaluation was essentially a study of operations for snowstorms.

Similarly, table 54 lists results of pavement temperature data. The pavement temperatures were recorded at the times of the measurements and observations, usually by RWIS sensors. In part (b) of this table, the data of the last rows indicate the predominance of pavement temperatures above -6.7°C (20°F), which make up nearly 80 percent of the data. The category -3.3°C to 0°C (26°F to 32°F) was the dominant single category with 45 percent.

Table 53. Results of precipitation observations from 17 data sets, showing (a) number, and (b) percentage of observations in a category, for combined test and control section data.

site & season	(*a*) NUMBER OF PRECIPITATION OBSERVATIONS							
	none	rain	freezing rain	sleet	light snow	snow	not made	total
CA 94/95	182	14	0	14	658	350	0	1218
CO 94/95	1104	7	0	0	1102	884	0	3097
IA 94/95	429	35	102	20	102	114	43	845
KS 94/95	504	82	259	38	366	129	0	1378
MO 94/95	108	21	0	0	143	232	0	504
NH 94/95	124	37	195	93	406	337	0	1192
NV 94/95	1144	72	2	25	721	598	14	2576
NY 94/95, AC	1204	0	5	0	2093	2131	0	5433
NY 94/95, PCC	556	0	0	0	1042	1117	0	2715
O0 94/95	455	230	119	32	902	505	0	2243
O1 94/95	35	184	34	11	216	238	0	718
WI 94/95	56	98	14	0	267	196	0	631
MD 93/94	393	7	56	0	210	2229	0	2895
NH 93/94	138	60	28	59	650	542	116	1593
NV 93/94	206	15	0	6	57	59	0	343
NY 93/94, AC	1185	394	172	154	2933	2872	0	7710
WI 93/94	112	0	0	28	168	322	0	630
total	7935	1256	986	480	12036	12855	173	35721

site & season	(*b*) PERCENTAGE OF ALL PRECIPITATION OBSERVATIONS MADE DURING SEASON						
	none	rain	freezing rain	sleet	light snow	snow	not made
CA 94/95	15.0	1.2	0.0	1.2	54.0	28.8	0.0
CO 94/95	35.6	0.2	0.0	0.0	35.5	28.5	0.0
IA 94/95	50.8	4.2	12.1	2.4	12.1	13.5	5.1
KS 94/95	36.6	5.9	18.8	2.7	26.5	9.4	0.0
MO 94/95	21.4	4.2	0.0	0.0	28.4	46.0	0.0
NH 94/95	10.4	3.1	16.4	7.8	34.1	28.3	0.0
NV 94/95	44.4	2.8	0.1	1.0	28.0	23.2	0.5
NY 94/95, AC	22.2	0.0	0.1	0.0	38.5	39.2	0.0
NY 94/95, PCC	20.5	0.0	0.0	0.0	38.4	41.2	0.0
O0 94/95	20.3	10.3	5.3	1.4	40.2	22.5	0.0
O1 94/95	4.9	25.6	4.7	1.5	30.1	33.2	0.0
WI 94/95	8.9	15.5	2.2	0.0	42.3	31.0	0.0
MD 93/94	13.6	0.2	1.9	0.0	7.3	77.0	0.0
NH 93/94	8.7	3.8	1.8	3.7	40.8	34.0	7.3
NV 93/94	60.1	4.4	0.0	1.8	16.6	17.2	0.0
NY 93/94, AC	15.4	5.1	2.2	2.0	38.1	37.2	0.0
WI 93/94	17.8	0.0	0.0	4.4	26.6	51.2	0.0
total	22.2	3.5	2.8	1.3	33.7	36.0	0.5

Table 54. Results of pavement temperature readings from 17 data sets, showing (a) number, and (b) percentage of readings in a category, for combined test and control section data.

site & season	(*a*) NUMBER OF PAVEMENT TEMPERATURE READINGS							
	$T_p \leq -13.3°C$ ($T_p \leq 8°F$)	$-13.3 < T_p \leq -10°C$ ($8 < T_p \leq 14°F$)	$-10 < T_p \leq -6.7°C$ ($14 < T_p \leq 20°F$)	$-6.7 < T_p \leq -3.3°C$ ($20 < T_p \leq 26°F$)	$-3.3 < T_p \leq 0°C$ ($26 < T_p \leq 32°F$)	$T_p > 0°C$ ($T_p > 32°F$)	no data	total
CA 94/95	0	0	0	119	1031	68	0	1218
CO 94/95	0	0	118	679	1882	418	0	3097
IA 94/95	0	0	0	0	712	133	0	845
KS 94/95	0	39	182	277	423	428	59	1408
MO 94/95	0	0	0	42	394	68	0	504
NH 94/95	0	0	261	504	427	0	0	1192
NV 94/95	0	0	0	148	1988	440	0	2576
NY 94/95, AC	270	694	647	1203	1880	739	0	5433
NY 94/95, PCC	136	358	323	605	924	369	0	2715
O0 94/95	0	0	0	859	1138	246	0	2243
O1 94/95	0	0	0	114	516	88	0	718
WI 94/95	0	0	28	154	436	13	0	631
MD 93/94	155	329	480	932	928	67	4	2895
NH 93/94	0	348	524	226	168	327	0	1593
NV 93/94	0	0	56	23	160	104	0	343
NY 93/94, AC	0	590	1463	2179	2776	530	172	7710
WI 93/94	0	42	140	56	392	0	0	630
total	561	2400	4222	8120	16175	4038	235	35751

site & season	(*b*) PERCENTAGE OF ALL PAVEMENT TEMPERATURE READINGS MADE DURING SEASON						
	$T_p \leq -13.3°C$ ($T_p \leq 8°F$)	$-13.3 < T_p \leq -10°C$ ($8 < T_p \leq 14°F$)	$-10 < T_p \leq -6.7°C$ ($14 < T_p \leq 20°F$)	$-6.7 < T_p \leq -3.3°C$ ($20 < T_p \leq 26°F$)	$-3.3 < T_p \leq 0°C$ ($26 < T_p \leq 32°F$)	$T_p > 0°C$ ($T_p > 32°F$)	no data
CA 94/95	0.0	0.0	0.0	9.8	84.6	5.6	0.0
CO 94/95	0.0	0.0	3.8	21.9	60.8	13.5	0.0
IA 94/95	0.0	0.0	0.0	0.0	84.2	15.7	0.0
KS 94/95	0.0	2.8	12.9	19.7	30.1	30.4	4.2
MO 94/95	0.0	0.0	0.0	8.3	78.2	13.5	0.0
NH 94/95	0.0	0.0	21.9	42.3	35.8	0.0	0.0
NV 94/95	0.0	0.0	0.0	5.8	77.1	17.1	0.0
NY 94/95, AC	5.0	12.8	11.9	22.2	34.6	13.6	0.0
NY 94/95, PCC	5.0	13.2	11.9	22.2	34.0	13.6	0.0
O0 94/95	0.0	0.0	0.0	38.3	50.7	11.0	0.0
O1 94/95	0.0	0.0	0.0	15.9	71.9	12.3	0.0
WI 94/95	0.0	0.0	4.4	24.4	69.0	2.1	0.0
MD 93/94	5.4	11.4	16.6	32.2	32.1	2.3	0.1
NH 93/94	0.0	21.8	32.8	14.2	10.6	20.5	0.0
NV 93/94	0.0	0.0	16.3	6.7	46.7	30.3	0.0
NY 93/94, AC	0.0	7.7	19.0	28.3	36.0	6.9	2.2
WI 93/94	0.0	6.7	22.2	8.9	62.2	0.0	0.0
total	1.6	6.7	11.8	22.7	45.2	11.3	0.7

Table 55. Results of pavement condition observations from 17 data sets, showing (a) number, and (b) percentage of observations in a category, for combined test and control section data.

site & season	*(a)* NUMBER OF PAVEMENT CONDITION OBSERVATIONS								
	dry/damp	wet	slush	loose snow	packed snow	frost	black/ glaze ice	not made	total
CA 94/95	70	221	368	293	182	0	84	0	1218
CO 94/95	756	510	427	499	241	0	664	0	3097
IA 94/95	86	431	28	55	141	0	65	39	845
KS 94/95	360	187	189	181	234	0	227	0	1378
MO 94/95	21	182	94	112	95	0	0	0	504
NH 94/95	154	36	132	729	118	0	23	0	1192
NV 94/95	452	1000	466	152	449	0	57	0	2576
NY 94/95, AC	330	2043	618	1800	288	8	346	0	5433
NY 94/95, PCC	151	1073	296	867	115	0	213	0	2715
O0 94/95	120	1157	263	518	164	0	21	0	2243
O1 94/95	138	257	18	278	0	0	27	0	718
WI 94/95	63	105	231	183	42	0	7	0	631
MD 93/94	61	469	297	609	858	35	566	0	2895
NH 93/94	179	244	222	725	132	0	7	84	1593
NV 93/94	39	150	19	11	94	4	12	14	343
NY 93/94, AC	1252	1479	2205	2460	234	0	80	0	7710
WI 93/94	28	189	112	196	77	0	0	28	630
total	4260	9733	5985	9668	3464	47	2399	165	35721

site & season	*(b)* PERCENTAGE OF ALL PAVEMENT CONDITION OBSERVATIONS MADE DURING SEASON							
	dry/damp	wet	slush	loose snow	packed snow	frost	black/ glaze ice	not made
CA 94/95	5.7	18.2	30.2	24.0	14.9	0.0	6.9	0.0
CO 94/95	24.4	16.5	13.8	16.1	7.8	0.0	21.5	0.0
IA 94/95	10.2	51.0	3.3	6.5	16.7	0.0	7.7	4.6
KS 94/95	26.1	13.5	13.7	13.1	17.0	0.0	16.5	0.0
MO 94/95	4.2	36.2	18.6	22.2	18.8	0.0	0.0	0.0
NH 94/95	12.9	3.0	11.1	61.1	9.9	0.0	1.9	0.0
NV 94/95	17.6	38.8	18.1	5.9	17.4	0.0	2.2	0.0
NY 94/95, AC	6.1	37.6	11.4	33.1	5.3	0.1	6.4	0.0
NY 94/95, PCC	5.6	39.5	10.9	31.9	4.2	0.0	7.8	0.0
O0 94/95	5.4	51.6	11.7	23.1	7.3	0.0	0.9	0.0
O1 94/95	19.2	35.8	2.5	38.7	0.0	0.0	3.8	0.0
WI 94/95	10.0	16.6	36.6	29.0	6.7	0.0	1.1	0.0
MD 93/94	2.1	16.2	10.3	21.0	29.6	1.2	19.6	0.0
NH 93/94	11.2	15.3	13.9	45.5	8.3	0.0	0.4	5.3
NV 93/94	11.4	43.7	5.5	3.2	27.4	1.2	3.5	4.1
NY 93/94, AC	16.2	19.2	28.6	31.9	3.0	0.0	1.0	0.0
WI 93/94	4.4	30.0	17.8	31.1	12.2	0.0	0.0	4.4
total	11.9	27.2	16.8	27.1	9.7	0.1	6.7	0.5

Table 55 lists the results of the pavement condition observations. The categories "dry/damp," "wet," "slush," and "loose snow" make up 83 percent of the total observations, while "packed snow" and "black/glaze ice" categories make up 16 percent. The breakdown of these data by test and control section is shown in tables 56 and 57. Only slight differences between the sections are indicated in the total rows of tables 56 and 57. Traffic rate data are not included in this tabular presentation because of the lack of complete data from many of the sites.

A multiple linear regression analysis of the New York test section friction data from the 1993/1994 season is presented in the New York site report.(15) The analysis was performed to investigate the effect of several measured variables on friction during storms. It was not made to provide a model of the relationship between friction and the measured variables, and should not be interpreted as such. The initial part of the analysis was a best subsets regression analysis of normalized friction values vs. precipitation rate, pavement temperature, traffic rate, and air temperature.(19) The result was that a multiple linear regression of normalized friction as a function of pavement temperature, precipitation rate, and traffic rate, in that order of importance, would provide the best fit of the data, and that air temperature would be redundant information. The subsequent regression analysis established an equation of a normalized friction as a function of pavement temperature, precipitation rate, and traffic rate.(15,19) The coefficient of determination value (R^2) of the regression, adjusted for the number of independent variables, was low, indicating that indeed the equation is not a good model of the data.

Figures 58, 59, and 60 each illustrate test section friction data as a function of two variables in part (a), and corresponding graphs showing planar sections of the multiple linear regression equation in part (b). Respectively, the figures contain plots of normalized test section friction vs. pavement temperature and precipitation rate (figure 58), pavement temperature and traffic rate (figure 59), and traffic rate and precipitation rate (figure 60). The important results of this analysis were to show (1) that reductions in friction with decreasing pavement temperature, increasing precipitation rate, and decreasing traffic rate should generally be expected during a storm, even when successful anti-icing operations are being conducted, and (2) that of the three independent variables, traffic rate appears to have the least effect on friction. It is important to recognize that the analysis does not account for operations or time during a storm but, in effect, averages out their influences by the use of the data from 12 storms.

The successful New York anti-icing operations during the 1993/1994 season were discussed previously in section 5.2.1. This success is further indicated by the evidence of the severity of the 1993/1994 storm conditions, i.e., the approximately 40 percent "snow" observations (shown in table 53) and the number of pavement temperatures in the -13.3°C to -10°C (8°F to 14°F) and -10°C to -6.7°C (14°F to 20°F) categories (as indicated in table 54), and by the evidence of the success in avoiding poor pavement conditions, i.e., the very low percentages of packed snow and black/glaze ice observations on the test section (shown in table 57). Thus, while in this New York data set there is little indication that a bonded snowpack occurred, there is clear indication that in spite of these successful operations, motorists were exposed to considerable reductions in friction.

Table 56. Results of pavement condition observations from 17 data sets, showing number of observations in a category, for separate test and control section data.

site, season & section	NUMBER OF PAVEMENT CONDITION OBSERVATIONS								
	dry/damp	wet	slush	loose snow	packed snow	frost	black/ glaze ice	empty	total
CA 94/95, control	35	112	183	133	105		42		610
CA 94/95, test	35	109	185	160	77		42		608
CO 94/95, control	388	230	173	246	125		390		1552
CO 94/95, test	368	280	254	253	116		274		1545
IA 94/95, control	38	209	14	23	72		50	19	425
IA 94/95, test	48	222	14	32	69		15	20	420
KS 94/95, control	214	86	72	46	113		158		689
KS 94/95, test	146	101	117	135	121		69		689
MO 94/95, control	7	89	56	51	52				255
MO 94/95, test	14	93	38	61	43				249
NH 94/95, control	80	15	68	352	60		14		589
NH 94/95, test	74	21	64	377	58		9		603
NV 94/95, control	228	443	247	90	244		36		1288
NV 94/95, test	224	557	219	62	205		21		1288
NY 94/95, control, AC	161	1082	308	914	129	0	134		2728
NY 94/95, test, AC	169	961	310	886	159	8	212		2705
NY 94/95, control, PCC	76	554	142	437	55		94		1358
NY 94/95, test, PCC	75	519	154	430	60		119		1357
O0 94/95, control	61	576	148	246	82		7		1120
O0 94/95, test	59	581	115	272	82		14		1123
O1 94/95, control	77	122	12	131			26		368
O1 94/95, test	61	135	6	147			1		350
WI 94/95, control	28	56	105	99	21		7		316
WI 94/95, test	35	49	126	84	21		0		315
MD 93/94, control	29	203	176	307	426	35	279		1455
MD 93/94, test	32	266	121	302	432	0	287		1440
NH 93/94, control	80	123	101	365	75		7	39	790
NH 93/94, test	99	121	121	360	57		0	45	803
NV 93/94, control	22	83	8	3	49	2	0	7	174
NV 93/94, test	17	67	11	8	45	2	12	7	169
NY 93/94, control, AC	621	768	1040	1237	136		58		3860
NY 93/94, test, AC	631	711	1165	1223	98		22		3850
WI 93/94, control	14	91	63	91	42			14	315
WI 93/94, test	14	98	49	105	35			14	315
total, control	2159	4842	2916	4771	1786	37	1302	79	17892
total, test	2101	4891	3069	4897	1678	10	1097	86	17829

Table 57. Results of pavement condition observations from 17 data sets, showing percentage of observations in a category, for separate test and control section data.

site, season & section	PERCENTAGE OF ALL PAVEMENT CONDITION OBSERVATIONS MADE IN SECTION DURING SEASON							
	dry/damp	wet	slush	loose snow	packed snow	frost	black/ glaze ice	empty
CA 94/95, control	5.7	18.4	30.0	21.8	17.2		6.9	
CA 94/95, test	5.8	17.9	30.4	26.3	12.7		6.9	
CO 94/95, control	25.0	14.8	11.2	15.9	8.1		25.1	
CO 94/95, test	23.8	18.1	16.4	16.4	7.5		17.7	
IA 94/95, control	8.9	49.2	3.3	5.4	16.9		11.8	4.5
IA 94/95, test	11.4	52.9	3.3	7.6	16.4		3.6	4.8
KS 94/95, control	31.1	12.5	10.4	6.7	16.4		22.9	
KS 94/95, test	21.2	14.7	17.0	19.6	17.6		10.0	
MO 94/95, control	2.8	34.9	22.0	20.0	20.4			
MO 94/95, test	5.6	37.3	15.3	24.5	17.3			
NH 94/95, control	13.6	2.6	11.5	59.8	10.2		2.4	
NH 94/95, test	12.3	3.5	10.6	62.5	9.6		1.5	
NV 94/95, control	17.7	34.4	19.2	7.0	18.9		2.8	
NV 94/95, test	17.4	43.2	17.0	4.8	15.9		1.6	
NY 94/95, control, AC	5.9	39.7	11.3	33.5	4.7	0.0	4.9	
NY 94/95, test, AC	6.3	35.5	11.5	32.8	5.9	0.3	7.8	
NY 94/95, control, PCC	5.6	40.8	10.5	32.2	4.1		6.9	
NY 94/95, test, PCC	5.5	38.2	11.4	31.7	4.4		8.8	
O0 94/95, control	5.5	51.4	13.2	22.0	7.3		0.6	
O0 94/95, test	5.3	51.7	10.2	24.2	7.3		1.2	
O1 94/95, control	20.9	33.2	3.3	35.6			7.1	
O1 94/95, test	17.4	38.6	1.7	42.0			0.3	
WI 94/95, control	8.9	17.7	33.2	31.3	6.7		2.2	
WI 94/95, test	11.1	15.6	40.0	26.7	6.7		0.0	
MD 93/94, control	2.0	14.0	12.1	21.1	29.3	2.4	19.2	
MD 93/94, test	2.2	18.5	8.4	21.0	30.0	0.0	19.9	
NH 93/94, control	10.1	15.6	12.8	46.2	9.5		0.9	4.9
NH 93/94, test	12.3	15.1	15.1	44.8	7.1		0.0	5.6
NV 93/94, control	12.6	47.7	4.6	1.7	28.2	1.1	0.0	4.0
NV 93/94, test	10.1	39.6	6.5	4.7	26.6	1.2	7.1	4.1
NY 93/94, control, AC	16.1	19.9	26.9	32.0	3.5		1.5	
NY 93/94, test, AC	16.4	18.5	30.3	31.8	2.6		0.6	
WI 93/94, control	4.4	28.9	20.0	28.9	13.3			4.4
WI 93/94, test	4.4	31.1	15.6	33.3	11.1			4.4
All, control	12.1	27.1	16.3	26.7	10.0	0.2	7.3	0.4
All, test	11.8	27.4	17.2	27.5	9.4	0.1	6.2	0.5

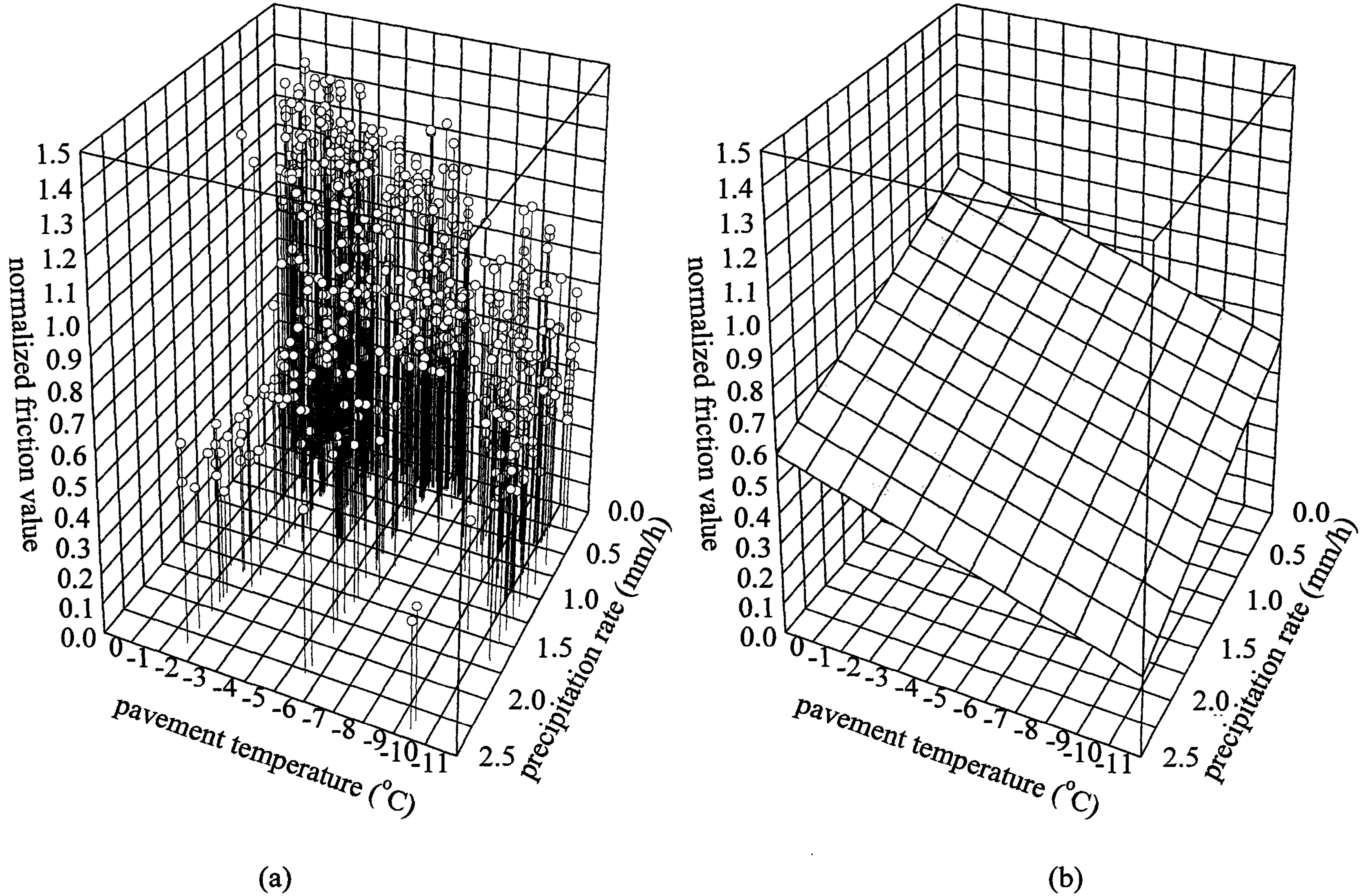
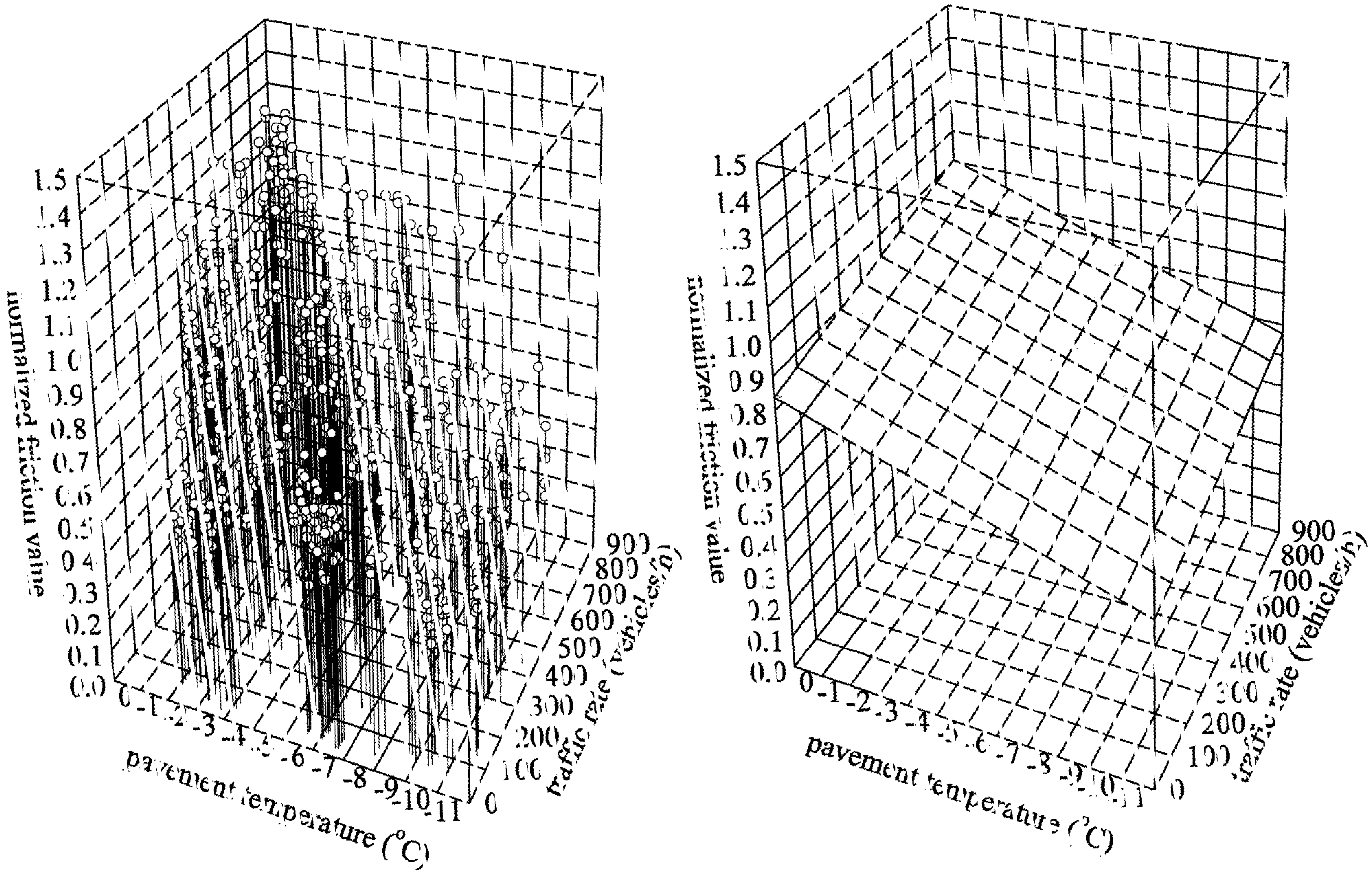
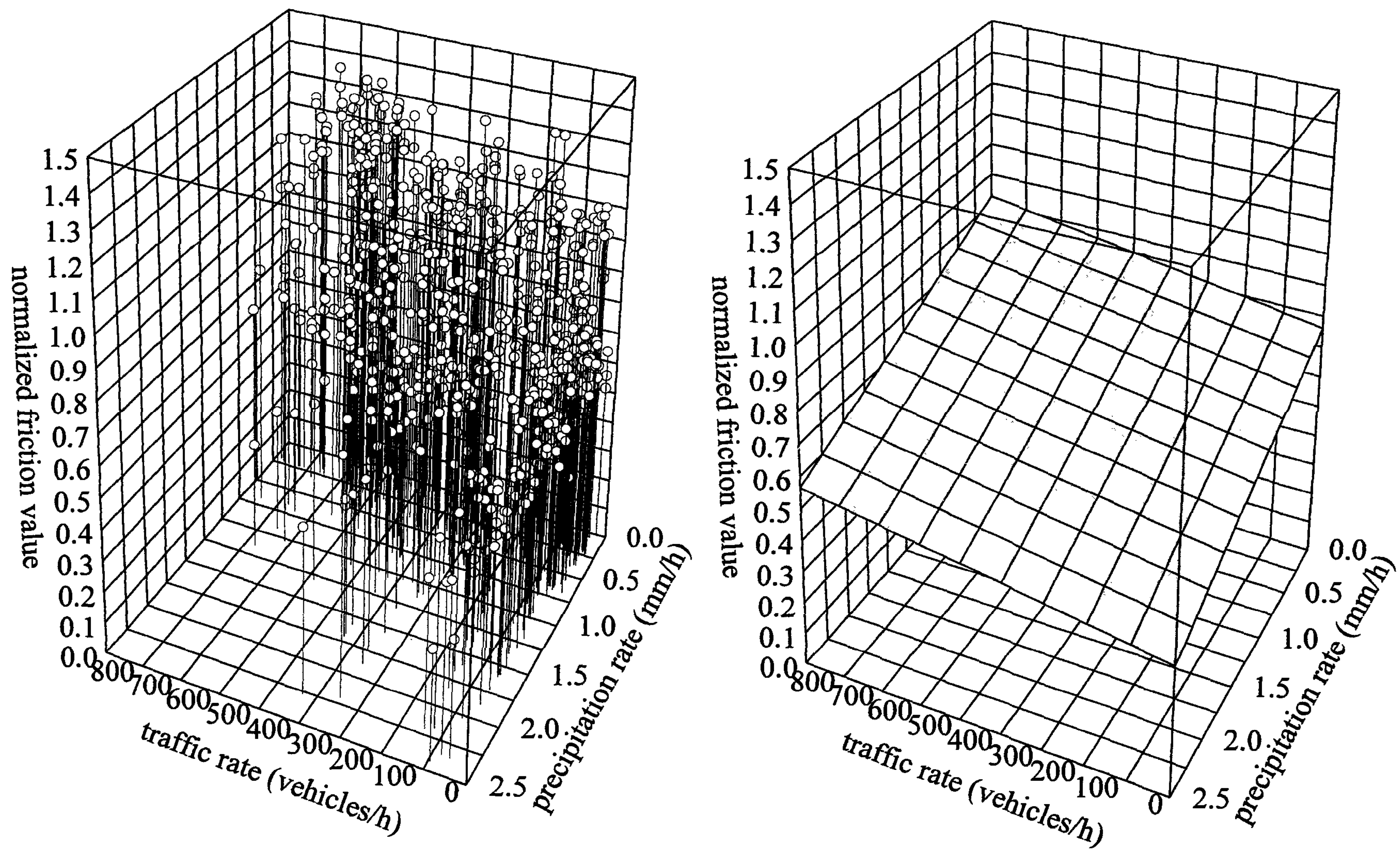


Figure 58. New York normalized friction data, test section, winter 1993/1994. (a) Plot of friction data as as function of pavement temperature and precipitation rate, and (b) 200 vehicles/h traffic rate plane from multiple linear regression analysis.



(a) (b)

Figure 59. New York normalized friction data, test section, winter 1993/1994. (a) Plot of friction data as a function of pavement temperature and traffic rate, and (b) 0.5-mm/h precipitation rate plane from multiple linear regression analysis.



(a)

(b)

Figure 60. New York normalized friction data, test section, winter 1993/1994. (a) Plot of friction data as a function of precipitation rate and traffic rate, and (b) -4°C pavement temperature plane from multiple linear regression analysis.

Excessive reductions in friction were commented upon frequently in the previous discussions of individual storms. The data shown in figures 61 through 77 reflect these reductions. These figures combine data plots that are presented in the site reports, and show normalized friction vs. pavement condition category, section, section and pavement temperature category, and section and precipitation category. As indicated in nearly all of the graphs of normalized friction vs. section and precipitation category in these figures, the friction medians and distributions are considerably lower for snow than for light snow, reflecting worse pavement conditions. Because snow and light snow dominated the precipitation in the data sets, as indicated in table 53, these differences in friction are truly reflective of the effect that snowfall intensity had on friction and pavement conditions during the analyzed storms. When combined with the evidence from many of the individual storms that packed snow conditions are most likely to occur soon after an increase in snowfall intensity, these data suggest that snow intensity should be considered as important a variable as pavement temperature in the design of anti-icing operational practices. The "storm within a storm" approach suggested in section 5.2.1.5 was based upon results of the individual storm data histories. It becomes even more appropriate when considering the effect of snowfall intensity seen in the graphs shown here of normalized friction vs. section and precipitation category. The approach should provide a technique to combine the basic strategy of anti-icing practice, i.e., preventing a bonded snowpack, with a complementary strategy of limiting reductions in friction due to increases in snowfall rate.

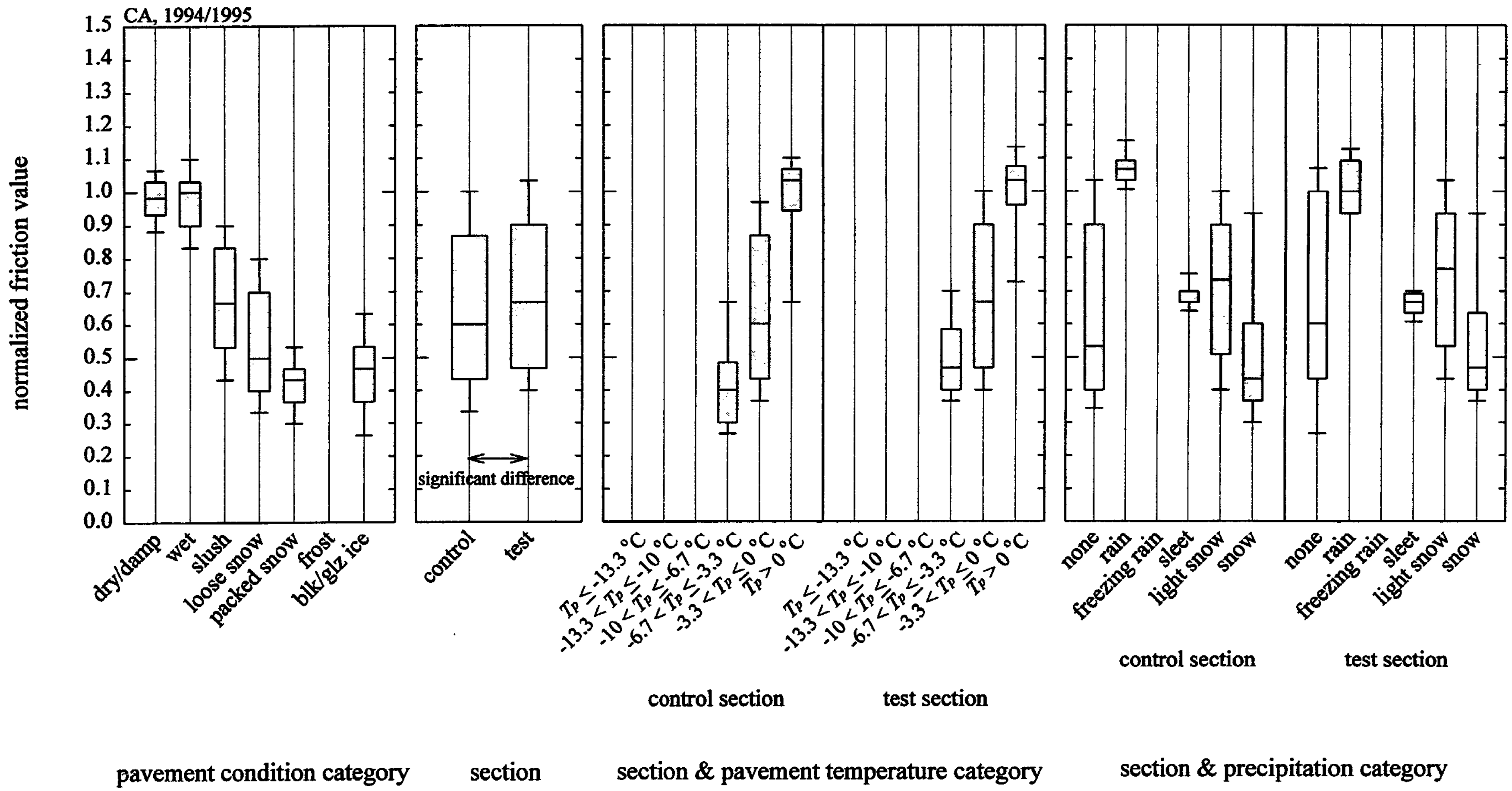


Figure 61. Tukey box plots of California friction measurement data from test and control sections, winter 1994/1995.

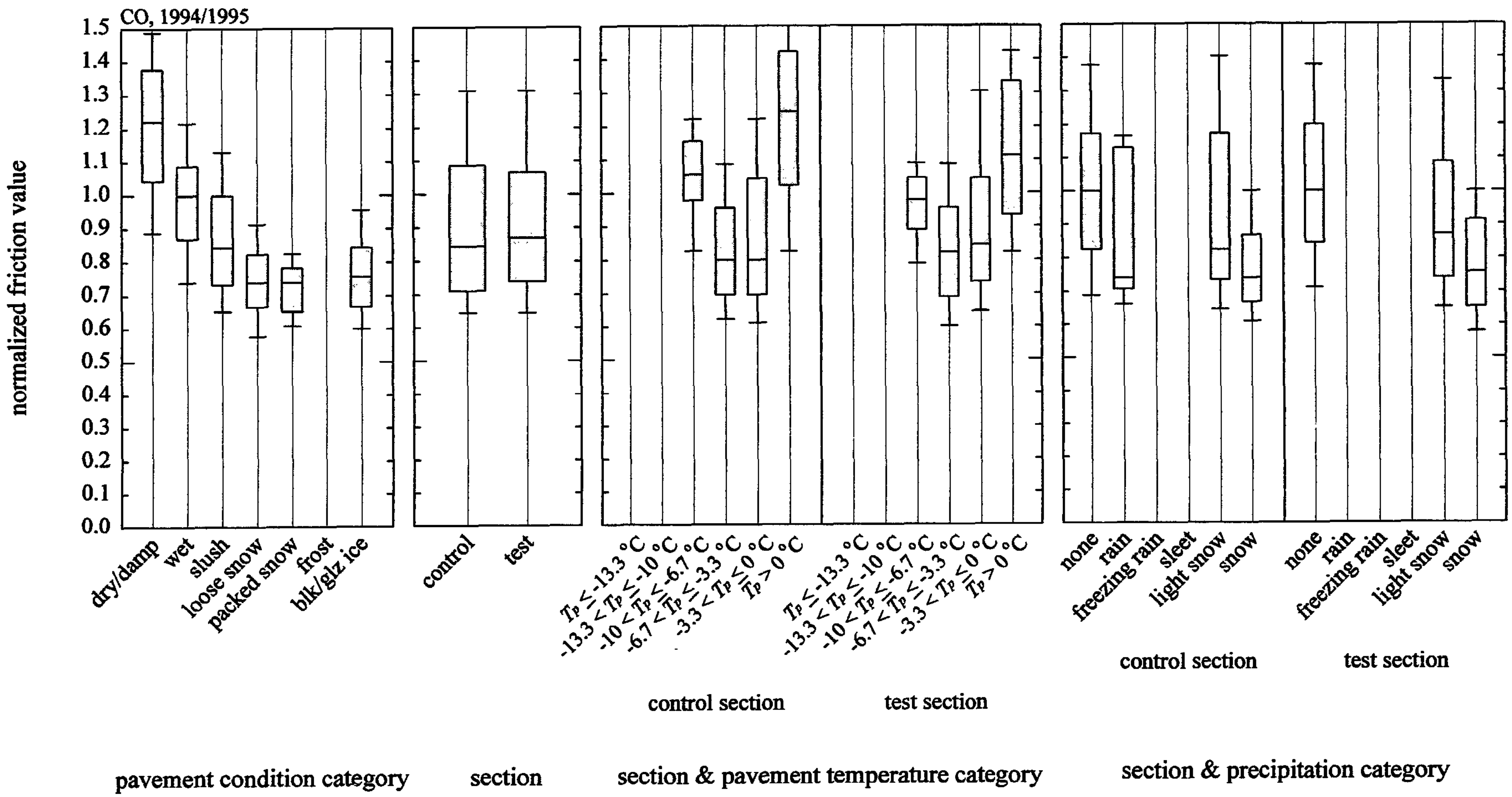


Figure 62. Tukey box plots of Colorado friction measurement data from test and control sections, winter 1994/1995.

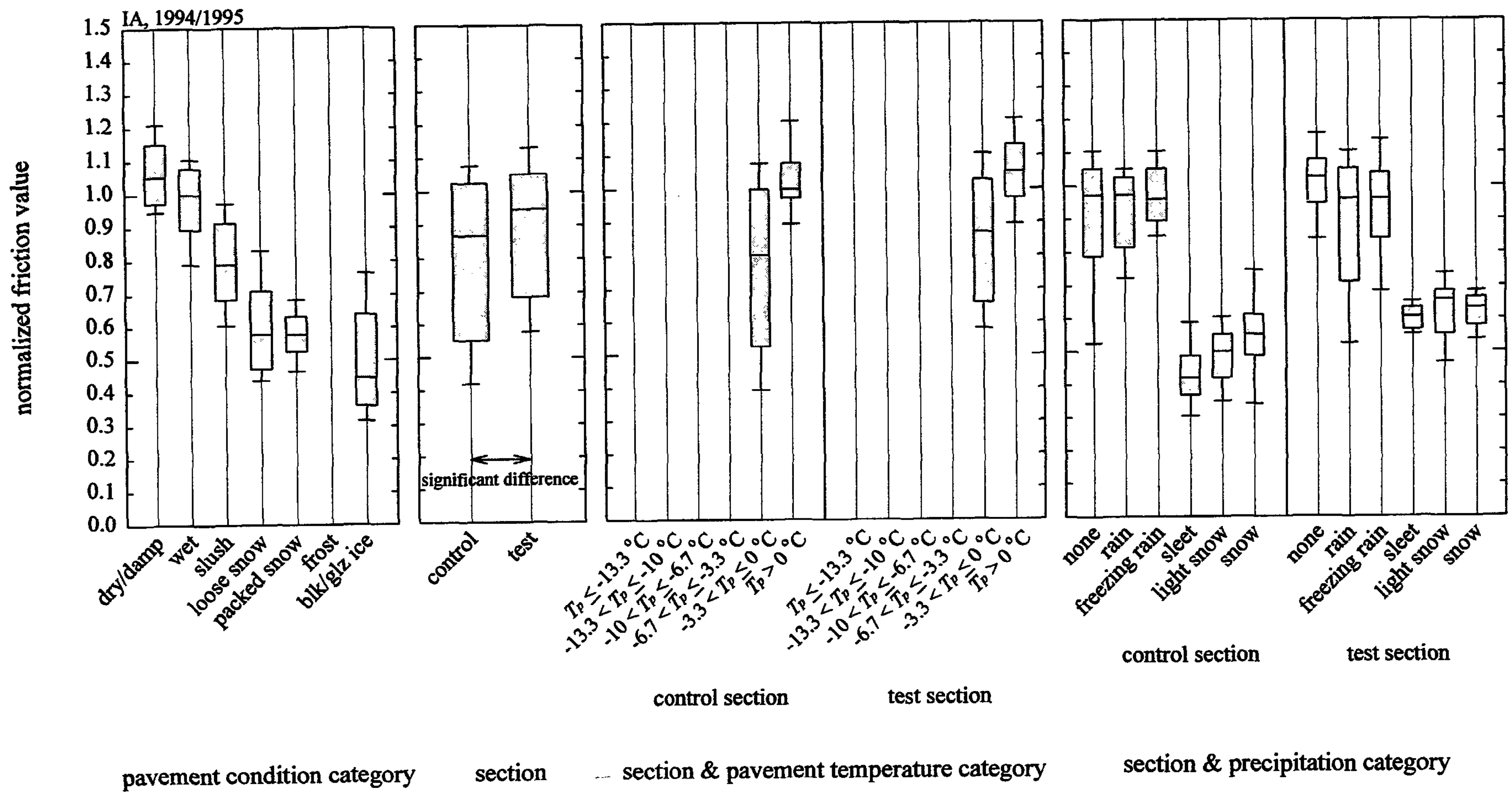


Figure 63. Tukey box plots of Iowa friction measurement data from test and control sections, winter 1994/1995.

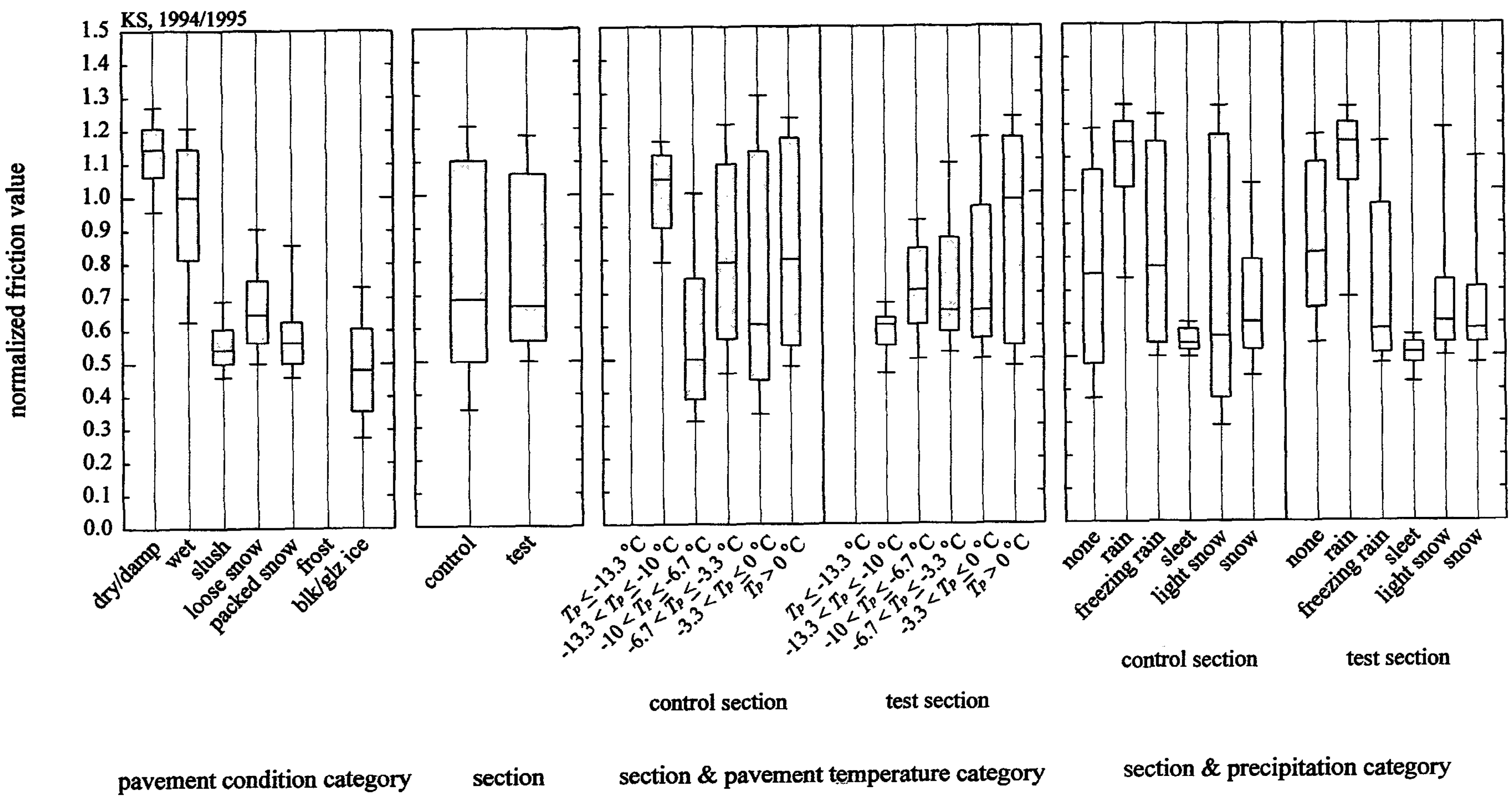


Figure 64. Tukey box plots of Kansas friction measurement data from test and control sections, winter 1994/1995.

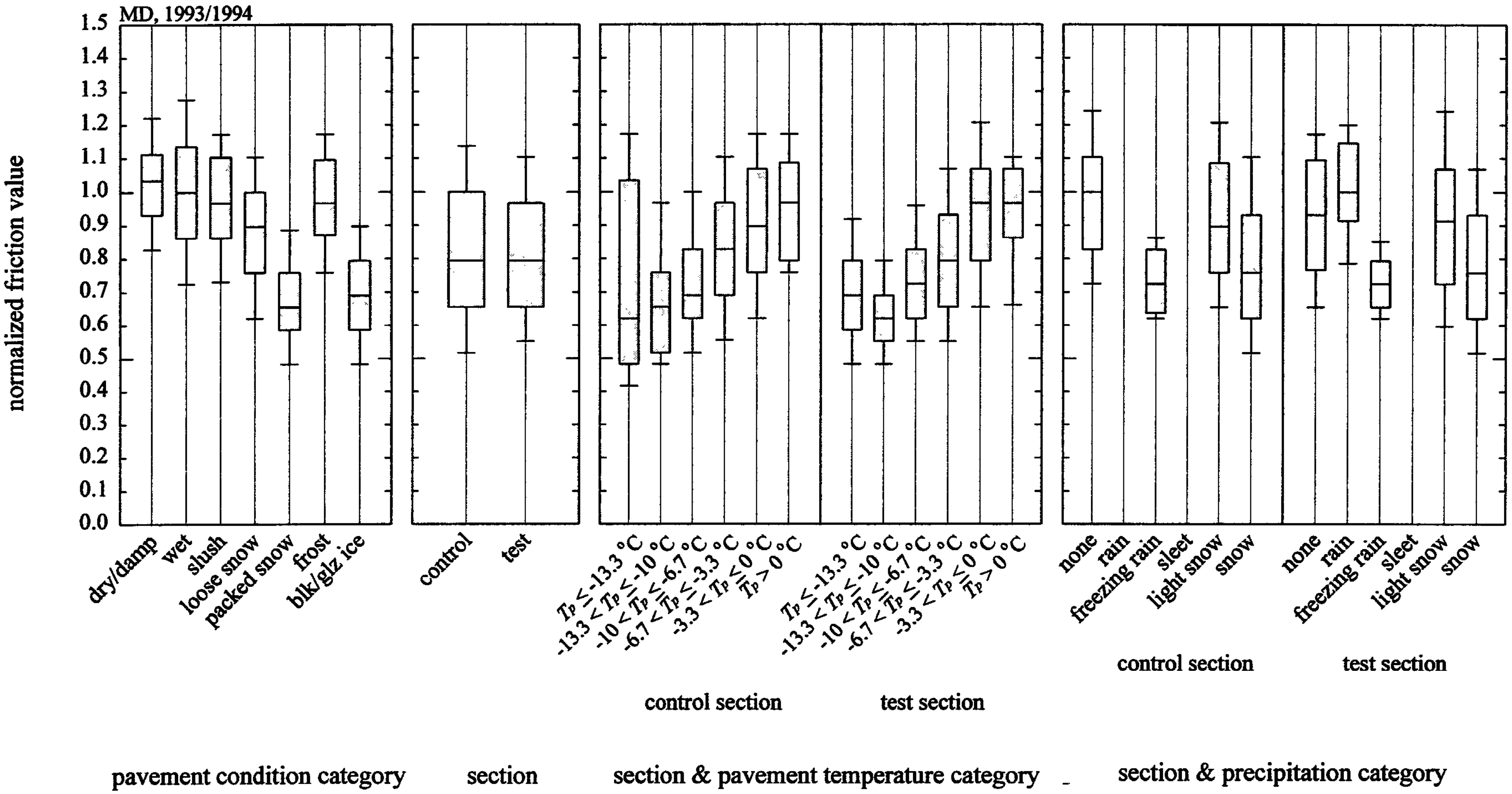


Figure 65. Tukey box plots of Maryland friction measurement data from test and control sections, winter 1993/1994.

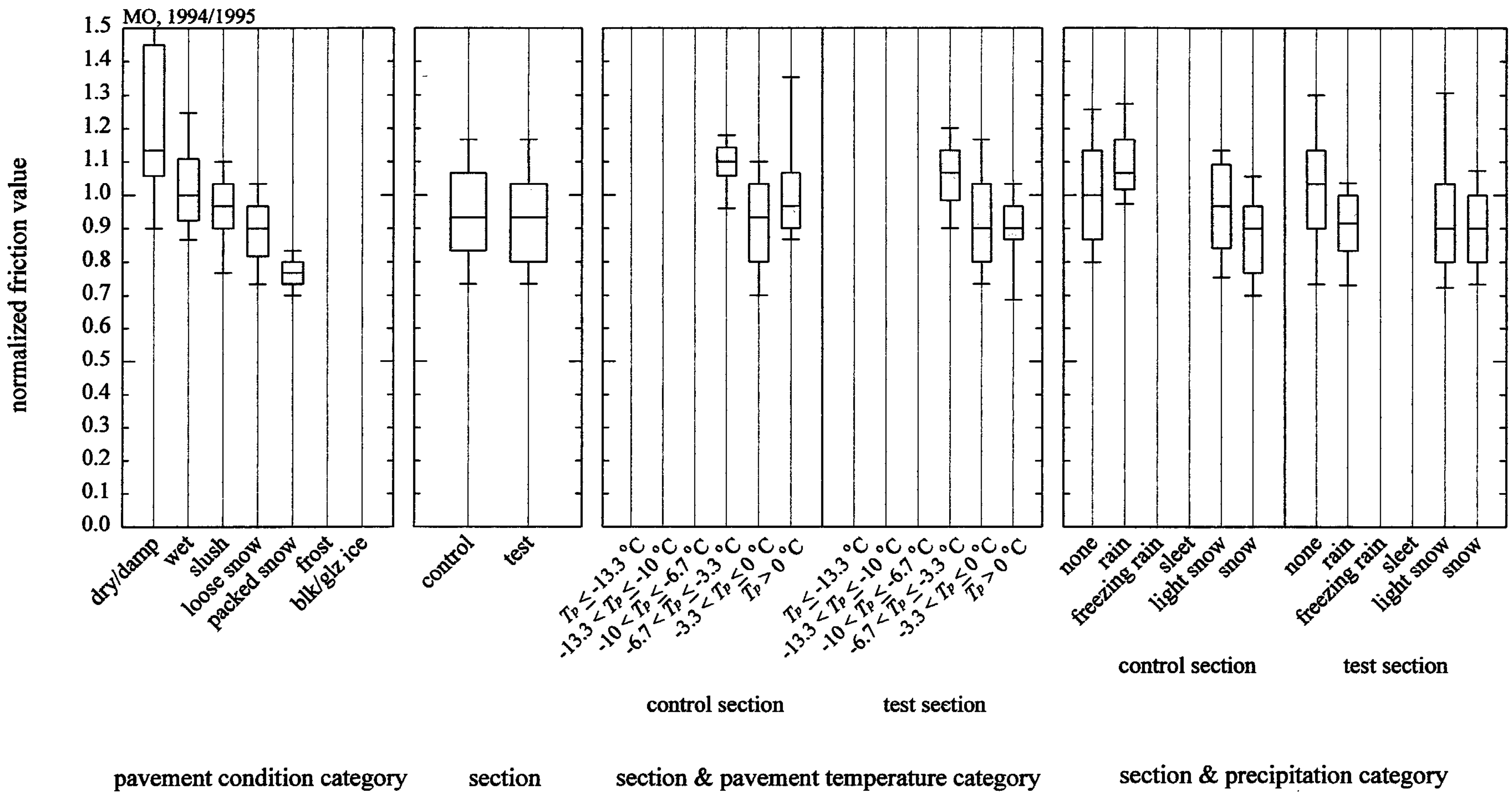


Figure 66. Tukey box plots of Missouri friction measurement data from test and control sections, winter 1994/1995.

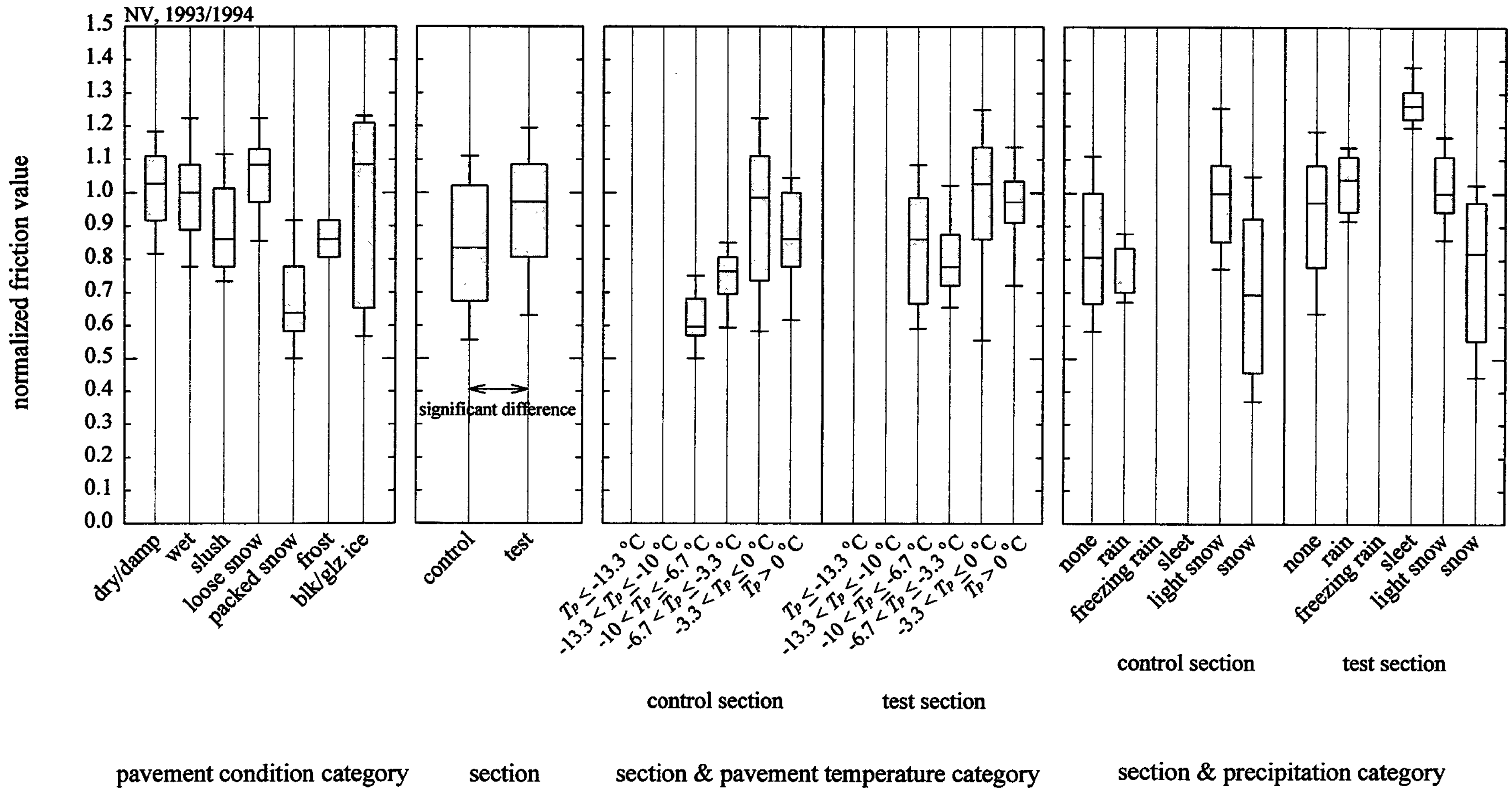


Figure 67. Tukey box plots of Nevada friction measurement data from test and control sections, winter 1993/1994.

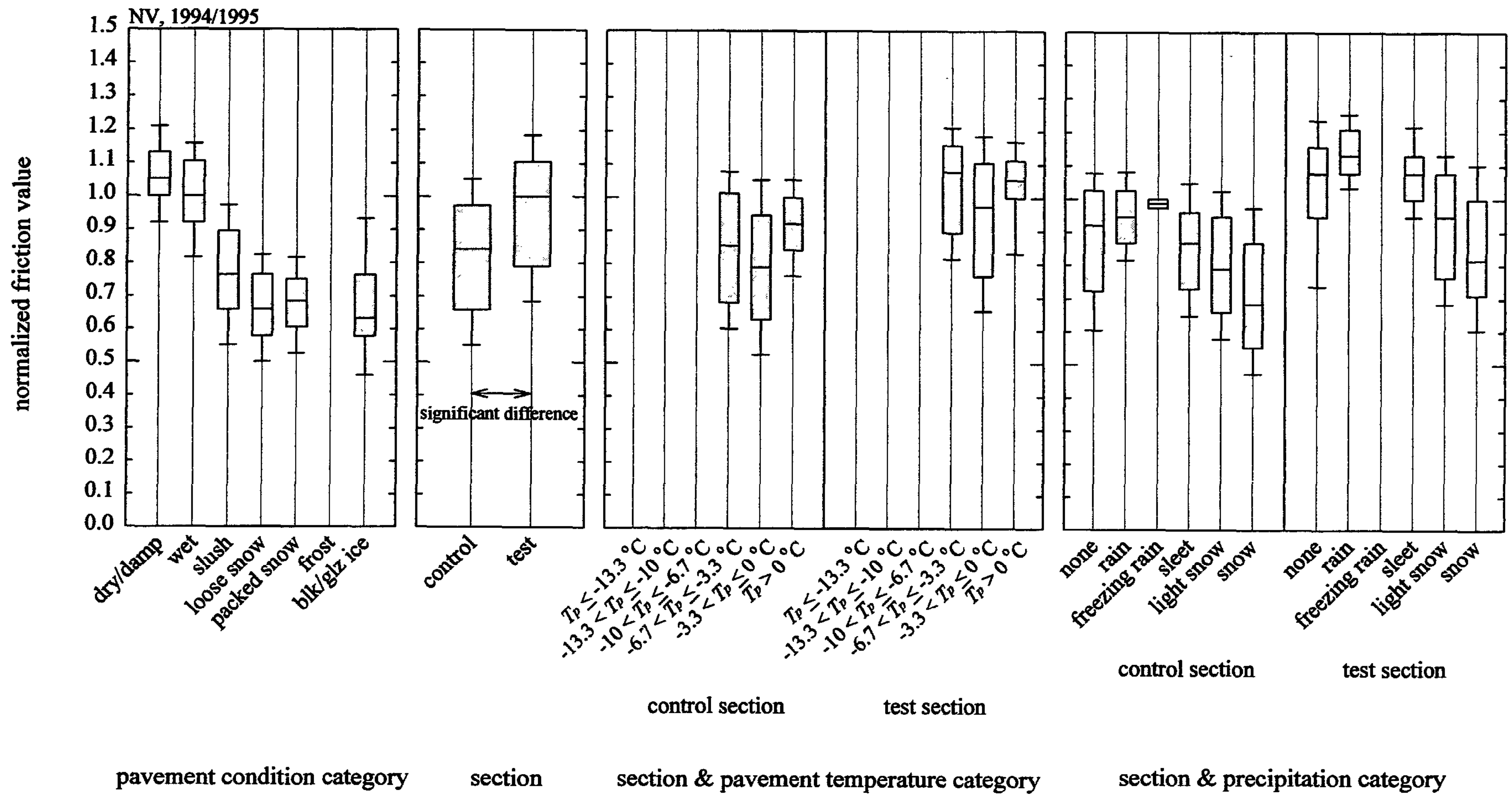


Figure 68. Tukey box plots of Nevada friction measurement data from test and control sections, winter 1994/1995.

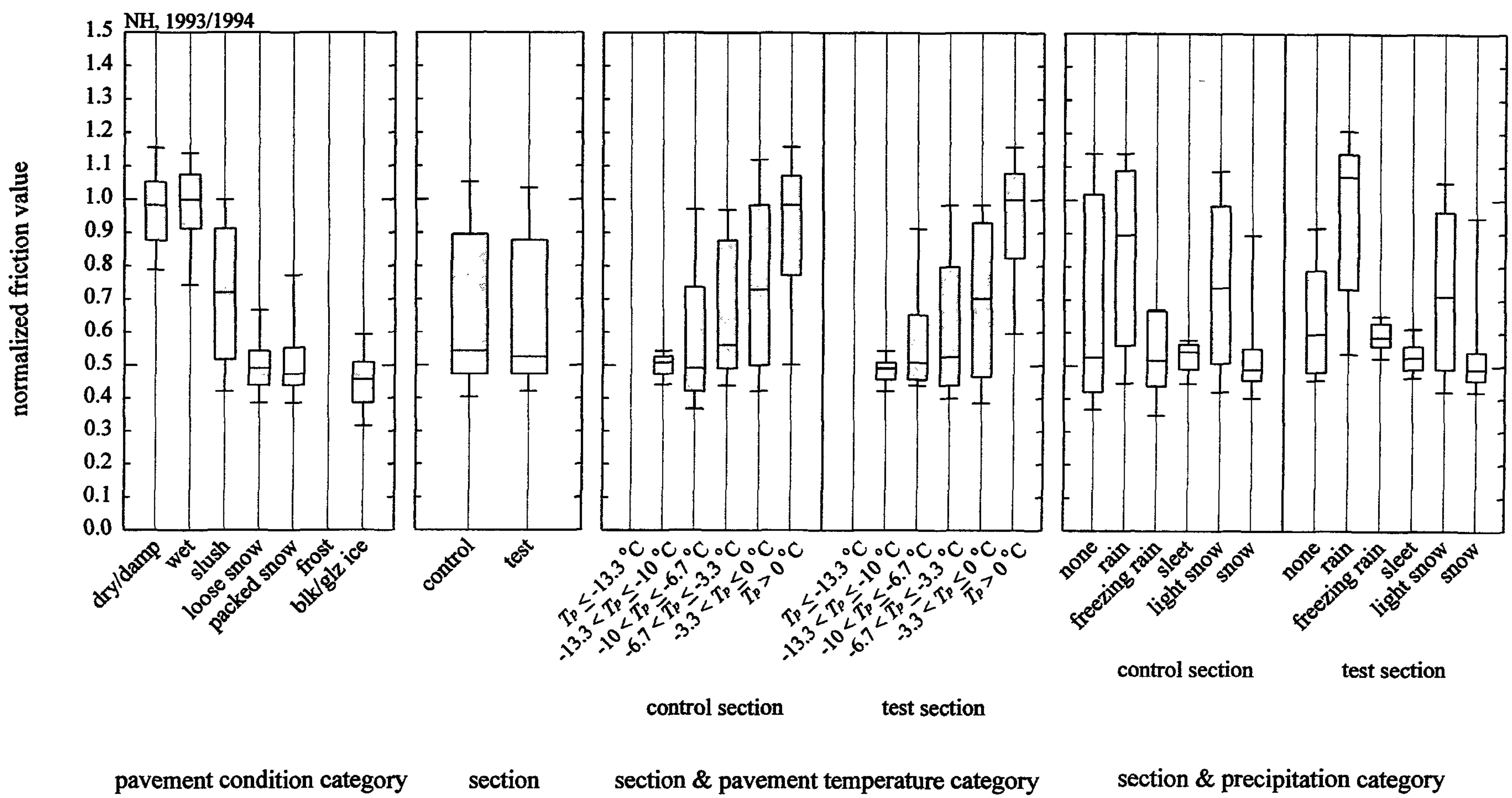


Figure 69. Tukey box plots of New Hampshire friction measurement data from test and control sections, winter 1993/1994.

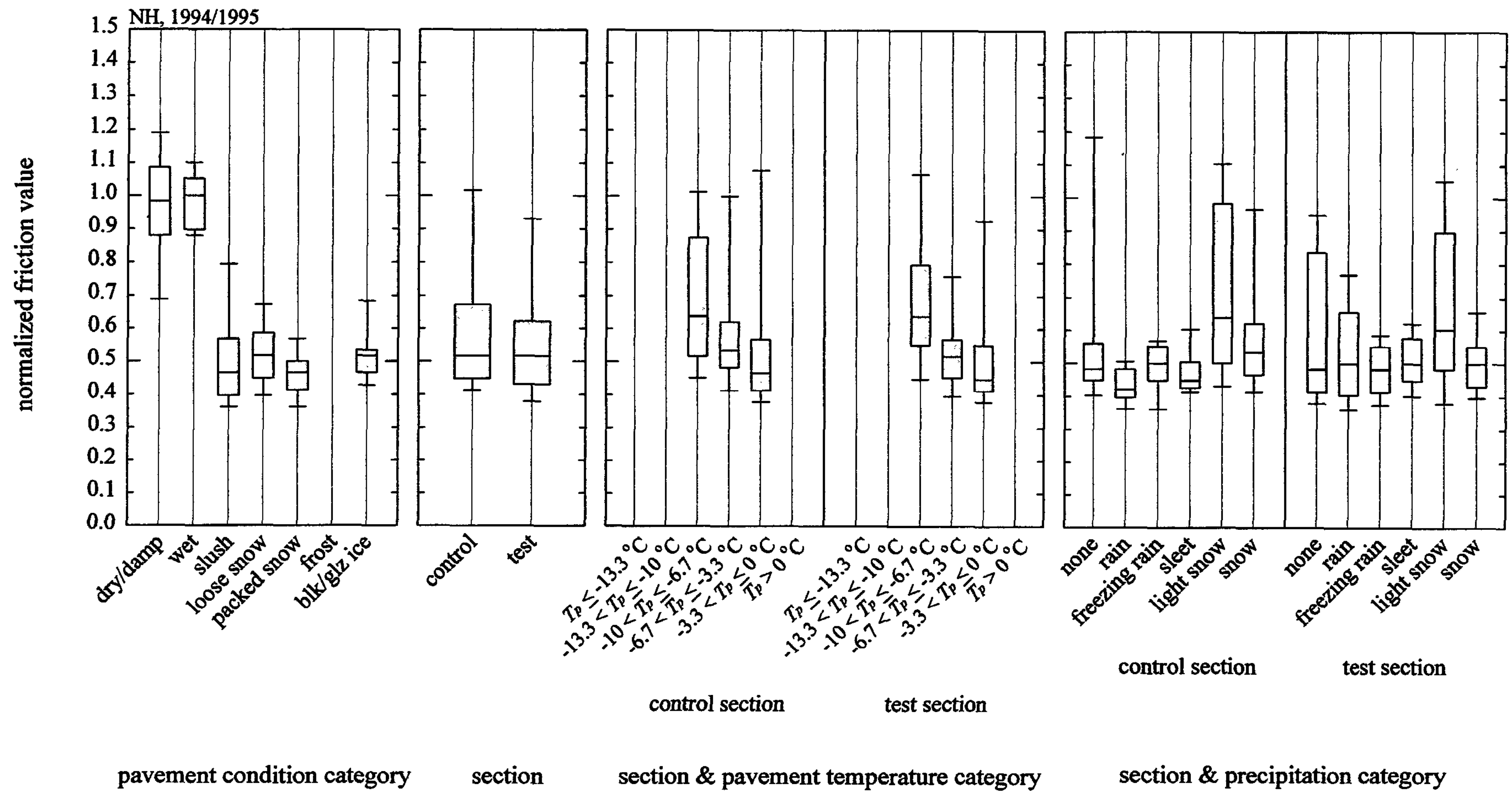


Figure 70. Tukey box plots of New Hampshire friction measurement data from test and control sections, winter 1994/1995.

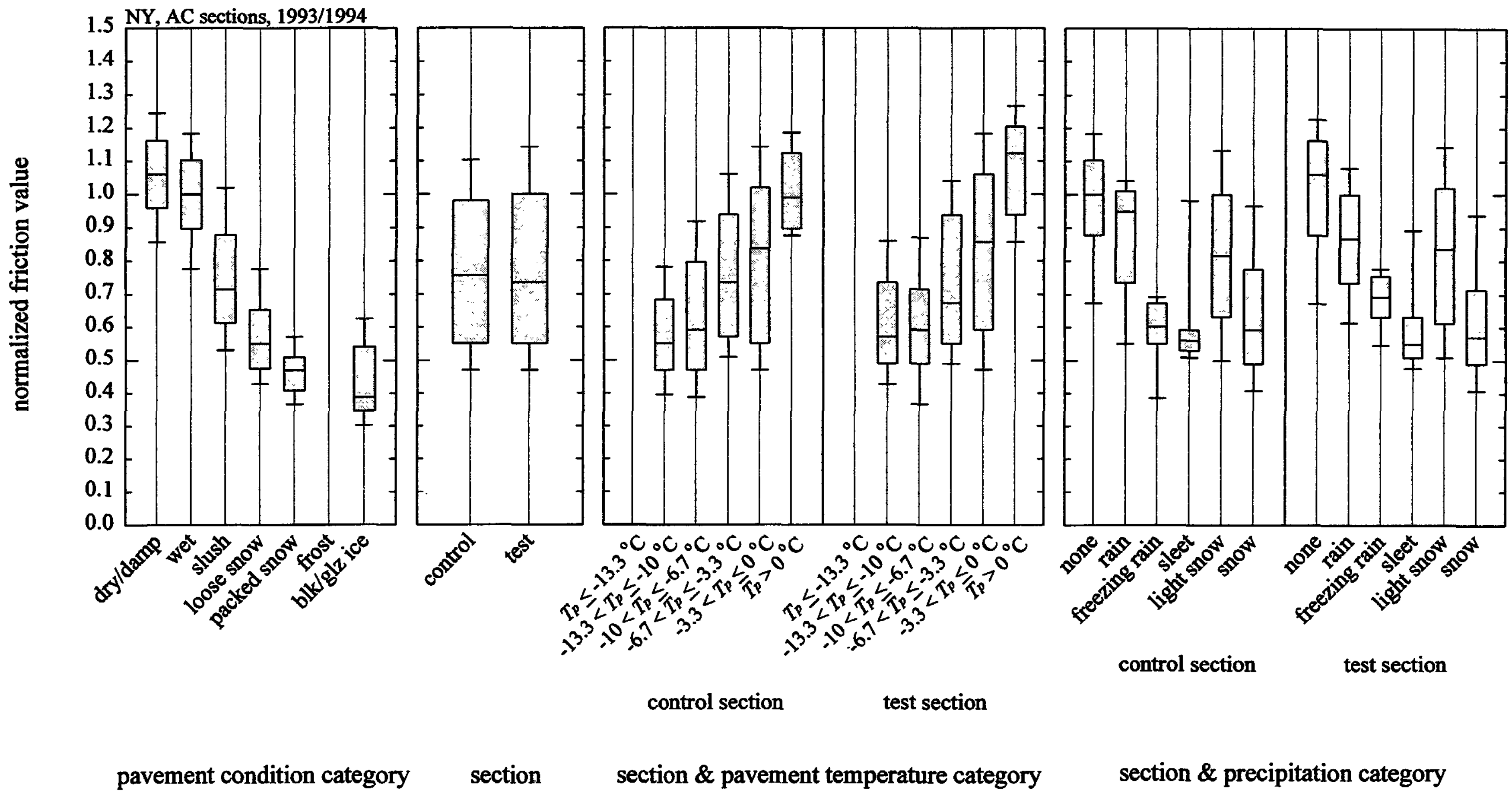


Figure 71. Tukey box plots of New York friction measurement data from test and control asphalt concrete sections, winter 1993/1994.

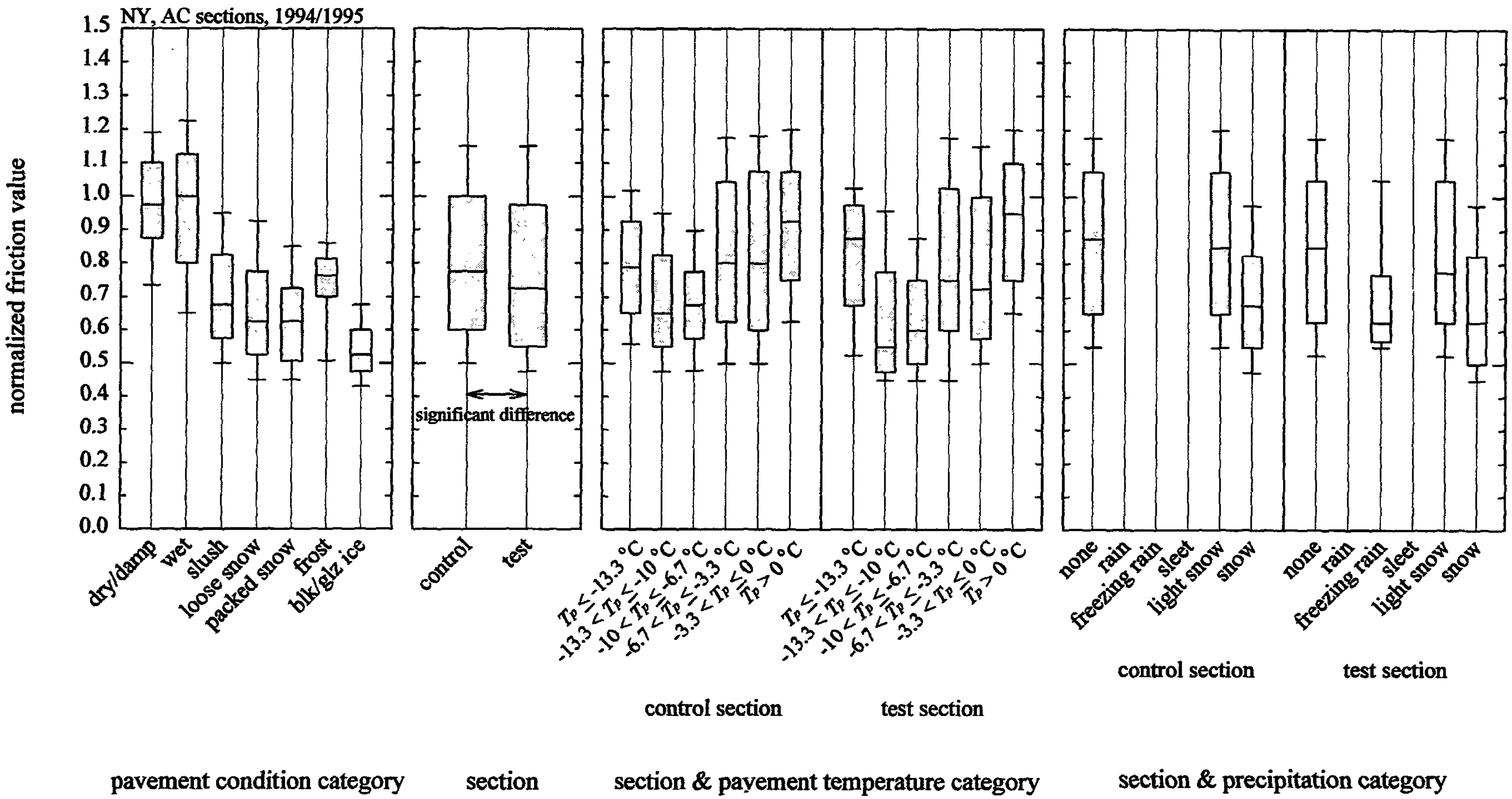


Figure 72. Tukey box plots of New York friction measurement data from test and control asphalt concrete sections, winter 1994/1995.

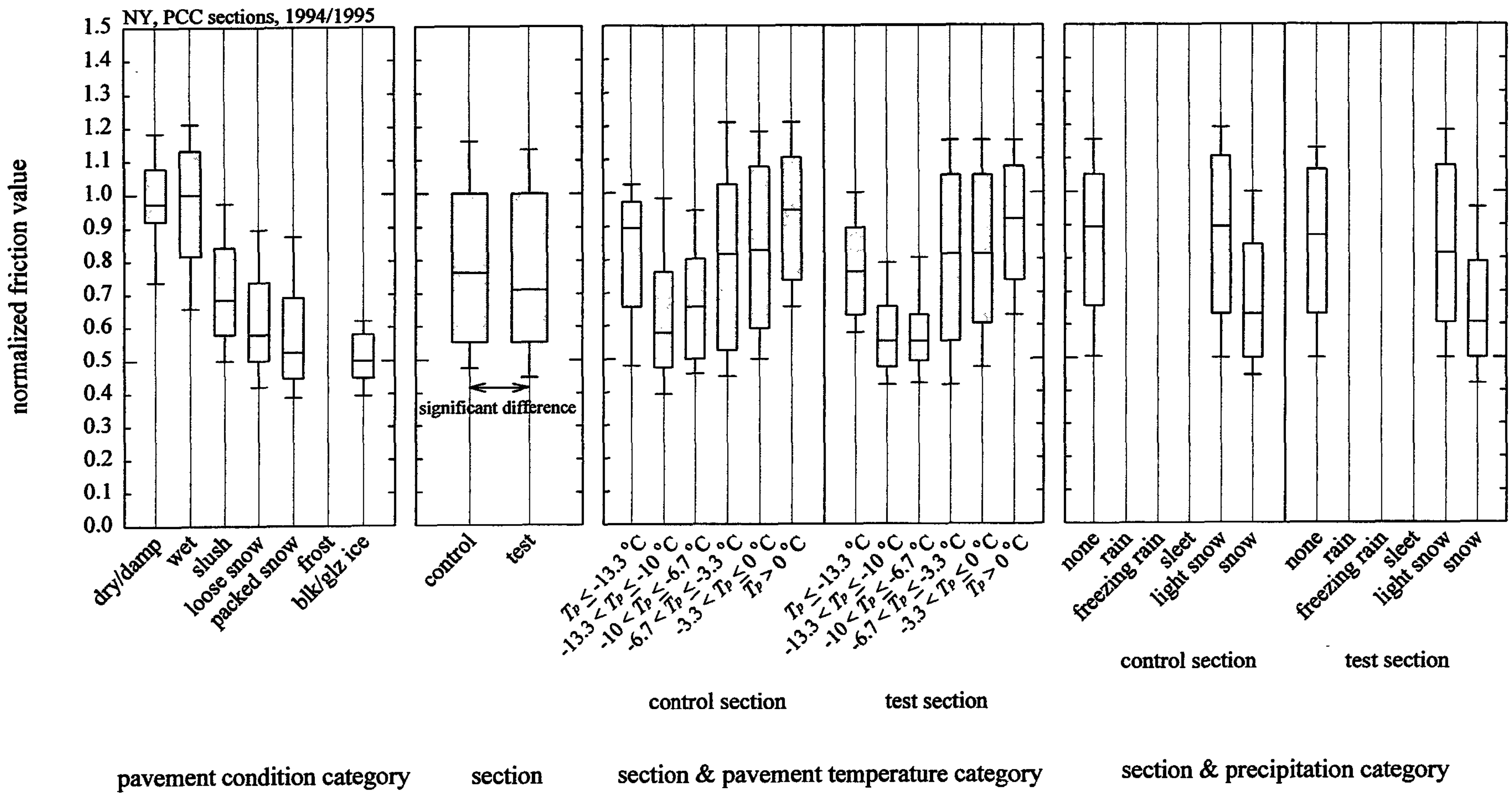


Figure 73. Tukey box plots of New York friction measurement data from test and control Portland cement concrete sections, winter 1994/1995.

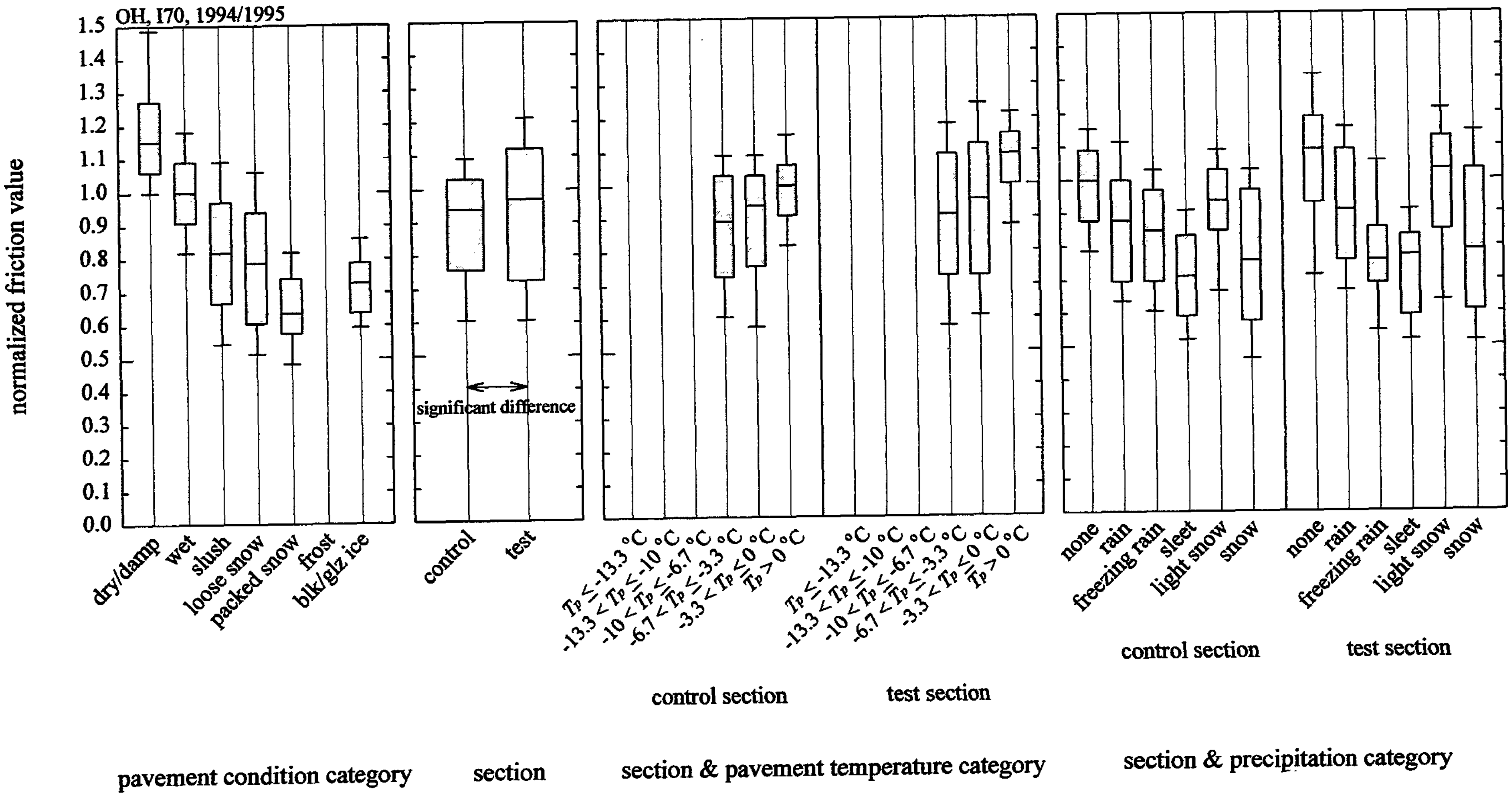


Figure 74. Tukey box plots of Ohio, I-70 friction measurement data from test and control sections, winter 1994/1995.

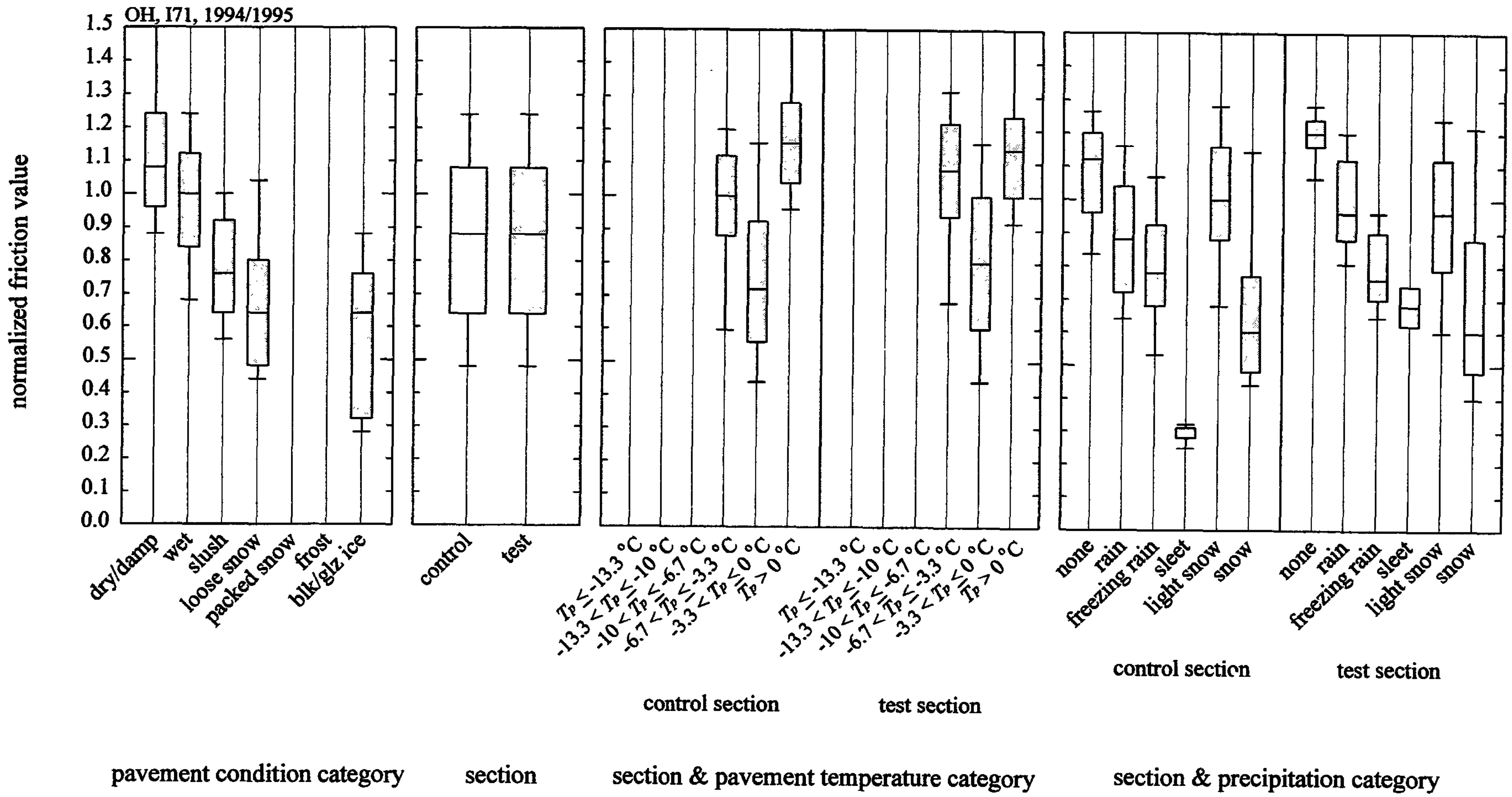


Figure 75. Tukey box plots of Ohio, I-71 friction measurement data from test and control sections, winter 1994/1995.

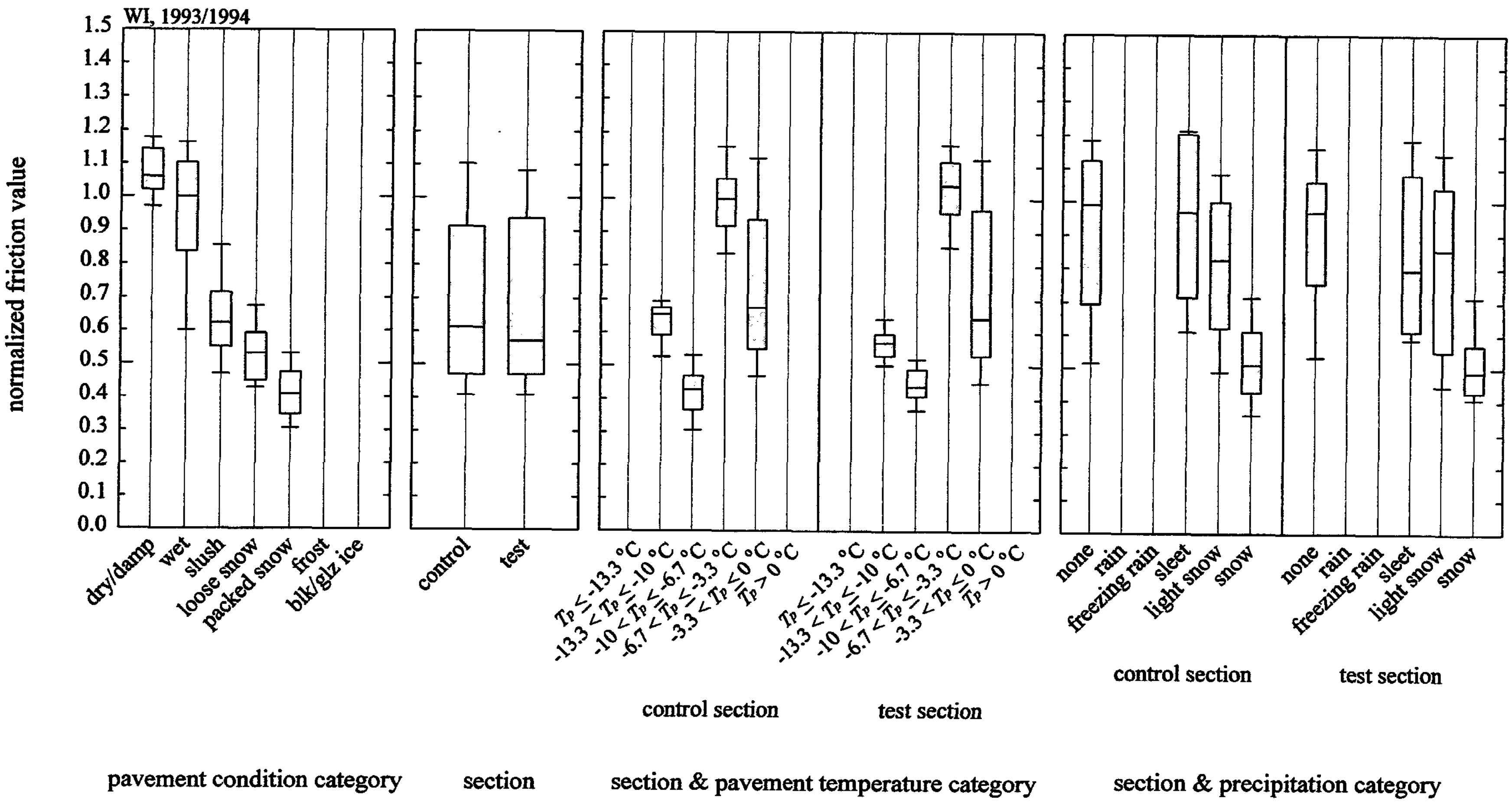


Figure 76. Tukey box plots of Wisconsin friction measurement data from test and control sections, winter 1993/1994.

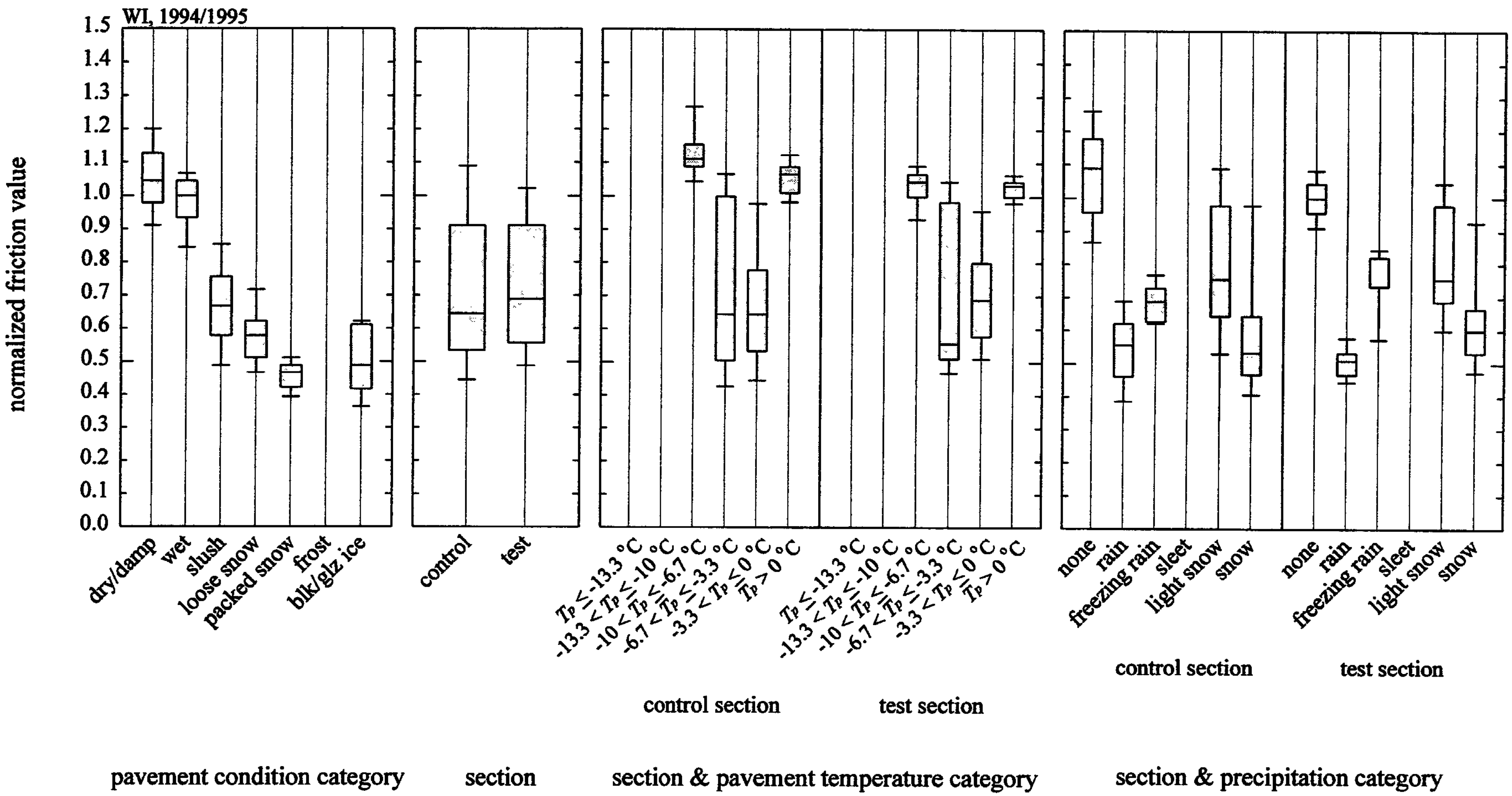


Figure 77. Tukey box plots of Wisconsin friction measurement data from test and control sections, winter 1994/1995.

6. COST ANALYSIS

6.1 INTRODUCTION

This chapter describes an analysis of snow and ice control cost data provided by five States—California, Nevada, New Hampshire, New York, and Wisconsin. The data are from the test and control section operations conducted according to the experimental program described in chapter 2. Table 58 lists the storms of the analysis. These include most of the storms for which cost data sets were provided, which were chosen based on completeness of relevant data. To provide cross references to illustrative data of the storms, table 58 also indicates the figure numbers of corresponding storm data history graphs that were developed according to the process described in chapter 4.

It is important to emphasize that the cost analysis is not of operations on full-patrol sections: it is of operations on relatively short test and control sections and is thereby not wholly indicative of full-patrol operational costs. However, if the analysis would have been of separate patrol sections, comparisons of effectiveness would not have been direct as they were for the test and control sections of this project, since these sections were subjected to nearly identical storm conditions. Yet, because true operational costs are best calculated when a full patrol is considered, full-patrol comparisons would have been preferred if cost rather than effectiveness was the primary focus of the evaluation.

6.2 APPROACH

Subsequent tables in this chapter present spreadsheets of the cost data provided by the five States, results of their analysis for the test and control sections, and indications of the effectiveness achieved. The data were taken from two sources: (1) cost data provided by the States for each storm on the form shown in figure 78, and (2) driving lane operations data provided in the field evaluation storm data packages, i.e., the documentation for each storm described in appendix A.

As indicated in figure 78, direct costs of material, equipment, and labor, average traffic speed, summary of actions, and estimates of other costs were requested from the States. Of these, the direct costs were the most used data in the analysis. The operations data from the storm data packages provided only material use and information on the number of operational passes, but when analyzed together with friction, pavement condition, precipitation, and pavement temperature data, provided insight into the cost of achieving effectiveness under particular conditions. Analysis of the operations and effectiveness data from the storm data packages isolated the driving lane operations and material use because it was on the driving lane where the effectiveness measurements and observations were made.

Three different types of results stem from the cost analysis:

1. Results from data provided on the cost forms (figure 78), by section and storm, which include:

   - Breakdown into labor, equipment, and materials use and cost.
   - Cost per section area, by labor, equipment, and materials, and totals categories.
   - Test/control cost ratios, by labor, equipment, and materials, and totals categories.
   - Cost per section area per duration of operation, by labor, equipment, and materials, and totals categories (New York only).
   - Vehicle average speeds (New Hampshire, New York, and Wisconsin only).

Table 58. Storm data sets for which cost data were submitted and included in the analysis.

Site	Storm Dates	Storm ID	Location of Data History Graphs
California	December 5-7, 1994	CA412A	Figure 48, section 5.3.5
California	December 11-12, 1994	CA412B	Figure 79, appendix C
California	December 13-14, 1994	CA412C	Figure 49, section 5.3.5
California	January 22-23, 1995	CA501B	Figure 80, appendix C
California	March 22-23, 1995	CA503A	Figure 81, appendix C
Nevada	December 11-12, 1994	NV412A	Figure 82, appendix C
Nevada	January 6-7, 1995	NV501B	Figure 25, section 5.3.1
Nevada	January 26-27, 1995	NV501G	Figure 83, appendix C
Nevada	February 13-14, 1995	NV502A	Figure 26, section 5.3.1
Nevada	March 22-23, 1995	NV503B	Figure 27, section 5.3.1
New Hampshire	January 6-7, 1995	NH501B	Figure 34, section 5.3.3
New Hampshire	January 11-13, 1995	NH501C	Figure 35, section 5.3.3
New Hampshire	February 4-5, 1995	NH502A	Figure 36, section 5.3.3
New Hampshire	February 15-16, 1995	NH502B	Figure 37, section 5.3.3
New Hampshire	February 27-28, 1995	NH502C	Figure 38, section 5.3.3
New York	January 6-7, 1995	NY501A	Figure 7, section 5.2.1
New York	January 23-25, 1995	NY501F	Figure 8, section 5.2.1
New York	January 25-27, 1995	NY501G	Figure 84, appendix C
New York	January 28, 1995	NY501H	Figure 85, appendix C
New York	February 1-2, 1995	NY502A	Figure 9, section 5.2.1
New York	February 4-7, 1995	NY502B	Figure 86, appendix C
New York	February 7-8, 1995	NY502C	Figure 10, section 5.2.1
New York	February 10, 1995	NY502E	Figure 87, appendix C
New York	February 11-12, 1995	NY502F	Figure 88, appendix C
New York	February 23-25, 1995	NY502H	Figure 89, appendix C
New York	March 8-9, 1995	NY503B	Figure 11, section 5.2.1
Wisconsin	January 10, 1995	WI501A	Figure 90, appendix C
Wisconsin	January 19-20, 1995	WI501B	Figure 29, section 5.3.2
Wisconsin	February 14-15, 1995	WI502A	Figure 30, section 5.3.2
Wisconsin	March 4-5, 1995	WI503A	Figure 31, section 5.3.2

2. Results from driving lane operations and effectiveness data (developed from the field evaluation analysis process described previously in chapter 4), by section and storm, which include:

- Driving lane operations and material use/costs, from summary tables.
- Driving lane pavement condition observations.
- Driving lane friction measurement statistics.
- Precipitation observations at times of friction measurements.
- Pavement temperatures at times of friction measurements.

3. Results from full-season analyses (developed from the field evaluation analysis process described previously in chapter 4), which include:

- Summary tables of driving lane operations and material use with costs.
- Table with pavement condition observations of the season (in chapter 5).
- Figures with friction data (in chapter 5).
- Table with precipitation observations at times of friction measurements (in chapter 5).
- Table with pavement temperatures at times of friction measurements (in chapter 5).

Costs of Snow and Ice Control — Winter 1994/95

State ______ Storm no. ______ Dates ______________

Direct costs

	Amt used (ton) Test	Control	Unit cost	Cost/lane-mi Test	Control
Materials (total cost)*					
Chemicals					
Chem 1 ________	____	____	______	____	____
Chem 2 ________	____	____	______	____	____
Chem 3 ________	____	____	______	____	____
Abrasives^	____	____	______	____	____
	Hours		Rate		
Labor†					
Class 1	____	____	______	____	____
Class 2	____	____	______	____	____
Class 3	____	____	______	____	____
Other	____	____	______	____	____
Equipment (door to door)	Hours		Rate		
Unit 1	____	____	______	____	____
Unit 2	____	____	______	____	____
Unit 3	____	____	______	____	____
Unit 4	____	____	______	____	____
Average traffic speed	mi/hr		Totals	____	____
on test	____				
on control		____			

Summary of actions — Hour

- Call-out time ______
- Start of storm ______
- End of storm ______
- End of clean-up ______

Estimate of other costs

- Dispatchers ______
- Reduction of patrols ______
- Other significant costs ______→What are they?____________________

*Total cost includes purchase cost, transportation to storage site, storage, truck loading, handling and mixing of solid chemicals, solution preparation of liquid chemicals.

^Include both materials costs and clean-up costs.

†Fully burdened labor costs; use flat rate.

Figure 78. Cost data form.

Results of individual storms are contained in the subsequent tables of this chapter, which are divided into parts to distinguish different types of analyses and results. Parts a-e and k of the tables present results of analysis of the data submitted on the cost data forms (item 1. in list above), whereas parts f-j present results of analysis of the driving lane operations and effectiveness data from field evaluation storm data packages (item 2. above). Part l of the tables contains cost results of full-season analyses (item 3. above), while the corresponding effectiveness, precipitation, and pavement temperature data of the five States are presented in chapter 5. The full-season results are included to provide a wider context in which to view the driving lane cost analysis. Data histories and operations summaries of many of the individual storms of the cost analysis are contained in chapter 5, while data histories of the remaining storms are presented in appendix C (see table 58).

To completely describe the cost analysis tables, the individual parts must be identified. Parts a-c tabulate labor and equipment effort in hours, materials consumed in treatment of the test and control sections, and unit and total costs for each of these categories and their sum, for the selected storms. Since the sections used by each State varied in length, part d lists the cost per lane-kilometer based on the data described. For the New York data this part also includes the cost per lane-kilometer per hour of operation. This analysis was included for New York because, unlike the other sites, the test and control operations were nearly full patrol-section operations and thus provided realistic cost per time information for the level of service at that site. Part e of each table gives the ratio of test to control costs for the section lengths represented. Driving lane operations and material use and costs are tabulated in part f of each table, as is the ratio of test to control material costs. Parts g and h present pavement condition observation and friction measurement statistics from the driving lane as measures of the effectiveness achieved, while parts i and j present precipitation and pavement temperature data as statistical measures of the conditions influencing the material used on the test and control section driving lanes. Parts i and j supplement the data histories as a source of information on the storm conditions influencing the costs. Part k lists vehicle speed information for sites where data were available (it is left out when this information was not available). Part l lists full-season costs of the driving lane material use corresponding to data presented in the previous chapter (in table 45, table 29, table 15, table 37, and table 32, respectively, for California, Nevada, New Hampshire, New York, and Wisconsin).

Nevada broke out the cost of abrasive clean-up, so these calculations are repeated for costs with and without clean-up. New York included the cost of clean-up in the reported sand/salt mix cost. (California and New Hampshire did not perform road clean-up at their experimental sites, while Wisconsin did not use abrasives in the storms analyzed.)

6.3 RESULTS

Results with the tabulations described above are presented here in table 59 a-l for California, table 60 a-l for Nevada, table 61 a-l for New Hampshire, table 62 a-l for New York, and table 63 a-l for Wisconsin. Of the 30 events contained in the tables, only 8 showed test section total costs (labor, equipment, and materials) equal to or less than control section costs. These are from one storm in California, three in Nevada (including cost of abrasive clean-up), and four in New York. Considering only the ratio of test to control section material costs presents a different picture: all but 4 of the 11 events in New York showed equal or lower material costs on the test section compared to the control, and Nevada again had three. This section describes some conclusions that can be drawn from the State data.

Table 59. Cost-analysis spreadsheet, California storms.

a. Labor

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
TEST SECTION						
Labor 1 (h)	4.25	3.5	1.75	1.75	1.25	
Unit cost	$47.33	$47.33	$47.33	$47.33	$47.33	
Cost	$201.15	$165.66	$82.83	$82.83	$59.16	
Total labor cost	$201.15	$165.66	$82.83	$82.83	$59.16	$591.63
CONTROL SECTION						
Labor 1 (h)	4.25	4.5	2	1.75	1	
Unit cost	$47.33	$47.33	$47.33	$47.33	$47.33	
Cost	$201.15	$212.99	$94.66	$82.83	$47.33	
Total labor cost	$201.15	$212.99	$94.66	$82.83	$47.33	$638.96

b. Equipment

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
TEST SECTION						
Equipment 1 (h)	0.75	0.25	0.75	0.5	0.5	
Unit cost	$45.34	$45.34	$45.34	$45.34	$45.34	
Cost	$34.01	$11.34	$34.01	$22.67	$22.67	
Equipment 2 (h)	2	1.5	1	1.25	0.75	
Unit cost	$18.68	$18.68	$18.68	$18.68	$18.68	
Cost	$37.36	$28.02	$18.68	$23.35	$14.01	
Equipment 3 (h)	1.5	1.75	0	0	0	
Unit cost	$34.41	$34.41	$34.41	$34.41	$34.41	
Cost	$51.61	$60.21	$0.00	$0.00	$0.00	
Total equipment cost	$122.97	$99.57	$52.68	$46.02	$36.68	$357.92
CONTROL SECTION						
Equipment 1 (h)	2.75	2.25	1.75	1.75	1	
Unit cost	$18.68	$18.68	$18.68	$18.68	$18.68	
Cost	$51.36	$42.03	$32.69	$32.69	$18.68	
Equipment 2 (h)	1.5	1.75	0.25	0	0	
Unit cost	$34.41	$34.41	$34.41	$34.41	$34.41	
Cost	$51.61	$60.21	$8.60	$0.00	$0.00	
Total equipment cost	$102.98	$102.24	$41.29	$32.69	$18.68	$297.87

c. Materials

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
TEST SECTION						
$MgCl_2$ solution (L)	1136	379	1160	757	413	3844
Unit cost	$0.137	$0.137	$0.137	$0.137	$0.137	
Cost	$156.00	$52.00	$159.33	$104.00	$56.73	$528.06
Abrasive (t)	5.1	4.7	1.5	1.8	1.1	14.2
Unit cost	$11.30	$11.30	$11.30	$11.30	$11.30	
Cost	$57.40	$53.30	$16.40	$20.50	$12.30	$159.90
Total material cost	$213.40	$105.30	$175.73	$124.50	$69.03	$687.96
CONTROL SECTION						
Salt (t)	0.5	0.9	0.5	0.4	0.2	2.5
Unit cost	$55.00	$55.00	$55.00	$55.00	$55.00	
Cost	$29.94	$49.90	$29.94	$19.96	$9.98	$139.72
Abrasive (t)	5.1	4.7	1.8	1.8	1.1	14.5
Unit cost	$11.30	$11.30	$11.30	$11.30	$11.30	
Cost	$57.40	$53.30	$20.50	$20.50	$12.30	$164.00
Total material cost	$87.34	$103.20	$50.44	$40.46	$22.28	$303.72

Table 59. Cost-analysis spreadsheet, California storms (continued).

d. Cost per section area (cost/lane-km)

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
TEST SECTION, 6.4 lane-km area						
Labor	$31.25	$25.73	$12.87	$12.87	$9.19	$91.90
Equipment	$19.10	$15.47	$8.18	$7.15	$5.70	$55.60
Materials	$33.15	$16.36	$27.30	$19.34	$10.72	$106.87
Labor, equipment and materials	$83.50	$57.56	$48.35	$39.36	$25.61	$254.38
CONTROL SECTION, 6.4 lane-km area						
Labor	$31.25	$33.09	$14.70	$12.87	$7.35	$99.26
Equipment	$16.00	$15.88	$6.41	$5.08	$2.90	$46.27
Materials	$13.57	$16.03	$7.84	$6.29	$3.46	$47.18
Labor, equipment and materials	$60.81	$65.00	$28.95	$24.23	$13.71	$192.71

e. Test/control cost ratios (considering costs per section area)

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
Labor	1.0	0.8	0.9	1.0	1.3	0.9
Equipment	1.2	1.0	1.3	1.4	2.0	1.2
Materials	2.4	1.0	3.5	3.1	3.1	2.3
Labor, equipment and materials	1.4	0.9	1.7	1.6	1.9	1.3

f. Driving lane operations and material use

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A	Total
TEST SECTION						
total number of passes	17	15	7	6	6	51
number of passes with plowing	1	1	2	2	2	8
number of passes applying $MgCl_2$ solution	3	2	2	1	1	9
total application $MgCl_2$ solute (kg/lane-km)	63	43	42	21	21	191
cost of $MgCl_2$ solution (/lane-km)	$27.18	$18.36	$18.12	$9.18	$9.12	$81.96
number of passes with rock salt application	0	2	0	0	0	2
total application rock salt (kg/lane-km)	0	56	0	0	0	56
cost of rock salt (/lane-km)	$0.00	$3.10	$0.00	$0.00	$0.00	$3.10
number of passes with abrasives application	14	11	4	5	3	37
total application abrasives (kg/lane-km)	789	620	225	282	169	2086
cost of abrasives (/lane-km)	$8.92	$7.01	$2.55	$3.18	$1.91	$23.57
total cost of materials (/lane-km)	$36.09	$28.47	$20.67	$12.36	$11.03	$108.62
CONTROL SECTION						
total number of passes	17	15	8	7	6	53
number of passes with plowing	0	0	1	2	2	5
number of passes applying $MgCl_2$ solution	0	0	0	0	0	0
total application $MgCl_2$ solute (kg/lane-km)	0	0	0	0	0	0
cost of $MgCl_2$ solution (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
number of passes with rock salt application	3	3	2	2	1	11
total application rock salt (kg/lane-km)	85	85	56	56	28	310
cost of rock salt (/lane-km)	$4.65	$4.65	$3.10	$3.10	$1.55	$17.05
number of passes with abrasives application	14	12	5	5	3	39
total application abrasives (kg/lane-km)	789	676	282	282	169	2198
cost of abrasives (/lane-km)	$8.92	$7.64	$3.18	$3.18	$1.91	$24.84
total cost of materials (/lane-km)	$13.57	$12.29	$6.29	$6.29	$3.46	$41.89
Test/Control Material Cost Ratio	2.7	2.3	3.3	2.0	3.2	2.6

Table 59. Cost-analysis spreadsheet, California storms (continued).

g. Driving lane pavement condition observations (percent of all section observations)

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A
TEST SECTION					
dry/damp	26				
wet	11	5	47	22	7
slush	37	35	28	39	7
loose snow	5	35	6	38	50
packed snow	5	10	19		36
frost					
black/glaze ice	16	15			
total percent	100	100	100	100	100
CONTROL SECTION					
dry/damp	26				
wet	16	5	44	22	7
slush	37	20	25	56	7
loose snow	0	40	6	22	43
packed snow	5	20	25		43
frost	16				
black/glaze ice		15			
total percent	100	100	100	100	100
Significant difference in test and control?	no	yes	no	yes	no

h. Driving lane friction measurement statistics

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A
TEST SECTION					
25th percentile of friction values	0.16	0.13	0.14	0.21	0.12
Median of friction values	0.26	0.15	0.22	0.24	0.14
75th percentile of friction values	0.29	0.18	0.30	0.27	0.20
CONTROL SECTION					
25th percentile of friction values	0.17	0.12	0.14	0.20	0.09
Median of friction values	0.24	0.14	0.22	0.23	0.12
75th percentile of friction values	0.28	0.17	0.29	0.26	0.16
Significant difference in test and control?	no	yes	no	no	yes
Test median friction greater than control?	yes	yes	no	yes	yes

i. Precipitation observations at times of friction measurements (percent of all section observations)

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A
TEST SECTION					
none	32	15			21
light rain or rain				6	
freezing rain					
sleet				6	
light snow	63	55	25	89	36
snow or blowing snow	5	30	75	0	43
total percent	100	100	100	100	100
CONTROL SECTION					
none	37	20			21
light rain or rain				6	
freezing rain					
sleet				6	
light snow	58	55	25	84	36
snow or blowing snow	5	25	75	6	43
total percent	100	100	100	100	100
Significant difference in test and control?	no	no	no	no	no

Table 59. Cost-analysis spreadsheet, California storms (continued).

j. Pavement temperatures at times of friction measurements (percent of all section observations)

Storm Dates and ID	12/5-7/94 CA412A	12/11-12/94 CA412B	12/13-14/94 CA412C	1/22-23/95 CA501B	3/22-23/95 CA503A
TEST SECTION					
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)					
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)					
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)					64
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	95	95	94	94	32
$T_p > 0$ °C ($T_p > 32$ °F)	5	5	6	6	4
total percent	100	100	100	100	100
CONTROL SECTION					
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)					
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)					
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)					57
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	95	92	94	95	40
$T_p > 0$ °C ($T_p > 32$ °F)	5	8	6	6	3
total percent	100	100	100	100	100
Significant difference in test and control?	no	no	no	no	no

l. Winter 1994/1995, summary of material costs for documented driving lane operations of storms CA412A, CA412B, CA412C, CA501B, and CA503A

	test section	control section
cost of $MgCl_2$ solution /lane-km	\$81.97	\$0.00
(total cost /lane-mi)	(\$131.90)	(\$0.00)
cost of rock salt /lane-km	\$3.10	\$17.06
(total cost /lane-mi)	(\$4.99)	(\$27.45)
cost of abrasives /lane-km	\$23.57	\$24.84
(total cost /lane-mi)	(\$37.93)	(\$39.98)
total material cost /lane-km	\$108.65	\$41.90
(total material cost /lane-mi)	(\$174.81)	(\$67.42)
test material cost/control material cost ratio:	2.6	

Table 60. Cost-analysis spreadsheet, Nevada storms.

a. Labor

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
TEST SECTION						
Labor 1 (h)	4	12	10	12	8	
Unit cost	$15.77	$15.77	$15.77	$15.77	$15.77	
Cost	$63.08	$189.24	$157.70	$189.24	$126.16	
Labor 2 (h)	0	0	0	4	8	
Unit cost	$16.37	$16.37	$16.37	$16.37	$13.80	
Cost	$0.00	$0.00	$0.00	$65.48	$110.40	
Total labor cost	$63.08	$189.24	$157.70	$254.72	$236.56	$901.30
CONTROL SECTION						
Labor 1 (h)	4	12	10	12	8	
Unit cost	$14.49	$15.77	$14.49	$15.77	$15.77	
Cost	$57.96	$189.24	$144.90	$189.24	$126.16	
Labor 2 (h)	0	0	0	12	8	
Unit cost	$13.28	$13.28	$13.28	$13.28	$10.87	
Cost	$0.00	$0.00	$0.00	$159.36	$86.96	
Labor 3 (h)	0	0	0	4.50	4.00	
Unit cost	$14.49	$14.49	$14.49	$14.49	$12.65	
Cost	$0.00	$0.00	$0.00	$65.21	$50.60	
Labor 4 (h)	0	0	0	4.50	0.00	
Unit cost	$8.21	$8.21	$8.21	$8.21		
Cost	$0.00	$0.00	$0.00	$36.95	$0.00	
Total labor cost	$57.96	$189.24	$144.90	$450.75	$263.72	$1,106.57

b. Equipment

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
TEST SECTION						
Equipment 1 (h)	4	12	10	16	16	
Unit cost	$16.61	$16.61	$16.61	$16.61	$16.61	
Cost	$66.44	$199.32	$166.10	$265.76	$265.76	
Total equipment cost	$66.44	$199.32	$166.10	$265.76	$265.76	$963.38
CONTROL SECTION						
Equipment 1 (h)	4	12	10	16	20	
Unit cost	$12.25	$12.25	$12.25	$12.25	$12.25	
Cost	$49.00	$147.00	$122.50	$196.00	$245.00	
Total equipment cost	$49.00	$147.00	$122.50	$196.00	$245.00	$759.50

Table 60. Cost-analysis spreadsheet, Nevada storms (continued).

c. Materials

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
TEST SECTION without cost of sand cleanup						
$MgCl_2$ solution (L)	1499	4278	3199	10258	11106	30340
Unit cost	$0.145	$0.145	$0.145	$0.145	$0.145	
Cost	$217.80	$621.50	$464.75	$1,490.50	$1,613.70	$4,408.25
1:5 salt/sand mix (t)	0	0	0	0	10.3	10.3
Unit cost	$12.61	$12.61	$12.61	$12.61	$13.67	
Cost	$0.00	$0.00	$0.00	$0.00	$141.36	$141.36
Total material cost	$217.80	$621.50	$464.75	$1,490.50	$1,755.06	$4,549.61
TEST SECTION with estimated cost of sand cleanup						
$MgCl_2$ solution (L)	1499	4278	3199	10258	11106	30340
Unit cost	$0.145	$0.145	$0.145	$0.145	$0.145	
Cost	$217.80	$621.50	$464.75	$1,490.50	$1,613.70	$4,408.25
1:5 salt/sand mix (t)	0	0	0	0	10.3	10.3
Unit cost	$37.10	$37.10	$37.10	$38.16	$38.16	
Cost	$0.00	$0.00	$0.00	$0.00	$394.62	$394.62
Total material cost	$217.80	$621.50	$464.75	$1,490.50	$2,008.32	$4,802.87
CONTROL SECTION without cost of sand cleanup						
1:5 salt/sand mix (t)	18.3	13.3	26.4	38.7	34.8	131.5
Unit cost	$12.61	$12.61	$12.61	$13.67	$13.67	
Cost	$230.97	$167.48	$332.68	$529.23	$475.04	$1,735.41
Total material cost	$230.97	$167.48	$332.68	$529.23	$475.04	$1,735.41
CONTROL SECTION with estimated cost of sand cleanup						
1:5 salt/sand mix (t)	18.3	13.3	26.4	38.7	34.8	131.5
Unit cost	$37.10	$37.10	$38.16	$38.16	$38.16	
Cost	$679.52	$492.73	$1,006.64	$1,477.42	$1,326.14	$4,982.44
Total material cost	$679.52	$492.73	$1,006.64	$1,477.42	$1,326.14	$4,982.44

d. Cost per section area (cost/lane-km)

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
TEST SECTION, 19 lane-km area						
Labor	$3.27	$9.80	$8.17	$13.19	$12.25	$46.67
Equipment	$3.44	$10.32	$8.60	$13.76	$13.76	$49.88
Materials (without cleanup)	$11.28	$32.18	$24.07	$77.18	$90.88	$235.58
Materials (with cleanup)	$11.28	$32.18	$24.07	$77.18	$103.99	$248.70
Labor, equipment and materials (without cleanup)	$17.98	$52.30	$40.83	$104.13	$116.89	$332.14
Labor, equipment and materials (with cleanup)	$17.98	$52.30	$40.83	$104.13	$130.00	$345.25
CONTROL SECTION, 19 lane-km area						
Labor	$3.00	$9.80	$7.50	$23.34	$13.66	$57.30
Equipment	$2.54	$7.61	$6.34	$10.15	$12.69	$39.33
Materials (without cleanup)	$11.96	$8.67	$17.23	$27.40	$24.60	$89.86
Materials (with cleanup)	$35.19	$25.51	$52.12	$76.50	$68.67	$258.00
Labor, equipment and materials (without cleanup)	$17.50	$26.08	$31.07	$60.89	$50.94	$186.49
Labor, equipment and materials (with cleanup)	$40.72	$42.92	$65.97	$109.99	$95.01	$354.62

Table 60. Cost-analysis spreadsheet, Nevada storms (continued).

e. Test/control cost ratios (considering costs per section area)

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
Labor	1.1	1.0	1.1	0.6	0.9	0.8
Equipment	1.4	1.4	1.4	1.4	1.1	1.3
Materials (without cleanup)	0.9	3.7	1.4	2.8	3.7	2.6
Materials (with cleanup)	0.3	1.3	0.5	1.0	1.5	1.0
Labor, equipment and materials (without cleanup)	1.0	2.0	1.3	1.7	2.3	1.8
Labor, equipment and materials (with cleanup)	0.4	1.2	0.6	0.9	1.4	1.0

f. Driving lane operations and material use

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B	Total
TEST SECTION						
total number of passes	2	6	2	11	15	36
number of passes with plowing	1	3	0	5	9	18
number of passes applying $MgCl_2$ solution	1	3	2	6	7	19
total application $MgCl_2$ solute (kg/lane-km)	26	72	56	159	242	555
cost of $MgCl_2$ solution (/lane-km)	$11.96	$32.83	$25.30	$72.18	$109.50	$251.78
number of passes with rock salt application	0	0	0	0	1	1
total application rock salt (kg/lane-km)	0	0	0	0	89	89
cost of rock salt (/lane-km)	$0.00	$0.00	$0.00	$0.00	$2.85	$2.85
number of passes with abrasives application	0	0	0	0	1	1
total application abrasives (kg/lane-km)	0	0	0	0	446	446
cost of abrasives without cleanup (/lane-km)	$0.00	$0.00	$0.00	$0.00	$3.90	$3.90
cost of abrasives with cleanup (/lane-km)	$0.00	$0.00	$0.00	$0.00	$17.02	$17.02
cost of materials without cleanup (/lane-km)	$11.96	$32.83	$25.30	$72.18	$116.25	$258.53
cost of materials with cleanup (/lane-km)	$11.96	$32.83	$25.30	$72.18	$129.37	$271.65
CONTROL SECTION						
total number of passes	4	7	5	12	4	32
number of passes with plowing	2	4	0	6	3	15
number of passes applying $MgCl_2$ solution	1	0	0	0	0	1
total application $MgCl_2$ solute (kg/lane-km)	0	0	0	0	0	0
cost of $MgCl_2$ solution (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
number of passes with rock salt application	0	4	5	10	4	23
total application rock salt (kg/lane-km)	167	132	219	474	247	1239
cost of rock salt (/lane-km)	$5.33	$4.21	$6.99	$15.14	$7.87	$39.54
number of passes with abrasives application	0	4	5	10	4	23
total application abrasives (kg/lane-km)	834	657	1097	2367	1231	6186
cost of abrasives without cleanup (/lane-km)	$7.29	$5.75	$9.59	$20.69	$10.76	$54.07
cost of abrasives with cleanup (/lane-km)	$31.80	$25.07	$41.83	$90.27	$46.97	$235.93
cost of materials without cleanup (/lane-km)	$12.61	$9.96	$16.58	$35.83	$18.64	$93.61
cost of materials with cleanup (/lane-km)	$37.12	$29.28	$48.82	$105.41	$54.84	$275.47
Test/Control Material Cost Ratio						
without cleanup	0.9	3.3	1.5	2.0	6.2	2.8
with cleanup	0.3	1.1	0.5	0.7	2.4	1.0

Table 60. Cost-analysis spreadsheet, Nevada storms (continued).

g. Driving lane pavement condition observations (percent of all section observations)

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B
TEST SECTION					
dry/damp				3	0
wet		75		37	39
slush		25		9	13
loose snow				8	5
packed snow				42	37
frost					
black/glaze ice				0	6
total percent		100		100	100
CONTROL SECTION					
dry/damp					
wet		61		22	25
slush		39		14	15
loose snow				16	12
packed snow				44	45
frost					
black/glaze ice				4	3
total percent		100		100	100
Significant difference in test and control?		yes		yes	yes

h. Driving lane friction measurement statistics

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B
TEST SECTION					
25th percentile of friction values		0.38		0.29	0.27
Median of friction values		0.40		0.32	0.32
75th percentile of friction values		0.43		0.39	0.41
CONTROL SECTION					
25th percentile of friction values		0.29		0.23	0.22
Median of friction values		0.33		0.27	0.25
75th percentile of friction values		0.37		0.33	0.35
Significant difference in test and control?		yes		yes	yes
Test median friction greater than control?		yes		yes	yes

i. Precipitation observations at times of friction measurements (percent of all section observations)

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B
TEST SECTION					
none		11		29	30
light rain or rain		25			
freezing rain					
sleet		11			
light snow		23		30	25
snow or blowing snow		30		42	45
total percent		100		100	100
CONTROL SECTION					
none		13		35	33
light rain or rain		24			
freezing rain					
sleet		9			
light snow		19		18	13
snow or blowing snow		35		47	53
total percent		100		100	100
Significant difference in test and control?		no		no	yes

Table 60. Cost-analysis spreadsheet, Nevada storms (continued).

j. Pavement temperatures at times of friction measurements (percent of all section observations)

Storm Dates and ID	12/11-12/94 NV412A	1/6-7/95 NV501B	1/26-27/95 NV501G	2/13-14/95 NV502A	3/22-23/95 NV503B
TEST SECTION					
$T_p \le -13.3$ °C ($T_p \le 8$ °F)					
-13.3 °C $< T_p \le -10$ °C (8 °F $< T_p \le 14$ °F)					
-10 °C $< T_p \le -6.7$ °C (14 °F $< T_p \le 20$ °F)					
-6.7 °C $< T_p \le -3.3$ °C (20 °F $< T_p \le 26$ °F)				17	4
-3.3 °C $< T_p \le 0$ °C (26 °F $< T_p \le 32$ °F)		72		67	67
$T_p > 0$ °C ($T_p > 32$ °F)		28		16	29
total percent		100		100	100
CONTROL SECTION					
$T_p \le -13.3$ °C ($T_p \le 8$ °F)					
-13.3 °C $< T_p \le -10$ °C (8 °F $< T_p \le 14$ °F)					
-10 °C $< T_p \le -6.7$ °C (14 °F $< T_p \le 20$ °F)					
-6.7 °C $< T_p \le -3.3$ °C (20 °F $< T_p \le 26$ °F)				17	6
-3.3 °C $< T_p \le 0$ °C (26 °F $< T_p \le 32$ °F)		76		70	64
$T_p > 0$ °C ($T_p > 32$ °F)		24		13	30
total percent		100		100	100
Significant difference in test and control?		no		no	no

l. Winter 1994/1995, summary of material costs for documented driving lane operations of storms NV411A, NV411B, NV412A, NV412B, NV412C, NV501A, NV501B, NV501C, NV501D, NV501F, NV501G, NV502A, NV503A, and NV503B

	test section	control section
cost of MgCl2 solution /lane-km (total cost /lane-mi)	\$515.36 (\$829.22)	\$0.00 (\$0.00)
cost of rock salt /lane-km (total cost /lane-mi)	\$6.01 (\$9.67)	\$79.31 (\$127.60)
cost of abrasives *without cleanup* /lane-km (total cost /lane-mi)	\$8.21 (\$13.21)	\$108.48 (\$174.54)
cost of abrasives *with cleanup* (estimated) /lane-km (total cost /lane-mi)	\$35.83 (\$57.64)	\$473.30 (\$761.54)
total material cost *without cleanup* /lane-km (total material cost /lane-mi)	\$529.59 (\$852.10)	\$187.78 (\$302.14)
total material cost *with cleanup* /lane-km (total material cost /lane-mi)	\$557.20 (\$896.54)	\$552.61 (\$889.14)
test material cost/control material cost ratio, without cleanup:	2.8	
test material cost/control material cost ratio, with cleanup:	1.0	

Table 61. Cost-analysis spreadsheet, New Hampshire storms.

a. Labor

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
TEST SECTION						
Labor 1 (h)	12.5	13	6	10	12	
Unit cost	$14.45	$14.45	$14.45	$14.45	$14.45	
Cost	$180.63	$187.85	$86.70	$144.50	$173.40	
Total labor cost	$180.63	$187.85	$86.70	$144.50	$173.40	$773.08
CONTROL SECTION						
Labor 1 (h)	3	7.2	5	3	6.2	
Unit cost	$14.45	$14.45	$14.45	$14.45	$14.45	
Cost	$43.35	$104.04	$72.25	$43.35	$89.59	
Total labor cost	$43.35	$104.04	$72.25	$43.35	$89.59	$352.58

b. Equipment

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
TEST SECTION						
Equipment 1 (h)	7.5	8	3	2	2	
Unit cost	$24.41	$24.41	$24.41	$24.41	$24.41	
Cost	$183.08	$195.28	$73.23	$48.82	$48.82	
Equipment 2 (h)	5	5	3	1	4	
Unit cost	$12.27	$12.27	$12.27	$12.27	$12.27	
Cost	$61.35	$61.35	$36.81	$12.27	$49.08	
Equipment 3 (h)	0	0	27	7	6	
Unit cost	$12.21	$12.21	$12.21	$12.21	$12.21	
Cost	$0.00	$0.00	$329.67	$85.47	$73.26	
Total equipment cost	$244.43	$256.63	$439.71	$146.56	$171.16	$1,258.49
CONTROL SECTION						
Equipment 1 (h)	3	7.2	5	3	6.2	
Unit cost	$12.27	$12.27	$12.27	$12.27	$12.27	
Cost	$36.81	$88.34	$61.35	$36.81	$76.07	
Total equipment cost	$36.81	$88.34	$61.35	$36.81	$76.07	$299.39

c. Materials

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
TEST SECTION						
KAc solution (t)	2.1	2.2	4.1	2.1	2.1	12.6
Unit cost	$747.13	$747.13	$747.13	$747.13	$747.13	
Cost	$1,565.72	$1,619.94	$3,097.55	$1,531.83	$1,565.72	$9,380.75
Salt (t)	5.4	8.2	3.6	1.8	3.6	22.7
Unit cost	$46.51	$46.51	$46.51	$46.51	$46.51	
Cost	$253.14	$379.71	$168.76	$84.38	$168.76	$1,054.75
Abrasive (t)	0	13.6	2.7	0	0	16.3
Unit cost	$3.86	$3.86	$3.86	$3.86	$3.86	
Cost	$0.00	$52.50	$10.50	$0.00	$0.00	$63.00
Total material cost	$1,818.86	$2,052.15	$3,276.81	$1,616.21	$1,734.48	$9,443.75
CONTROL SECTION						
Salt (t)	2.3	2.7	0	2.4	2.3	9.7
Unit cost	$46.51	$46.51	$46.51	$46.51	$46.51	
Cost	$107.58	$126.57	$0.00	$109.69	$105.48	$449.32
Abrasive (t)	1.8	1.8	1.8	0.9	1.9	8.3
Unit cost	$3.86	$3.86	$3.86	$3.86	$3.86	
Cost	$7.00	$7.00	$7.00	$3.50	$7.35	$31.85
Total material cost	$114.58	$133.57	$7.00	$113.19	$112.83	$481.17

Table 61. Cost-analysis spreadsheet, New Hampshire storms (continued).

d. Cost per section area (cost/lane-km)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
TEST SECTION, 16 lane-km area						
Labor	$11.22	$11.67	$5.39	$8.98	$10.77	$48.04
Equipment	$15.19	$15.95	$27.32	$9.11	$10.64	$78.20
Materials	$113.02	$127.52	$203.61	$100.43	$107.78	$586.81
Labor, equipment and materials	$139.43	$155.13	$236.32	$118.51	$129.19	$713.04
CONTROL SECTION, 12 lane-km area						
Labor	$3.74	$8.98	$6.24	$3.74	$7.73	$30.43
Equipment	$3.18	$7.62	$5.29	$3.18	$6.57	$25.84
Materials	$9.89	$11.53	$0.60	$9.77	$9.74	$41.53
Labor, equipment and materials	$16.81	$28.13	$12.13	$16.69	$24.03	$97.79

e. Test/control cost ratios (considering costs per section area)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
Labor	3.0	1.3	0.9	2.4	1.4	1.6
Equipment	4.8	2.1	5.2	2.9	1.6	3.0
Materials	11.4	11.1	337.0	10.3	11.1	14.1
Labor, equipment and materials	8.3	5.5	19.5	7.1	5.4	7.3

f. Driving lane operations and material use

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C	Total
TEST SECTION						
total number of passes	5	6	15	4	6	36
number of passes with plowing	4	5	14	3	5	31
number of passes applying KAc solution	1	1	1	1	1	5
total application KAc solute (kg/lane-km)	64	83	146	64	80	437
cost of KAc solution (/lane-mi)	$95.78	$124.74	$217.73	$95.78	$119.01	$653.03
number of passes with rock salt application	2	3	2	1	2	10
total application rock salt (kg/lane-km)	141	507	225	113	225	1212
cost of rock salt (/lane-mi)	$6.55	$23.59	$10.49	$5.24	$10.49	$56.36
number of passes with abrasives application	0	0	1	0	1	2
total application abrasives (kg/lane-km)	0	0	85	0	507	592
cost of abrasives (/lane-mi)	$0.00	$0.00	$0.33	$0.00	$1.96	$2.28
total cost of materials (/lane-mi)	$102.33	$148.33	$228.55	$101.02	$131.45	$711.68
CONTROL SECTION						
total number of passes	4	8	5	5	4	26
number of passes with plowing	4	7	4	5	4	24
number of passes applying KAc solution	0	0	0	0	0	0
total application KAc solute (kg/lane-km)	0	0	0	0	0	0
cost of KAc solution (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
number of passes with rock salt application	3	4	1	2	3	13
total application rock salt (kg/lane-km)	261	331	78	162	233	1064
cost of rock salt (/lane-km)	$12.12	$15.40	$3.60	$7.54	$10.81	$49.48
number of passes with abrasives application	1	2	3	1	1	8
total application abrasives (kg/lane-km)	61	159	324	113	92	748
cost of abrasives (/lane-km)	$0.23	$0.61	$1.25	$0.43	$0.35	$2.89
total cost of materials (/lane-km)	$12.36	$16.02	$4.86	$7.97	$11.17	$52.37
Test/Control Material Cost Ratio	8.3	9.3	47.1	12.7	11.8	13.6

Table 61. Cost-analysis spreadsheet, New Hampshire storms (continued).

g. Driving lane pavement condition observations (percent of all section observations)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C
TEST SECTION					
dry/damp	10	35	6	15	2
wet		2	6	4	
slush	10	5	6	26	12
loose snow	69	45	62	42	86
packed snow	10	6	21	14	
frost					
black/glaze ice		8	0		0
total percent	100	100	100	100	100
CONTROL SECTION					
dry/damp	12	33	11	15	4
wet		1	3	1	
slush	0	6	7	24	12
loose snow	54	52	53	59	80
packed snow	34	1	26	1	
frost					
black/glaze ice		8	1		3
total percent	100	100	100	100	100
Significant difference in test and control?	yes	no	no	yes	no

h. Driving lane friction measurement statistics

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C
TEST SECTION					
25th percentile of friction values	0.23	0.33	0.25	0.23	0.26
Median of friction values	0.26	0.38	0.29	0.26	0.30
75th percentile of friction values	0.32	0.49	0.32	0.35	0.33
CONTROL SECTION					
25th percentile of friction values	0.25	0.33	0.28	0.24	0.28
Median of friction values	0.26	0.39	0.31	0.27	0.30
75th percentile of friction values	0.29	0.52	0.47	0.31	0.33
Significant difference in test and control?	no	no	yes	no	no
Test median friction greater than control?	no	no	no	no	no

i. Precipitation observations at times of friction measurements (percent of all section observations)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C
TEST SECTION					
none		8	15	30	
light rain or rain		7		15	
freezing rain	21	8		16	52
sleet	46	7		9	
light snow	34	58	23	16	31
snow or blowing snow		13	61	15	17
total percent	100	100	100	100	100
CONTROL SECTION					
none		7	11	28	
light rain or rain		0		14	
freezing rain	34	7		8	45
sleet	32	7		16	
light snow	34	67	26	17	38
snow or blowing snow		12	63	16	17
total percent	100	100	100	100	100
Significant difference in test and control?	no	no	no	no	no

Table 61. Cost-analysis spreadsheet, New Hampshire storms (continued).

j. Pavement temperatures at times of friction measurements (percent of all section observations)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C
TEST SECTION					
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)					
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)		93	15		
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)	1	7	85		100
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	99			100	
$T_p > 0$ °C ($T_p > 32$ °F)					
total percent	100	100	100	100	100
CONTROL SECTION					
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)					
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)		93	15		
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)	11	7	85		100
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	89			100	
$T_p > 0$ °C ($T_p > 32$ °F)					
total percent	100	100	100	100	100
Significant difference in test and control?	no	no	no	no	no

k. Vehicle average speed (km/h)

Storm Dates and ID	1/6-7/95 NH501B	1/11-13/95 NH501C	2/4-5/95 NH502A	2/15-16/95 NH502B	2/27-28/95 NH502C
TEST SECTION					
southbound	81	74	81	84	105
northbound	68	74	81	71	61
CONTROL SECTION					
southbound	87	87	no data	101	69
northbound	82	81	76	122	77

l. Winter 1994/1995, summary of material costs for documented driving lane operations of storms NH501A, NH501B, NH501C, NH502A, NH502B, and NH502C

	test section	control section
cost of KAc solution /lane-km	$748.97	$0.00
(total cost /lane-mi)	($1,205.09)	($0.00)
cost of rock salt /lane-km	$59.65	$56.70
(total cost /lane-mi)	($95.98)	($91.24)
cost of abrasives /lane-km	$2.28	$3.70
(total cost /lane-mi)	($3.68)	($5.96)
total material cost /lane-km	$810.90	$60.41
(total material cost /lane-mi)	($1,304.75)	($97.19)
test material cost/control material cost ratio:	13.4	

Table 62. Cost-analysis spreadsheet, New York storms.

a. Labor

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
TEST SECTION												
total labor cost	$2,183.71	$1,712.02	$2,115.75	$758.26	$1,438.89	$3,945.51	$1,715.27	$739.41	$2,640.17	$612.95	$2,079.57	$19,941.51
CONTROL SECTION												
total labor cost	$1,739.82	$1,276.00	$1,882.75	$551.35	$1,242.69	$7,652.25	$1,330.21	$1,020.71	$2,667.22	$532.36	$2,594.30	$22,489.66

b. Equipment

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
TEST SECTION												
total equipment cost	$235.00	$310.25	$394.08	$79.20	$486.62	$1,530.33	$554.65	$112.05	$328.38	$676.38	$662.60	$5,369.54
CONTROL SECTION												
total equipment cost	$164.80	$275.90	$190.70	$50.58	$388.75	$1,733.43	$417.25	$77.70	$322.65	$527.25	$542.65	$4,691.66

c. Materials

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
TEST SECTION												
Coarse and fine salt (t)	5.9	11.2	18.5	2.6	10.2	20.2	19.7	2.5	6.1	29.5	32.2	158.7
Unit cost	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	
Cost	$177.76	$339.09	$559.30	$77.79	$308.14	$610.25	$595.18	$74.50	$183.24	$891.82	$973.17	
$CaCl_2$ solute (t)	1.1	1.6	1.8	0.3	1.4	1.5	1.1	0.5	0.8	3.4	3.8	17.3
Unit cost	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	
Cost	$87.91	$128.53	$146.26	$24.38	$110.07	$118.93	$90.86	$40.63	$67.96	$279.23	$310.99	
1:3 salt/sand mix (t)	0	0	0	0	3.1	26.9	0	0	10.7	2.2	0	43.0
Unit cost	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	
Cost	$0.00	$0.00	$0.00	$0.00	$112.36	$961.04	$0.00	$0.00	$383.38	$77.71	$0.00	
Total material cost	$265.67	$467.62	$705.57	$102.16	$530.56	$1,690.22	$686.04	$115.13	$634.58	$1,248.76	$1,284.16	$7,730.47
CONTROL SECTION												
Coarse salt (t)	9.0	16.1	22.6	2.7	11.4	24.7	26.3	3.2	5.8	30.1	38.8	190.8
Unit cost	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	$30.19	
Cost	$272.53	$485.08	$680.92	$81.90	$345.39	$745.01	$794.04	$98.06	$176.39	$908.53	$1,172.02	
$CaCl_2$ solute (t)	0	0	0	0	0	0	0	0	0	0	0	0
Unit cost	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	$81.43	
Cost	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	
1:3 salt/sand mix (t)	0	0	0	0	3.1	37.8	0	6.8	14.3	8.9	0	70.9
Unit cost	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	$35.69	
Cost	$0.00	$0.00	$0.00	$0.00	$111.71	$1,350.89	$0.00	$241.88	$508.69	$318.62	$0.00	
Total material cost	$272.53	$485.08	$680.92	$81.90	$457.10	$2,095.90	$794.04	$339.93	$685.08	$1,227.15	$1,172.02	$8,291.64

Table 62. Cost-analysis spreadsheet, New York storms (continued).

d. Cost per section area (cost/lane-km), and cost per section area per duration of operation (cost/lane-km-h)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
Call-out date	1/6	1/23	1/26	1/28	2/1	2/4	2/7	2/10	2/11	2/24	3/8	
Call-out time	19:27	18:00	0:30	16:00	17:45	2:00	17:00	10:00	12:00	0:00	6:00	
End of clean-up date	1/7	1/25	1/27	1/29	2/2	2/7	2/8	2/11	2/12	2/25	3/9	
End of clean-up time	19:30	4:00	11:30	0:00	21:00	16:45	17:30	7:30	16:45	1:00	14:30	
Duration (h)	24	34	35	8	27	87	24	22	29	25	32	347
TEST SECTION, 38 lane-km area												
Labor (cost/lane-km)	$56.81	$41.10	$48.90	$16.31	$29.92	$79.38	$33.43	$13.56	$47.03	$10.61	$35.03	$327.08
Equipment (cost/lane-km)	$6.11	$7.45	$9.11	$1.70	$10.12	$30.79	$10.81	$2.05	$5.85	$11.71	$11.16	$88.07
Materials (cost/lane-km)	$6.91	$11.23	$16.31	$2.20	$11.03	$34.01	$13.37	$2.11	$11.30	$21.62	$21.63	$126.80
Labor, equipment & materials (cost/lane-km)	$69.84	$59.77	$74.32	$20.21	$51.07	$144.18	$57.61	$17.73	$64.18	$43.95	$67.83	$541.95
Labor (cost/lane-km-h)	$2.36	$1.21	$1.40	$2.04	$1.10	$0.92	$1.36	$0.63	$1.64	$0.42	$1.08	$0.94
Equipment (cost/lane-km-h)	$0.25	$0.22	$0.26	$0.21	$0.37	$0.35	$0.44	$0.10	$0.20	$0.47	$0.34	$0.25
Materials (cost/lane-km-h)	$0.29	$0.33	$0.47	$0.27	$0.40	$0.39	$0.55	$0.10	$0.39	$0.86	$0.67	$0.37
Labor, equipment & materials (cost/lane-km-h)	$2.90	$1.76	$2.12	$2.53	$1.87	$1.66	$2.35	$0.82	$2.23	$1.76	$2.09	$1.56
CONTROL SECTION, 39 lane-km area												
Labor (cost/lane-km)	$44.41	$30.10	$42.79	$11.68	$25.45	$151.71	$25.56	$18.47	$46.89	$9.10	$43.17	$364.47
Equipment (cost/lane-km)	$4.21	$6.51	$4.33	$1.07	$7.96	$34.37	$8.02	$1.41	$5.67	$9.01	$9.03	$76.03
Materials (cost/lane-km)	$6.96	$11.44	$15.47	$1.73	$9.36	$41.55	$15.26	$6.15	$12.04	$20.98	$19.50	$134.37
Labor, equipment & materials (cost/lane-km)	$55.58	$48.05	$62.60	$14.48	$42.77	$227.63	$48.83	$26.02	$64.61	$39.10	$71.70	$574.88
Labor (cost/lane-km-h)	$1.85	$0.89	$1.22	$1.46	$0.93	$1.75	$1.04	$0.86	$1.63	$0.36	$1.33	$1.05
Equipment (cost/lane-km-h)	$0.17	$0.19	$0.12	$0.13	$0.29	$0.40	$0.33	$0.07	$0.20	$0.36	$0.28	$0.22
Materials (cost/lane-km-h)	$0.29	$0.34	$0.44	$0.22	$0.34	$0.48	$0.62	$0.29	$0.42	$0.84	$0.60	$0.39
Labor, equipment & materials (cost/lane-km-h)	$2.31	$1.41	$1.79	$1.81	$1.57	$2.62	$1.99	$1.21	$2.25	$1.56	$2.21	$1.66

e. Test/control cost ratios (considering costs per section area)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
Labor	1.3	1.4	1.1	1.4	1.2	0.5	1.3	0.7	1.0	1.2	0.8	0.9
Equipment	1.5	1.1	2.1	1.6	1.3	0.9	1.3	1.5	1.0	1.3	1.2	1.2
Materials	1.0	1.0	1.1	1.3	1.2	0.8	0.9	0.3	0.9	1.0	1.1	0.9
Labor, equipment and materials	1.3	1.2	1.2	1.4	1.2	0.6	1.2	0.7	1.0	1.1	0.9	0.9

Table 62. Cost-analysis spreadsheet, New York storms (continued).

f. Driving lane operations and material use

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B	Total
TEST SECTION												
total number of passes	5	7	15	1	7	43	16	1	8	6	23	132
number of passes with plowing	4	0	6	0	0	35	14	0	4	0	20	83
number of passes with fine salt application	4	7	8	1	5	12	6	1	5	4	17	70
total application fine salt (kg/lane-km)	161	199	210	28	141	366	236	28	142	113	665	2288
cost of fine salt (/lane-km)	$4.85	$6.01	$6.34	$0.85	$4.26	$11.05	$7.12	$0.85	$4.28	$3.41	$20.06	$69.08
number of passes with coarse salt application	0	0	5	0	2	13	2	0	2	2	5	31
total application coarse salt (kg/lane-km)	0	0	328	0	116	727	209	0	83	127	376	1967
cost of coarse salt (/lane-km)	$0.00	$0.00	$9.92	$0.00	$3.51	$21.94	$6.32	$0.00	$2.52	$3.83	$11.36	$59.39
number of passes applying $CaCl_2$ prewetting	4	7	8	1	5	9	5	1	5	4	17	66
total application $CaCl_2$ solute (kg/lane-km)	10	13	14	2	9	16	11	2	10	7	45	138
cost of $CaCl_2$ solution (/lane-km)	$0.84	$1.03	$1.11	$0.15	$0.73	$1.32	$0.88	$0.15	$0.78	$0.59	$3.68	$11.26
number of passes with abrasives application	0	0	0	0	1	7	0	0	1	0	0	9
total application abrasives (kg/lane-km)	0	0	0	0	95	823	0	0	95	0	0	1013
cost of abrasives (/lane-km)	$0.00	$0.00	$0.00	$0.00	$3.63	$31.33	$0.00	$0.00	$3.62	$0.00	$0.00	$38.58
total cost of materials (/lane-km)	$5.69	$7.05	$17.36	$1.00	$12.12	$65.64	$14.32	$1.00	$11.20	$7.82	$35.10	$178.31
CONTROL SECTION												
total number of passes	4	7	13	1	5	33	13	1	4	3	17	101
number of passes with plowing	1	0	5	0	0	21	12	0	2	0	14	55
number of passes with fine salt application	0	0	0	0	0	1	0	0	0	0	0	1
total application fine salt (kg/lane-km)	0	0	0	0	0	28	0	0	0	0	0	28
cost of fine salt (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.86	$0.00	$0.00	$0.00	$0.00	$0.00	$0.86
number of passes with coarse salt application	3	7	11	1	5	18	9	1	4	3	14	76
total application coarse salt (kg/lane-km)	158	497	694	62	295	1100	602	65	162	166	1141	4942
cost of coarse salt (/lane-km)	$4.77	$15.00	$20.95	$1.89	$8.92	$33.20	$18.17	$1.96	$4.88	$5.00	$34.46	$149.20
number of passes applying $CaCl_2$ prewetting	0	0	0	0	0	1	0	0	0	0	0	1
total application $CaCl_2$ solute (kg/lane-km)	0	0	0	0	0	2	0	0	0	0	0	2
cost of $CaCl_2$ solution (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.16	$0.00	$0.00	$0.00	$0.00	$0.00	$0.16
number of passes with abrasives application	0	0	0	0	1	6	0	0	2	0	0	9
total application abrasives (kg/lane-km)	0	0	0	0	94	895	0	0	190	0	0	1179
cost of abrasives (/lane-km)	$0.00	$0.00	$0.00	$0.00	$3.59	$34.06	$0.00	$0.00	$7.25	$0.00	$0.00	$44.90
total cost of materials (/lane-km)	$4.77	$15.00	$20.95	$1.89	$12.51	$68.27	$18.17	$1.96	$12.13	$5.00	$34.46	$195.11
Test/Control Material Cost Ratio	1.2	0.5	0.8	0.5	1.0	1.0	0.8	0.5	0.9	1.6	1.0	0.9

Table 62. Cost-analysis spreadsheet, New York storms (continued).

g. Driving lane pavement condition observations (percent of all section observations)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B
TEST SECTION											
dry/damp			11			5	4		26	6	5
wet	66	94	27		57	14	28		31	57	28
slush	3	6	14		5	10	15			16	32
loose snow	26	0	27		13	52	21		44	21	27
packed snow	5		3		22	8	2				5
frost						1					
black/glaze ice			18		3	11	30				3
total percent	100	100	100		100	100	100		100	100	100
CONTROL SECTION											
dry/damp			5			6	4		27	6	3
wet	81	94	33		67	17	33		31	68	24
slush	0	6	8		8	5	22			20	40
loose snow	12	1	38		17	58	21		42	7	28
packed snow	7		3		8	8	0				5
frost						0					
black/glaze ice			13		0	7	20				0
total percent	100	100	100		100	100	100		100	100	100
Significant difference in test and control?	yes	no	no		yes	yes	yes		no	yes	yes

h. Driving lane friction measurement statistics

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B
TEST SECTION											
25th percentile of friction values	0.28	0.37	0.18		0.26	0.22	0.20		0.19	0.25	0.21
Median of friction values	0.40	0.40	0.21		0.40	0.28	0.25		0.22	0.31	0.25
75th percentile of friction values	0.46	0.42	0.28		0.47	0.36	0.30		0.25	0.40	0.31
CONTROL SECTION											
25th percentile of friction values	0.36	0.37	0.19		0.32	0.24	0.23		0.20	0.26	0.21
Median of friction values	0.43	0.41	0.21		0.42	0.29	0.29		0.23	0.32	0.25
75th percentile of friction values	0.47	0.45	0.29		0.47	0.36	0.33		0.25	0.42	0.31
Significant difference in test and control?	no	no	no		yes	yes	yes		yes	no	no
Test median friction greater than control?	no	no	no		no	no	no		no	no	no

Table 62. Cost-analysis spreadsheet, New York storms (continued).

i. Precipitation observations at times of friction measurements (percent of all section observations)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B
TEST SECTION											
none	58	41	5		30	16	32		23	40	5
light rain or rain											
freezing rain		1								1	
sleet											
light snow	30	50	59		59	41	40		8	17	33
snow or blowing snow	12	9	36		11	43	29		69	41	62
total percent	100	100	100		100	100	100		100	100	100
CONTROL SECTION											
none	52	17	5		30	17	28		18	45	0
light rain or rain											
freezing rain		0								0	
sleet											
light snow	35	80	58		63	37	53		13	22	27
snow or blowing snow	13	3	37		8	46	20		69	33	74
total percent	100	100	100		100	100	100		100	100	100
Significant difference in test and control?	no	yes	no		no	no	yes		no	yes	yes

j. Pavement temperatures at times of friction measurements (percent of all section observations)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B
TEST SECTION											
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)						14					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)						31			22		
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)						18	46		17		
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)	1				23	20	36		34	18	45
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	99	55	100		66	13	18		17	36	42
$T_p > 0$ °C ($T_p > 32$ °F)		45			12	4			11	46	13
total percent	100	100	100		100	100	100		100	100	100
CONTROL SECTION											
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)						14					
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)						32			19		
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)						18	51		16		
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)	7				19	21	35		38	17	45
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)	93	55	100		69	12	14		15	32	44
$T_p > 0$ °C ($T_p > 32$ °F)		45			12	3			12	50	11
total percent	100	100	100		100	100	100		100	100	100
Significant difference in test and control?	no	no	no		no	no	no		no	no	no

Table 62. Cost-analysis spreadsheet, New York storms (continued).

k. Vehicle average speed (km/h)

Storm Start Date and ID	1/6/95 NY501A	1/23/95 NY501F	1/25/95 NY501G	1/28/95 NY501H	2/1/95 NY502A	2/4/95 NY502B	2/7/95 NY502C	2/10/95 NY502E	2/11/95 NY502F	2/23/95 NY502H	3/8/95 NY503B
TEST SECTION	98				98	93	82	95		95	87
CONTROL SECTION	98				97	90	84	92		95	90

l. Winter 1994/1995, summary of material costs for documented driving lane operations of storms NY501A, NY501D, NY501F, NY501G, NY501H, NY502A, NY502B, NY502C, NY502E, NY502F, NY502H, and NY503B

	Test section	Control section
cost of fine salt /lane-km	$70.80	$0.86
(total cost /lane-mi)	($113.92)	($1.38)
cost of rock salt /lane-km	$59.40	$154.32
(total cost /lane-mi)	($95.58)	($248.30)
cost of $CaCl_2$ prewetting solution /lane-km	$11.55	$0.16
(total cost /lane-mi)	($18.59)	($0.25)
cost of abrasives /lane-km	$38.59	$44.91
(total cost /lane-mi)	($62.09)	($72.26)
total material cost /lane-km	$180.34	$200.24
(total material cost /lane-mi)	($290.17)	($322.19)
test material cost/control material cost ratio:	0.9	

Table 63. Cost-analysis spreadsheet, Wisconsin storms.

a. Labor

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
TEST SECTION					
Labor 1 (h)	8	3	5	0	
Unit cost	$23.30	$23.30	$23.30	$23.30	
Cost	$186.40	$69.90	$116.50	$0.00	
Labor 2 (h)	0	6.5	4.5	3	
Unit cost	$34.95	$34.95	$34.95	$34.95	
Cost	$0.00	$227.18	$157.28	$104.85	
Labor 3 (h)	0	0	0	10	
Unit cost	$46.60	$46.60	$46.60	$46.60	
Cost	$0.00	$0.00	$0.00	$466.00	
Total labor cost	$186.40	$297.08	$273.78	$570.85	$1,328.10
CONTROL SECTION					
Labor 1 (h)	3	2	2.5	0	
Unit cost	$23.30	$23.30	$23.30	$23.30	
Cost	$69.90	$46.60	$58.25	$0.00	
Labor 2 (h)	0	3.5	2	0	
Unit cost	$34.95	$34.95	$34.95	$34.95	
Cost	$0.00	$122.33	$69.90	$0.00	
Labor 3 (h)	0	0	0	6	
Unit cost	$46.60	$46.60	$46.60	$46.60	
Cost	$0.00	$0.00	$0.00	$279.60	
Total labor cost	$69.90	$168.93	$128.15	$279.60	$646.58

b. Equipment

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
TEST SECTION					
Equipment 1 (h)	0	0	3	2.5	
Unit cost	$27.88	$27.88	$27.88	$27.88	
Cost	$0.00	$0.00	$83.64	$69.70	
Equipment 2 (h)	0	0	2	2.5	
Unit cost	$3.86	$3.86	$3.86	$3.86	
Cost	$0.00	$0.00	$7.72	$9.65	
Equipment 3 (h)	4	4	7	6	
Unit cost	$18.94	$18.94	$18.94	$18.94	
Cost	$75.76	$75.76	$132.58	$113.64	
Total equipment cost	$75.76	$75.76	$223.94	$192.99	$568.45
CONTROL SECTION					
Equipment 1 (h)	3	5.5	4	5	
Unit cost	$27.88	$27.88	$27.88	$27.88	
Cost	$83.64	$153.34	$111.52	$139.40	
Equipment 2 (h)	0	3.5	2	4	
Unit cost	$3.86	$3.86	$3.86	$3.86	
Cost	$0.00	$13.51	$7.72	$15.44	
Equipment 3 (h)	3	2	3	4	
Unit cost	$1.82	$1.82	$1.82	$1.82	
Cost	$5.46	$3.64	$5.46	$7.28	
Total equipment cost	$89.10	$170.49	$124.70	$162.12	$546.41

Table 63. Cost-analysis spreadsheet, Wisconsin storms (continued).

c. Materials

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
TEST SECTION					
Salt solution (t)	1.63	3.15	3.20	2.39	10.37
Unit cost	$84.92	$84.92	$84.92	$84.92	
Cost	$138.67	$267.33	$271.95	$202.62	$880.57
Salt (t)	0	0	0	0.08	0
Unit cost	$30.53	$30.53	$30.53	$30.53	
Cost	$0.00	$0.00	$0.00	$2.49	$2.49
Total material cost	$138.67	$267.33	$271.95	$205.11	$883.06
CONTROL SECTION					
Salt (t)	0.66	1.72	3.27	1.87	7.52
Unit cost	$30.53	$30.53	$30.53	$30.53	
Cost	$20.22	$52.63	$99.72	$57.06	$229.63
Total material cost	$20.22	$52.63	$99.72	$57.06	$229.63

d. Cost per section area (cost/lane-km)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
TEST SECTION, 26 lane-km area					
Labor	$7.24	$11.54	$10.63	$22.17	$51.58
Equipment	$2.94	$2.94	$8.70	$7.49	$22.08
Materials	$5.39	$10.38	$10.56	$7.97	$34.29
Labor, equipment and materials	$15.57	$24.86	$29.89	$37.63	$107.95
CONTROL SECTION, 26 lane-km area					
Labor	$2.71	$6.56	$4.98	$10.86	$25.11
Equipment	$3.46	$6.62	$4.84	$6.30	$21.22
Materials	$0.79	$2.04	$3.87	$2.22	$8.92
Labor, equipment and materials	$6.96	$15.23	$13.69	$19.37	$55.25

e. Test/control cost ratios (considering costs per section area)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
Labor	2.7	1.8	2.1	2.0	2.1
Equipment	0.9	0.4	1.8	1.2	1.0
Materials	6.9	5.1	2.7	3.6	3.8
Labor, equipment and materials	2.2	1.6	2.2	1.9	2.0

Table 63. Cost-analysis spreadsheet, Wisconsin storms (continued).

f. Driving lane operations and material use

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A	Total
TEST SECTION					
total number of passes	2	9	6	3	20
number of passes with plowing	0	5	2	0	7
number of passes applying NaCl solution	2	4	4	3	13
total application NaCl solute (kg/lane-km)	63	182	125	92	463
cost of NaCl solution (/lane-km)	$5.39	$15.46	$10.60	$7.84	$39.28
number of passes with rock salt application[1]	0	0	0	0	0
total application rock salt[1] (kg/lane-km)	0	0	0	0	0
cost of rock salt (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00
total cost of materials (/lane-km)	$5.39	$15.46	$10.60	$7.84	$39.28
CONTROL SECTION					0
total number of passes	0	4	3	1	8
number of passes with plowing	0	3	2	1	6
number of passes applying NaCl solution	0	0	0	0	0
total application NaCl solute (kg/lane-km)	0	0	0	0	0
cost of NaCl solution (/lane-km)	$0.00	$0.00	$0.00	$0.00	$0.00
number of passes with rock salt application[1,2]	0	1	3	1	5
total application rock salt[1,2] (kg/lane-km)	0	49	197	85	331
cost of rock salt (/lane-km)	$0.00	$1.51	$6.02	$2.58	$10.11
total cost of materials (/lane-km)	$0.00	$1.51	$6.02	$2.58	$10.11
Test/Control Material Cost Ratio	—	10.3	1.8	3.0	3.9

[1]does not include spot applications on test and control sections during storm 3/5/95

[2]does not include spot applications on control section during storms 1/10/95 and 1/19/95

Table 63. Cost-analysis spreadsheet, Wisconsin storms (continued).

g. Driving lane pavement condition observations (percent of all section observations)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A
TEST SECTION				
dry/damp			0	23
wet			14	15
slush		15	57	62
loose snow		62	29	0
packed snow		23		
frost				
black/glaze ice			0	
total percent		100	100	100
CONTROL SECTION				
dry/damp			7	8
wet			14	23
slush		15	50	46
loose snow		62	21	23
packed snow		23		
frost				
black/glaze ice			7	
total percent		100	100	100
Significant difference in test and control?		no	yes	yes

h. Driving lane friction measurement statistics

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A
TEST SECTION				
25th percentile of friction values		0.23	0.23	0.32
Median of friction values		0.26	0.26	0.34
75th percentile of friction values		0.27	0.38	0.42
CONTROL SECTION				
25th percentile of friction values		0.20	0.25	0.30
Median of friction values		0.23	0.29	0.34
75th percentile of friction values		0.25	0.36	0.44
Significant difference in test and control?		yes	no	no
Test median friction greater than control?		yes	no	no

i. Precipitation observations at times of friction measurements (percent of all section observations)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A
TEST SECTION				
none			21	8
light rain or rain			50	
freezing rain			7	
sleet				
light snow		23	14	77
snow or blowing snow		77	7	15
total percent		100	100	100
CONTROL SECTION				
none			21	8
light rain or rain			50	
freezing rain			7	
sleet				
light snow		24	14	77
snow or blowing snow		76	7	15
total percent		100	100	100
Significant difference in test and control?		no	no	no

Table 63. Cost-analysis spreadsheet, Wisconsin storms (continued).

j. Pavement temperatures at times of friction measurements (percent of all section observations)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A
TEST SECTION				
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)				
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)				
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)			7	
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)			50	
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)		100	43	93
$T_p > 0$ °C ($T_p > 32$ °F)				7
total percent		100	100	100
CONTROL SECTION				
$T_p \leq -13.3$ °C ($T_p \leq 8$ °F)				
-13.3 °C $< T_p \leq -10$ °C (8 °F $< T_p \leq 14$ °F)				
-10 °C $< T_p \leq -6.7$ °C (14 °F $< T_p \leq 20$ °F)			7	
-6.7 °C $< T_p \leq -3.3$ °C (20 °F $< T_p \leq 26$ °F)			50	
-3.3 °C $< T_p \leq 0$ °C (26 °F $< T_p \leq 32$ °F)		100	43	92
$T_p > 0$ °C ($T_p > 32$ °F)				8
total percent		100	100	100
Significant difference in test and control?		no	no	no

k. Vehicle average speed (km/h)

Storm Dates and ID	1/10/95 WI501A	1/19-20/95 WI501B	2/14-15/95 WI502A	3/4-5/95 WI503A
TEST SECTION	93	87	85	87
CONTROL SECTION	92	77	85	85

l. Winter 1994/1995, summary of material costs for documented driving lane operations of storms WI501A, W501B, WI502A, and WI503A

	test section	control section
cost of NaCl salt brine /lane-km	$39.29	$0.00
(total cost /lane-mi)	($63.22)	($0.00)
cost of rock salt /lane-km	$0.00	$10.11
(total cost /lane-mi)	($0.00)	($16.27)
total material cost /lane-km	$39.29	$10.11
(total material cost /lane-mi)	($63.22)	($16.27)

test material cost/control material cost ratio: 3.9

6.3.1 California

The California cost-analysis spreadsheet is table 59. Five events were documented. As indicated in table 59 c and f, essentially the same quantity of abrasives was applied to both the test and control sections for the events. The abrasives costs reported in table 59 c do not include clean-up costs. The higher total cost of treatment on the test section, revealed in table 59 d, is due to use of $MgCl_2$ in solution at a cost of $0.137/L ($0.52/gal) vs. $55.00/t ($49.90/ton) for salt used on the control. Though slight savings in labor costs were recorded on the test section, the higher cost of equipment and materials resulted in an average 1.3 times higher test section treatment cost (table 59 e). Part h of table 59 shows that all events had nearly the same or slightly higher median friction values on the test section. In part g it can be seen that two events showed a significant difference in the pavement condition observations, and both favored the test section.

For the season, as indicated by results of the full-season analysis in figure 61, the distributions and medians of the test section friction values were higher than on the control section, and the difference in medians was significant, indicating that the test section operations provided a higher level of effectiveness for the added expenditures. This is corroborated somewhat by the pavement condition observations for the season in table 56, which indicate fewer observations of packed snow on the test section relative to the control section.

6.3.2 Nevada

The Nevada cost-analysis spreadsheet is table 60. Five events were documented. Use of the more costly $MgCl_2$ on the test section accounted in all but one case for the higher cost of test section materials compared to the sand/salt mix on the control section, as indicated in table 60 d and e. However, including an estimated cost of abrasives clean-up tipped the balance slightly in favor of the test section. The average ratio of test section to control section costs was 1.8 without considering clean-up, and 1.0 when including this cost. The estimated cost was $29.40/t ($26.67/ton) of abrasive spread. (This rate, provided by New York State DOT for their clean-up operations, was used for the Nevada analysis because the actual cost of the NDOT clean-up was not available.) The same or fewer equipment hours for the test section compared to the control (table 60 b) was offset by the higher unit cost of the liquid application equipment ($16.61/h vs. $12.25/h for the conventional spreader). Of the five storms that Nevada reported costs on, statistical analyses were performed on three. All of these showed significantly higher friction values on the test section and significant differences in the pavement condition observations that favored the test section (table 60 g and h).

For the seasonal analysis of 14 storms, as indicated in figure 68, the distributions and medians of the test section friction values were far higher than on the control section, and the difference in medians was significant, showing that the test section operations provided a much higher level of effectiveness. This is confirmed by the pavement condition observations for the season in table 56 and table 57, which indicate significantly better conditions overall on the test section relative to the control section, even though a fairly high percentage of packed snow observations (16 percent) was reported.

6.3.3 New Hampshire

The New Hampshire cost-analysis spreadsheet is table 61. Five events were documented. Potassium acetate (KAc), with a cost of $747/t ($678/ton) of solution, completely weighted the cost of test section treatment over the use of salt on the control section (table 61 d). The average ratio of test section to control section costs (table 61 e), incorporating labor, equipment, and material costs, was 7.3. As shown in table 61 f, the number of test and control section passes was nearly the same except for one event, when three times as many passes—mostly plowing—were performed on the test section. In only one case was there a significant difference in test vs. control section median friction values (table 61 h); this occurred when the many extra passes were required, and favored the control section. Both KAc and salt were applied to the test section, with the application rate of the latter averaging 1½ times higher than on the control. The unit cost of sand in table 61 c, \$3.85/t (\$3.50/ton), does not include a cost for clean-up.

For the seasonal analysis of six storms, as indicated in figure 70, a significant difference in friction distributions was found that slightly favored the control section, which reveals that the added expenditures did not provide greater effectiveness. This is confirmed by the pavement condition observations for the season in table 56 and table 57, which indicate similar conditions on test and control. Although for the season the percentage of freezing rain observations was relatively high, freezing rain dominated only one storm, and it was very light in intensity. It did not occur, however, until after several hours of snowfall and operations, and likely did not affect relative costs of test and control operations. Table 61 i indicates percentages of precipitation categories in the cost-analysis storms.

6.3.4 New York

The New York cost-analysis spreadsheet is table 62. Twelve events were documented. On average, the cost of treating the test section was slightly less than treating the control—the test/control ratio for total labor, equipment, and materials, as indicated in table 62 e, was 0.9. Material use and labor costs were also at this ratio, while equipment costs, which were the lowest portion of the total costs, were higher on the test section. Both test and control operations were essentially anti-icing operations. Both used salt at the same unit cost with the primary difference being that most often the salt applied on the test section was a finer gradation. The reported costs included costs of operations on ramps, service roads and mainline test and control section lanes. The salt/sand mix costs in table 62 c include clean-up at \$29.40/t (\$26.67/ton) of abrasive spread.

Focusing on the mainline driving lane operations detailed in table 62 f reveals several points. Fine salt (72 passes) usually prewetted with $CaCl_2$ was generally used on the test section, while coarse salt (31 passes), usually applied dry, was also used. In nine passes salt was applied in an abrasives mix. On the control section coarse salt (78 passes) was used nearly always, although salt applied in an abrasives mix was used during nine passes. The cost of test section materials was nearly equal, slightly lower, or much lower than control section material costs in all but 2 of the 12 storm events. Of the nine cost storms for which statistical analyses were conducted, the test section median friction was never higher than the control (table 62 h). In four storms the control section friction medians were significantly higher; in one of these there was a difference in pavement condition observations due to a greater number of packed snow observations (table 62 g).

For the seasonal analysis of 12 storms, as indicated in figures 72 and 73 for the AC and PCC surfaces, respectively, significant differences in friction medians were found that favored the control section, revealing that the added expenditures of the control section anti-icing operations provided greater effectiveness on balance. This is confirmed by the pavement condition observations for the season in tables 56 and 57, which indicate slightly more conditions of packed snow and icing on the test section. A very positive implication of these and other results from New York is that preventive operations built upon a foundation of conventional operations can be effective as anti-icing operations.

Considering the length of storm events did not result in a different ratio of test to control section costs, as indicated by the per hour data in table 62 d. Test section costs were slightly less whether or not the calculation presented in table 62 d considered storm duration. The reduction in labor cost contributed the largest share to the savings; it was 10 percent less for the test section.

6.3.5 Wisconsin

The Wisconsin cost-analysis spreadsheet is table 63. Four events were documented. The four storm events for which cost data are available from Wisconsin are insufficient to draw conclusions about the efficacy and value of the use of sodium chloride solution as the primary treatment method. The State experienced a much higher cost with the use of liquid on the test section compared to dry salt on the control. All cost categories, labor, equipment, and materials, showed higher costs for the test section (table 63 d). The average ratio of test section to control section costs was 2.0 (table 63 e). Note that the cost of sodium chloride solution is used in table 63 f, but the weight of the equivalent dry chemical is also given. In all but one case, more dry salt equivalent was applied on the test than on the control driving lane. And of the three cost storms for which statistical analyses were conducted, table 63 h reveals that the test section median friction was higher than the control in only the 1/19/95 storm (WI501B), in which over three times as much salt was placed. The additional material use and relatively high test section cost of treatment during this event can be attributed to the incidence of snow/blowing snow, for which the conventional control treatments included minimal salting.

For the seasonal analysis of the four storms, as indicated in figure 77, there was no significant difference in the medians of the test and control section friction, even though the test section friction was slightly higher. This is corroborated by the pavement condition observations for the season in tables 56 and 57, which indicate only slightly better conditions—less loose snow and icing and more slush—on the test section. This reveals that the added expenditures of the test section operations provided only slightly greater effectiveness at best.

6.4 DISCUSSION

The average ratios of test section to control section costs, incorporating labor, equipment, and material costs, were 1.3 for California, 1.0 for Nevada (including abrasives clean-up), 7.3 for New Hampshire, 0.9 for New York, and 2.0 for Wisconsin. That the test section costs were not consistently lower than control section costs is contrary to expectations going into this project. Three interrelated factors likely account for this. First, the costs for the documented operations do not reflect a comparison of typical conventional operations with anti-icing operations. Second, the anti-icing costs recorded do not reflect the full potential of anti-icing practices, which should be realized as more experience is gained and as recommendations from studies such as this are implemented.(1) Third, the higher prices of alternative chemicals—the benefits of which are not included in this analysis—can negate savings from other direct-cost-reducing measures.

All of the cost-analysis sites except New Hampshire had critical RWIS information available for both sections. As a result the use of pavement temperature information and accurate weather forecasts, particularly in Nevada and New York, resulted in little difference in the RWIS-based management and timing of treatments, so much so that the conventional strategy at the site could be characterized as anti-icing. Indeed, at these as well as at other sites in the project, the conventional operations made good use of informational sources, were prompt, were not wasteful, and were performed basically according to a preventive strategy. This is reflective of strong conventional practices that have been developed by many agencies throughout the United States, particularly those that have invested in RWIS technology. As such, the study generally does not demonstrate cost savings as much as it reveals techniques for improving effectiveness. Furthermore, while many of the control operations were preventive operations by design, for others there may well have been more than the conventional effort simply because of the on-going experiment (as in the so-called "Hawthorne Effect" whereby the extra attention paid to an experiment influences the results). Conventional operations in less scrutinized, more typical situations commonly do not start until a measurable amount of snow has accumulated, leading to more reactive practices than examined here.

The full potential of anti-icing practices will be realized through the efficiency of operations as well as their effectiveness. Rather than savings, efficiency may be a more suitable cost goal for managers to consider when changing to anti-icing practices because a goal of savings alone implies that the level of effectiveness achieved by the change in practice remains constant. Anti-icing in most situations means doing a better job than what is conventional, simply because it involves, at a minimum, an improved decision-making process. Given the opportunity to incorporate better tools into their practices, maintenance crews are likely to respond naturally with increased effectiveness. Indeed, beyond the activities of an individual crew, an agency may view improved road conditions as the primary benefit of improved operations, as this often relates more directly to what is needed by the public and by business concerns for increased safety and economy. The secondary issue of savings depends on efficiency, of course, but it also depends on the nature and components of the current practice that is to be improved upon: for example, what level of service it supports, whether it is more deicing than anti-icing, what materials it uses, and what information sources it uses. For those considering the costs of anti-icing operations, a comparison of the desired and current operations *and* level of service or effectiveness is important, as are indirect costs not covered in this analysis, such as the costs stemming from air and water quality, infrastructure corrosion, and investments in systems such as RWIS. But simply considering the more traceable issue of material use, the following examples of changes in operations and service level can be given by speculating from the results of this study (i.e., the cost analysis presented here and the seasonal material use and effectiveness data presented in the previous chapter):

- A change to an anti-icing practice from a practice that relies on applications of salt/abrasives mixes for chemical treatments will generally result in both far less chemical use and improved pavement conditions, when the anti-icing techniques have only to support the same high level of service.
- A change to an anti-icing practice from a practice that relies on applications of salt/abrasives mixes for chemical treatments will generally result in less chemical use and improved pavement conditions, when the anti-icing techniques must support a higher level of service.
- A change to an anti-icing practice from a practice that uses excessive amounts of chemical alone will generally result in less chemical use and no change pavement conditions, when the anti-icing techniques have only to support the same level of service.
- A change to an anti-icing practice from a practice that uses reasonable amounts of chemical alone can result in more chemical use and improved pavement conditions, when the anti-icing techniques must support a higher level of service.
- A change to an improved anti-icing practice from a currently implemented anti-icing practice can result in more or less chemical use and in improved pavement conditions, when the new anti-icing techniques have only to support the same level of service.

As suggested by these examples, the most significant reduction in costs will result from the elimination of the use of abrasives as an anti-icing treatment. Doing so will either extend the length of a patrol section or reduce short treatment passes resulting from the reduced area coverage provided by a truckload of material. Savings will also stem from the reduction in clean-up costs; New York estimates this adds $29.40/t ($26.67/ton) of abrasive spread, while other States have indicated higher costs. Of the five States for which seasonal costs have been tabulated here, Nevada showed the greatest use of abrasives on the control section. Applying the New York level of cost for clean-up brought Nevada's cost of test section treatment in line with the control section costs overall, and below them in three of the cost storms, even though a more expensive chemical was used on the test section, and even though a considerable increase in the level of effectiveness was achieved. Yet, as suggested by the material use examples above, one must also be cognizant of possible increases in costs using anti-icing treatments, particularly when the current operation is efficiently run. These may, for example, arise from additional plow passes that may be necessary to ensure effectiveness of the lesser amount of chemical applied as an anti-icing treatment. Similarly, additional chemical treatment passes may be necessary if smaller rates are applied on average for each pass in the effort to reduce over-treatment.

7. RECOMMENDATIONS FOR ANTI-ICING PRACTICE

7.1 INTRODUCTION

Recommendations for anti-icing practice are presented in this chapter. These were derived from the results of the field evaluation and cost analysis, and are limited to practices and techniques demonstrated in these results. They are presented with an organization that derives from the information presented in the preceding chapters on the field evaluation results and the cost analysis. Recommendations of a more general and thorough nature are presented in the project manual of practice, which also reflects the findings given below.[1]

7.2 SOLID AND PREWETTED SODIUM CHLORIDE APPLICATIONS DURING SNOWSTORMS

This section covers chemical applications using coarse or fine crushed rock salt, without abrasives, in anti-icing operations. The recommendations are made for snowstorm operations only, and apply only when conditions warrant chemical applications.

7.2.1 Timing of Initial and Subsequent Rock Salt Applications

Initial and subsequent rock salt operations should be anticipatory or prompt in nature, and should reflect an underlying readiness consistent with a preventive strategy. Operational decisions should be made systematically using modern and traditional decision-making tools such as weather and pavement temperature forecast information; real-time information such as weather radar, pavement temperature, chemical concentration, and other RWIS data; and observational information including patrol observations. The information should be systematically communicated to all personnel involved in operational decisions in order to enhance the timing of operations, and to avoid unnecessary chemical applications.

Initial applications should be placed soon after snowfall has begun or when the pavement temperature is dropping toward or below freezing. They should be made in anticipation of or in prompt response to worsening pavement conditions. Applications in advance of precipitation are not necessary for preventing bonded snowpack, but early applications when the pavement condition is no worse than wet, slushy, or lightly snow-covered are indeed necessary for successful anti-icing practice. Residual chemical from previous operations has a short-lived effect on highway conditions at the beginning of snowstorms, and should not be relied upon for timing of initial anti-icing operations without independent indications of adequate chemical concentration.

Subsequent applications should also be made in anticipation of or in prompt response to worsening pavement conditions. In snowstorms with generally steady precipitation and pavement temperature conditions, subsequent chemical operations made at regular intervals are generally adequate. However, in storms with significant changes in precipitation and pavement temperature conditions, operations will likely be at irregular intervals. In either case, systematic operations using all available decision-making tools should be conducted. The availability of chemical concentration data appears to enhance the timing of subsequent applications by providing indications of the dilution of the chemical. Where decision makers have confidence in these data, they should be used as a basis for establishing cycle times of the repeat applications for different conditions.

Traffic rush periods should be a factor in the timing of initial and subsequent salt applications. A good practice is to push completion of chemical operations ahead to coincide with the beginning of the rush period, both to provide a safe roadway during the critical period and to avoid operational delays that heavy traffic may cause. As increased traffic rates can have both good and bad effects on pavement condition, i.e., by the clearing or packing action of vehicles, timing decisions should reflect changes in conditions caused by traffic.

Decisions regarding the timing of the end or temporary cessation of operations should also be made using available tools, particularly pavement temperature and pavement temperature forecasts. Attentive use of these tools for ceasing operations, and the systematic communication of end-of-operations decisions to operators, appear to be crucial for eliminating unnecessary chemical applications made at the discretion of well-meaning operators who are unaware of the actual conditions.

7.2.2 Application Rates of Solid Sodium Chloride

In addition to the basic anti-icing purpose of preventing a strongly bonded snowpack, the purpose of both initial and subsequent anti-icing chemical operations should be to prevent, or to cause a quick recovery from, excessive drops in friction and deteriorating conditions during a storm. These are not independent purposes. Excessive drops in friction and deteriorating conditions always precede the development of a lightly or strongly bonded snowpack. The following recommendations reflect this relationship between the development of snowpack and the causative conditions. They are given for three snowstorm conditions where pavement temperatures warrant chemical applications: (1) light snowstorms of short and long duration; (2) primarily light snowstorms that contain short periods of moderate or heavy snow; and (3) moderate or heavy snowstorms of short and long duration. No distinction is made here between prewetted and dry sodium chloride, or between coarse and fine gradation rock salt. The recommendations are given for all types of salt applications made without abrasives. It is assumed, however, that there is moisture present to promote the formation of a brine solution. Issues of gradation and prewetting are further discussed in the following section.

In light snowstorms of short and long duration, salting operations should be conducted periodically with applications as uniform as possible of approximately 28 kg/lane-km (100 lb/lane-mi) in order to maintain roads at acceptable levels of friction and to prevent the formation of packed snow. In such storms plowing is usually not conducted, or only occasionally, and the frequency of the operations is governed primarily by chemical requirements. When pavement temperatures are near freezing levels, wet pavement conditions can generally be maintained with periodic applications of approximately 28 kg/lane-km (100 lb/lane-mi). When pavement temperatures are lower, i.e., in the range -2°C to -7°C (into the 20s Fahrenheit), loose snow, slush, or wet pavement conditions can generally be maintained, without development of packed snow, by periodic applications at the same rate.

Operations in primarily light snowstorms that contain short periods of moderate or heavy snow should consist of periodic applications of salt as uniformly as possible at approximately 28 kg/lane-km (100 lb/lane-mi) during the light snow conditions, and of uniform salt applications at the beginning of and during the heavier snow periods at approximately 55 kg/lane-km (200 lb/lane-mi). In such storms plowing is conducted mainly after or during periods of heavier snow so that removal of undissolved chemical by plowing operations is generally not a problem, and the frequency of the operations is governed primarily by chemical requirements. A limited period of heavier snow should be treated as "a storm within a storm." That is, anti-icing operations should be conducted just prior to or at the beginning of the intense snow period to reduce the likelihood that snowpack will develop or be sustained by a strong bond, and to increase the likelihood that plowing operations can readily remove any packed snow that may develop. Use of reliable short-term forecasting tools would facilitate the timing of these chemical operations, but they would otherwise be natural extensions of the responses to heavy snow seen in current snow and ice control practice. The result should be not only the prevention of the development of a strong bond between the packed snow and the pavement, but also the prevention of excessive reductions in friction that precede the development of snowpack. Operations similar to these, at pavement temperatures as low as -9°C (15°F), have been observed to be successful. When pavement temperatures are at freezing and steady, 28 kg/lane-km (100 lb/lane-mi) will likely be sufficient even for the periods of greater snowfall intensity.

Operations in moderate or heavy snowstorms of long duration should include periodic applications of salt at 42 to 55 kg/lane-km (150 to 200 lb/lane-mi). In such storms the frequency of the operations is controlled primarily by plowing requirements, and removal of unused chemical by plowing operations is likely when excessive application rates are used. Thus, it is important to limit chemical applications to rates that are not wasteful. Frequent chemical applications in the range of the rates given above, conducted with plowing operations, should be successful in preventing packed snow conditions during prolonged heavy snowfall. Operations at longer cycle times and higher application rates can be successful anti-icing operations, but may require additional solo plowing passes and yet not be as effective even when more chemical is used. However, if the desired frequency of plowing/chemical application passes can not be maintained during prolonged heavy snow periods, increasing the chemical application rate can effectively offset the lower number of passes. The increase should be limited to an amount of chemical that can go into solution and be effective within the period before the following operation in order to prevent chemical waste. When pavement temperatures are at freezing and steady, 28 kg/lane-km (100 lb/lane-mi) will likely be sufficient. Operations in moderate or heavy snowstorms of short duration should follow the procedure above for longer duration storms. However, as the number of plowing cycles will be limited by the duration of the storm, chemical waste by plowing of applied chemical will be less of a concern.

7.2.3 Effects of Salt Gradation and Prewetting on Pavement Condition

No differences are given in the above section for application rates of fine and coarse salt. Where early storm observations and measurements are available from this project, there is not enough evidence to suggest that the prewetted fine salt applied at the beginning of a storm is more effective than conventional rock salt applied at the beginning of a storm. In later stages of storms, comparisons of the effectiveness of subsequent fine salt and rock salt operations suggest that fine salt was no faster acting than the conventional rock salt. These results, although contrary to the expected chemical and physical effects of finer gradation and prewetting of salt, support the lack of a difference in the suggested application rates of fine and coarse salt. That no differences are given is also supported by the measures of effectiveness from the full-season data sets of the New York site.

In addition, no differences are given in the above section for application rates of prewetted vs. dry salt. Because there were no direct comparisons made of prewetted and dry salt at identical application rates during the project, the true effect of prewetting rock salt on pavement condition cannot be determined. Although the Ohio I-70 results clearly indicate that prewetting of rock salt is beneficial, most applications at the New York and Ohio sites were made onto pavements with sufficient moisture to promote the formation of a brine solution. For these reasons there is no distinction made above for the application rates of prewetted vs. dry salt, yet the preliminary conclusion from the Ohio I-70 results is that prewetting of rock salt can lead to better conditions with less chemical use.

7.3 LIQUID APPLICATIONS DURING SNOWSTORMS

This section covers applications using chemical solutions. The recommendations are made for snowstorm operations only, and apply when conditions warrant chemical applications.

7.3.1 Timing of Initial and Subsequent Chemical Applications

Many of the recommendations for the timing of solid chemical applications are appropriate for liquid applications as well. As for rock salt applications, initial and subsequent chemical solution operations should be anticipatory or prompt in nature, should reflect an underlying readiness consistent with a preventive strategy, and should be systematically based on information sources. Information should then be systematically communicated to all personnel involved in operational decisions in order to enhance the timing of operations, and to avoid unnecessary chemical applications.

Initial chemical solution applications should be made either (1) as a "pretreatment" in advance of a storm; or (2) as an "early storm treatment," i.e., soon after snowfall has begun and/or when the pavement temperature is dropping toward freezing. The pavement at the time of a pretreatment will usually be dry. In the case of early storm treatment, the application should be made onto dry, wet, light slush, or lightly snow-covered pavement. Late applications onto pavements with more than a light covering of slush or snow can result in excessive dilution of the chemical, and should be coordinated with plowing. Without detailed information on the concentration of residual chemical from previous operations, the existence of residual chemical should not be a factor in the timing or application rate of early storm or pre-storm treatments.

Timing of the pretreatments should be based upon weather and pavement temperature forecasts, radar images, local weather observations, and RWIS pavement temperature data. The use of this information has proven to be highly successful when treatments up to 6 h before a storm are desired. Benefits of pretreatments have been demonstrated by sodium chloride solution applications at the Wisconsin site. Relative to conventional practices in which surfaces are not treated until later in a storm, these benefits include higher friction and better pavement conditions when the precipitation is light snow, or light snow turning to snow, and when pavement temperatures are between -4°C and -1°C (the mid 20s to 30°F). These benefits are generally short-lived, however, and should not be expected over a long period. As was the practice in Wisconsin, subsequent chemical applications should be made as soon as conditions begin to deteriorate. In essence, pretreatments should be thought of as "buying time" in the earliest stages of a storm until subsequent chemical applications become effective.

Similar benefits from pretreatments using potassium acetate solution at the New Hampshire site were not observed, even though tests were made over a wide range of conditions. In general, the potassium acetate solution pretreatments were no more effective in the early stages of storms than the total absence of operations were on the control section.

Timing of early storm treatments should be based primarily upon the observed beginning of precipitation or on the drop in pavement temperature below freezing. Benefits of early storm treatments have been demonstrated by magnesium chloride applications in Nevada and by the sodium chloride solution applications at the Wisconsin site. These include higher friction and better pavement conditions early in a storm, as well as rapid recovery from earlier-than-expected deteriorating conditions. Rapid recovery from earlier-than-expected poor conditions is a primary benefit of anti-icing operations, reflecting their anticipatory nature and its ability to readily accommodate early and prompt responses to rapidly changing conditions.

Subsequent chemical solution applications should be made as needed in anticipation of or in prompt response to worsening or changing conditions. When pavements are covered with more than a light covering of slush or snow, the applications should be coordinated with plowing to ensure that dilution of the chemical will not be excessive. Subsequent applications should be based upon systematic use of informational sources such as weather and pavement temperature forecast information; real-time pavement temperature and other RWIS data such as chemical concentration indicators; friction measurement data; and observational data, including operator or patrol observations. As for solid chemical applications, in snowstorms with generally steady precipitation and pavement temperature conditions, subsequent chemical operations at regular intervals are generally adequate. However, in storms with significant changes in precipitation intensity and pavement temperature conditions, operations will be at irregular intervals. In either case, systematic operations using all available decision-making tools should be conducted. The availability of chemical concentration data appears to enhance the timing of reapplications of chemical solutions by providing indications of the dilution of the chemical. When decision makers have chemical concentration data, and have confidence in them, they should be used as a basis for establishing cycle times of the chemical solution applications.

7.3.2 Application Rates of Chemical Solutions

As discussed above for solid chemical applications, in addition to the basic anti-icing purpose of preventing a strongly bonded snowpack, the purpose of both initial and subsequent anti-icing operations should be to prevent, or to cause a quick recovery from, excessive drops in friction and deteriorating conditions during a storm. These are not independent purposes. Excessive drops in friction and deteriorating conditions always precede the development of a lightly or strongly bonded snowpack. The following recommendations reflect this relationship between the development of snowpack and the preceding conditions. They are given for three snowstorm conditions: (1) light snowstorms of short and long duration; (2) primarily light snowstorms that contain short periods of moderate or heavy snow; and (3) moderate or heavy snowstorms of short and long duration. Recommendations are also given for pretreatments ahead of snowfall. No distinction is given here with regard to chemicals that may be used, although they have been developed from results of sodium chloride and magnesium chloride solution applications.

In light snowstorms of short and long duration, liquid applications should be conducted periodically with dry chemical-equivalent applications of approximately 28 kg/lane-km (100 lb/lane-mi), uniformly placed, in order to maintain roads at acceptable levels of friction and to prevent the formation of packed snow. In such storms plowing is usually not conducted, or only occasionally, and the frequency of the operations is controlled primarily by chemical requirements. When pavement temperatures are near freezing levels, wet pavement conditions can generally be maintained with periodic applications of approximately 28 kg/lane-km (100 lb/lane-mi). When pavement temperatures are slightly lower, i.e., slightly below -1.5°C (in the high 20s Fahrenheit), loose snow, slush, or wet pavement conditions can generally be maintained, without development of packed snow, by periodic applications at the same rate.

Operations in primarily light snowstorms that contain short periods of moderate or heavy snow should consist of periodic and uniform liquid applications at approximately 28 kg/lane-km (100 lb/lane-mi) during the light snow conditions, and of uniform applications at the beginning of and during the heavier snow periods at approximately 55 kg/lane-km (200 lb/lane-mi). In such storms plowing is mainly conducted during and after periods of heavier snow, and the frequency of the operations is controlled primarily by chemical requirements. A limited period of heavier snow should be treated as "a storm within a storm," i.e., anti-icing operations should be conducted just prior to or at the beginning of the intense snow period to reduce the likelihood that snowpack will develop or be sustained by a strong bond. Use of reliable short-term forecasting tools would facilitate the timing of these operations, but they would otherwise be natural extensions of the responses to heavy snow seen in current snow and ice control practice. The result should be not only the prevention of the development of a strong bond between the packed snow and the pavement, but also the prevention of excessive reductions in friction that precede the development of snowpack. Operations similar to these, at pavement temperatures between -3°C and -1°C (the upper 20s Fahrenheit), have been observed to be successful. When pavement temperatures are at freezing and steady, 28 kg/lane-km (100 lb/lane-mi) will likely be sufficient even for the periods of greater snowfall intensity.

Operations in moderate or heavy snowstorms of long duration should include periodic chemical solution applications at 55 kg/lane-km (200 lb/lane-mi). In such storms the frequency of the operations is controlled primarily by plowing requirements. Frequent chemical applications in the range of the rates given above, conducted with plowing operations, should be successful in preventing strongly bonded packed snow and in mitigating the effects of any packed snow that develops. When pavement temperatures are at freezing and steady, 28 kg/lane-km (100 lb/lane-mi) will likely be sufficient. Applications in moderate or heavy snowstorms of short duration should be at these rates as well.

Pretreatment applications at rates close to 28 kg/lane-km (100 lb/lane-mi) provide benefits when early storm conditions are characterized by light snow or snow and pavement temperatures between -3°C and 0°C (the upper 20s and lower 30s Fahrenheit). Pretreatments should be used only for their short-lived effectiveness early in a storm. They should not be expected to provide a long-term benefit, and should be followed with subsequent applications in anticipation of or in prompt response to deteriorating conditions.

7.3.3 Transitions to Use of Solid Chemicals

At the chemical solution application sites of this project, a common practice was to supplement the liquid applications with solid applications after the initial stages in a storm or after an increase in snowfall intensity. Although the results of liquid applications during later storm stages and in periods of heavier snowfall have been successful, operational constraints such as the capacities of truck tanks and storage facilities, as well as operational preferences, may lead to anti-icing chemical operations that include transitions from liquid to solid applications. In such cases, the transition should be anticipated to allow continuous anti-icing operations and to avoid operational delays, and the solid chemical operations should be performed according to the recommendations of section 7.2, Solid and Prewetted Sodium Chloride Applications During Snowstorms.

7.4 ABRASIVES APPLICATIONS

Abrasives are not a freezing-point depressant and therefore cannot be an active material of an anti-icing operation that is conducted to prevent the formation or development of a bond between packed snow or ice and pavement. Where clean-up is performed, the cost analysis further indicates that the most significant reduction in operational costs will result from the elimination of the use of abrasives as an anti-icing treatment. However, as they were commonly used in this project, their uses within salt/abrasives mixes and alone (or "sweetened" with small percentages of salt) are discussed briefly here.

7.4.1 Applications of Salt/Abrasives Mixes

Use of salt/abrasives mixes at moderately or much higher application rates than straight chemical does not lead to corresponding improvements in hard-braking friction or pavement conditions. This result is common even when the application rate or total application of salt within the mix is moderately or greatly higher than the rate or total application of the chemical placed alone. Often in such comparisons, not only is there no significant improvement by the use of greater amounts of salt/abrasives mix, but the result is significantly worse. Furthermore, comparisons of test and control operations using identical salt/abrasives mixes show that more frequent applications at similar rates also do not lead to corresponding improvements in friction or pavement conditions. The comparisons even indicate that the more frequent applications can lead to slightly worse conditions. The implication of these results is that the presence of abrasives is detrimental to the anti-icing effectiveness of chemicals in the mix. Based upon these results, chemical applications in anti-icing operations should not be made in a mix with abrasives.

7.4.2 Applications of Abrasives Alone (or With Low Percentages of Chemicals)

Results of this project demonstrate that during storm periods when anti-icing operations are successful, i.e., when anti-icing operations have either prevented or have mitigated the hazards of snowpack, abrasives applications provide no consistent or apparent benefit in hard-braking friction, traction, or pavement condition. Abrasives applications should not be used to supplement successful anti-icing operations, based upon these results.

7.5 OPERATIONS DURING HIGH WIND

Often the conventional practice in windy and cold winter storm conditions with cold pavements is to refrain from normal chemical applications in order to prevent chemical-induced melting of blowing snow and retention of blowing snow by chemically wet pavement. In such a case, the wet pavement would otherwise be dry because the cold snow would not adhere to the pavement, and chemical operations would lead to bonded snow and poor conditions. The effectiveness of this approach, relative to trying to prevent bonded snow and ice by chemical applications, was confirmed in this study for an operation in Kansas when pavement temperatures were below -7°C (19°F) (storm KS503A, figure 23).

When pavement temperatures are below, yet near freezing, conventional chemical operations in windy conditions are also sometimes minimized for the same reasons as when the pavement is cold. However, operations in blowing snow conditions in Wisconsin (storm WI501B, figure 29) when pavement temperatures were between -1°C and -1.5°C (30°F and 29°F) have shown that higher friction and better traction can result from sustained anti-icing chemical operations in these conditions.

7.6 OPERATIONS DURING FREEZING RAIN EVENTS

The very few freezing rain events during this project do not allow general recommendations to be made for anti-icing practices. The companion manual of practice, however, provides guidelines for freezing rain operations based upon previous experience.[1]

7.7 RECOMMENDATION FROM THE COST ANALYSIS

In order to evaluate costs of improved practices and to fine-tune their efficiency, States pursuing initiation or expansion of anti-icing programs should record detailed operational data and accurate cost data for both the improved operations and for what they regard as their conventional operations. Unlike the evaluation of this project, which was performed on relatively short test and control sections, these data should be collected for full-patrol sections in order to provide the costs of complete operations. The data of the different operations can then be compared as an indicator of the cost-effectiveness of the newly implemented techniques. Whenever possible the costs of meeting objectives other than those directly related to operational effectiveness should be recognized in such a comparison. This is particularly true when practices or techniques are implemented to meet goals such as improving air and water quality or eliminating infrastructure corrosion.

The cost data of a storm or other weather event can be organized according to the total costs for materials (chemicals and abrasives), labor, and equipment employed in operations. For chemicals, this includes the purchase price, transportation to storage site, storage, truck loading, handling and mixing of solid chemicals, and solution preparation. For abrasives it should include both material costs and any clean-up costs. Labor costs should be fully burdened and include overtime, while equipment costs would be the agency's hourly rates times the hours used. Other costs can be considered, if appropriate. These include the cost of dispatchers, costs of specialized equipment, cost of patrols, etc.

In addition to recording costs and details of the operations, precipitation, pavement temperature, and other pertinent weather conditions should be recorded, as should measures of the effectiveness of the operations, in order to quantify the direct benefits of the operations and the conditions under which those benefits were realized. The weather and pavement conditions may include measures such as those used in this project—precipitation and pavement temperature data from RWIS or other sources, precipitation observations, pavement condition observations, friction measurements, and traction judgments—or other measures devised by maintenance personnel. For storm events, the conditions should be recorded throughout. This allows the maintenance crew to quantify and identify, for example, their ability to maintain acceptable conditions throughout the storm, or how long it takes to return to acceptable conditions after they have deteriorated or after the end of the storm. If this were done for separate patrol sections as suggested above, comparisons of effectiveness would not be direct as they would be for adjacent sections that are subjected to nearly identical storm conditions. However, because costs are best calculated when a full patrol is considered, full-patrol comparisons would be preferred when costs are the focus.

While the implementation of systematic anti-icing practices can be thought of as a means for maintaining roads in the best condition possible during a winter storm, and a way to do so in an efficient manner, it should not be thought of as an improvement that will automatically result in reduced overall costs. Savings will depend on the current practice, i.e., what level of service governs, what materials it uses, whether it is more deicing than anti-icing, and what information sources it uses. Examples of success include providing the same level of maintenance effectiveness at less total cost, and providing a higher level of maintenance effectiveness at the same cost. As these examples illustrate, an examination of both costs *and* level of maintenance effectiveness, for both the improved *and* conventional operations, is very important. It allows both costs and success to be quantified, and gives an agency the ability to see what it is getting for its investment.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER WORK

8.1 INTRODUCTION

This chapter presents a summary of the report contents, conclusions, and recommendations for further work. Although the recommendations for anti-icing practice of the preceding chapter are conclusions from the study, they are not repeated here. See chapter 7 for these recommendations.

8.2 SUMMARY

Highway anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant. Its operations consist of chemical applications and coordinated plowing. It is a preventive strategy distinct from deicing, which is the traditional delayed strategy of mechanically or chemically removing compacted snow or ice that is already bonded to pavement. In anti-icing practice the first application of the snow and ice-control chemical is generally before the start of freezing precipitation or soon after the precipitation begins, but always before a strong bond between the pavement and any ice or packed snow on the pavement surface has a chance to form. Subsequent anti-icing operations are conducted either to prevent a strong ice-pavement bond, or alternatively, to prevent any bond from forming. In fact, all anti-icing operations, at the beginning of a storm and throughout the storm, are conducted for the same reasons: to prevent a bond from forming, or to minimize the strength of any bond that does form. Although anti-icing practices have been in use for many years, the term has evolved to mean a modern snow and ice control strategy that makes systematic use of an array of new technologies such as road weather information systems, portable pavement temperature sensors, site-specific weather and pavement forecasts, and sophisticated chemical application equipment, as well as conventional and traditional technologies and practices. With thoughtful, methodical, and vigilant use of available information sources, whether they be cutting-edge or traditional, anti-icing can provide two major benefits: optimal use of labor and materials, and increased traffic safety.

Anti-icing operations are most appropriate on routes where a high level of winter maintenance is required. This is because the vigilance and timeliness required for success are consistent with the maintenance effort required by policy. It is also because the preventive strategy of anti-icing is more consistent with the objective of maintaining bare pavement throughout a storm than is deicing. An anti-icing strategy at lower service levels is not as successful at maintaining good conditions simply because less attention is paid to the operations by design. This is not to imply, however, that preventive operations will not be effective on lower service roadways. For longer duration storms, however, the ability of early chemical applications to prevent bonded snow or ice is usually diminished or eliminated by dilution of the chemical.

This project, FHWA Test and Evaluation Project No. 28, "Anti-Icing Technology," was initiated to implement and evaluate existing anti-icing technologies that were tested and reviewed under SHRP project H-208, "Development of Anti-Icing Technology."[(2)] Participants were the State highway agencies of California, Colorado, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Hampshire, New York, Ohio, Oregon, Washington, and Wisconsin. The project included a two-winter experimental anti-icing evaluation, and analysis of the experimental data. The experimental program comprised field operations and experiments conducted by State highway agency personnel, and the data analysis consisted of graphical and statistical analysis conducted by a project team. Implementation was promoted in two ways. First, the personnel at the experimental sites were tasked with developing their own anti-icing practices, using guidance provided by the project team. By this approach the innovation of the site personnel was utilized as a resource, and the anti-icing developments made over the course of years at the sites were formalized and implemented. Second, the techniques of anti-icing were promoted during two national meetings sponsored by FHWA, in the training sessions of the project, in oral presentations made by FHWA and project team personnel to national organizations and State agencies, and in written presentations by the FHWA project manager appearing in highway newsletters and magazines.

The experiments were performed according to a process that allowed consistent analyses of the data from all sites. The intent was to provide data whose analysis would lead to recommendations for good anti-icing practices. The effectiveness measures were based on pavement surface measurements and observations, i.e., measurements of friction and observations of pavement condition. Other data were recorded to establish weather, pavement and traffic conditions throughout a storm in order to demonstrate and investigate relationships between the effectiveness measures and the conditions. Material, labor, and equipment usage were recorded as well, in order to establish the costs of achieving the level of effectiveness. An experiment consisted of anti-icing operations on a "test section," conventional operations on a "control section," documentation of the operations, and measurements and observations during a single storm. The anti-icing operations were conducted according to the treatment strategy that was developed by the site personnel, and the conventional operations were according to the standard practice at the site, with no influence from the anti-icing operations.

Storm data sets were analyzed individually and in blocks of storms from a given season and site. The multiple storm analysis, called a full-season analysis, was developed to provide wider indications of the effectiveness of an anti-icing treatment strategy than would be provided by the analysis of an individual storm. In effect, it allowed the "big picture" to be examined. An attempt was made to gain the broader understanding that a full-season analysis provided before interpreting individual storms. With this approach, the context of the individual storm operations and results was better understood, and the analysis could be better interpreted. Cost analyses were performed on individual storms in five States: California, Nevada, New Hampshire, New York, and Wisconsin. These were based on data obtained for the categories of materials (chemicals and abrasives), labor, and equipment, for the test and control sections of selected storm events.

8.3 CONCLUSIONS

An indication of the overall project storm conditions was provided from a summary of multiple storm analyses from several sites. This showed that snow and light snow dominated the precipitation observations, and that pavement temperatures above -6.7°C (20°F) dominated at the times of the observations, making up nearly 80 percent of the pavement temperature data. Corresponding pavement condition observations showed that the categories dry/damp, wet, slush, and loose snow made up 83 percent of the effectiveness observations, while packed snow and black/glaze ice categories made up about 17 percent. Only slight differences between overall project test and control pavement conditions were indicated, although the test sections had fewer observations of packed snow and ice than did the control sections. The fairly high percentage of packed snow and ice observations suggests that the effectiveness of anti-icing practices can be improved significantly beyond current practice.

Analysis of the combined effects of pavement temperature, precipitation rate, and traffic rate on friction showed (1) that reductions in friction with decreasing pavement temperature, increasing precipitation rate, and decreasing traffic rate should generally be expected during a storm, even when successful anti-icing operations are being conducted; and (2) that of the three independent variables, traffic rate appears to have the weakest effect on friction, while pavement temperature has the strongest, and precipitation rate occupies the middle ground. Further analysis of friction with precipitation showed that in the storms of this project, the friction was considerably lower in "snow" than in "light snow," reflecting a consistent deterioration of pavement conditions with increase in snowfall intensity. Data histories from many of the individual storms support this result, showing that packed snow conditions are most likely to occur soon after an increase in snowfall intensity. These data, taken together, suggest that snow intensity should be considered as important a variable as pavement temperature in the design of anti-icing operations, and that attention to snow intensity will result in the greatest improvements in anti-icing effectiveness, particularly during storms. For this purpose, a "storm within a storm" approach to anti-icing operations is proposed. This applies primarily to light snowstorms that contain short periods of moderate or heavy snow, and involves practices combining the basic strategy of anti-icing, i.e., preventing a bonded snowpack, with a complementary strategy of limiting reductions in friction due to increases in snowfall rate. This is one of the most important conclusions of this evaluation, and stems directly from the evaluation technique.

Other important conclusions based on the evaluation include:

- Anti-icing operations, without abrasives applications, can lead to a considerably higher degree of operational success throughout a storm relative to conventional practices. When dangerous packed snow conditions develop, anti-icing operations can lead to a weaker bond between the pavement and snowpack and an earlier breakup of the pack that is attributable solely to the preceding operations.
- Overall seasonal success in preventing sustained snowpack conditions can be achieved with vigilant and systematic anti-icing operations.
- Well-timed initial chemical applications can prevent or mitigate reductions in friction, as well as support the anti-icing objective of preventing a strong bond from developing.
- Initial rock salt or prewetted rock salt applications in advance of precipitation are not always necessary for preventing bonded snowpack, but early applications when the pavement condition is no worse than wet, slushy, or lightly snow-covered are clearly necessary for successful anti-icing practice.
- Initial chemical solution applications should be made either as a pretreatment in advance of a storm or as an early storm treatment.
- In the case of a chemical solution pretreatment, the practice is not always as straightforward as applying the solution onto dry pavement before the time at which precipitation starts. In particular, in storms that begin with rain or snow falling on a pavement with above-freezing temperatures, pretreatments long before pavement temperatures drop to freezing should be avoided because of the excessive dilution of the chemical that will occur. In storms that begin with freezing precipitation falling onto a pavement with below-freezing temperatures, however, pretreatments are indeed appropriate.
- In the case of an early storm chemical solution treatment, the application should be made onto dry, wet, light slush, or lightly snow-covered pavement. Late applications onto pavements with more than a light covering of slush or snow can result in excessive dilution of the chemical, and risk failure. They should therefore be coordinated with plowing.
- Relative to conventional practices in which surfaces are not treated until later in a storm, benefits from sodium chloride solution pretreatments can include higher friction and better pavement conditions early in a storm. These benefits have been observed to be short-lived, however, and should not be expected to endure over a long period. Subsequent chemical applications should be made as soon as conditions begin to deteriorate. In essence, pretreatments should be thought of as buying time in the earliest stages of a storm until subsequent operations become effective.
- Similar benefits from pretreatments using a potassium acetate-based solution were not observed, even though tests were made over a wide range of conditions. In general, the potassium acetate solution pretreatments were no more effective in the early stages of storms than the total lack of operations were on the control section.
- An anti-icing treatment strategy, because of its preventive nature, can readily accommodate prompt responses to earlier-than-expected storm conditions. These responses can result in increased friction

and improved pavement conditions, rather than rapid reductions in friction and deteriorating conditions, which are typical of normal operational delays.

- Residual chemical from previous operations has a short-lived effect on highway conditions at the beginning of snowstorms, and should not be relied upon for timing of initial anti-icing operations without independent indications of adequate chemical concentration.
- Subsequent chemical applications that are made in prompt response to changing conditions can improve friction and pavement conditions. Subsequent chemical applications that are made in anticipation of changing conditions can prevent deteriorating conditions or mitigate their effects.
- The availability of chemical concentration indicators appears to enhance the timing of subsequent applications by providing indications of the dilution of the chemical. Where decision makers have confidence in these data, they should be used as the basis for establishing cycle times of the repeat applications for different conditions.
- Plowing ahead of liquid applications is essential when it is snowing hard, with conditions of loose snow on the pavement.
- Although the results of liquid applications during later stages in storms and in periods of heavier snowfall have been successful, operational constraints such as the capacities of truck tanks and storage facilities, as well as operational preferences, may lead to anti-icing chemical operations that include transitions from liquid to solid applications. In such cases, the transition should be anticipated to allow continuous anti-icing operations and to avoid operational delays, and the solid chemical operations should be performed according to anti-icing practices.
- An inadequate chemical base caused simply by a delay in operations can result in the development of a sustained snowpack.
- Rock salt can be successfully used as the primary chemical treatment in anti-icing operations.
- Prewetting rock salt can result in improved effectiveness of anti-icing operations.
- There is no evidence from this project to suggest that prewetted fine salt applied at the beginning of a storm is more effective than rock salt applied at the beginning of a storm, nor to suggest that subsequent fine salt applications are faster acting than the rock salt. While not conclusive, these results are contrary to the expected effects of a finer gradation.
- Abrasives are not a freezing-point depressant and therefore cannot be an active material of an anti-icing operation that is conducted to prevent bond formation between packed snow or ice and pavement. Use of salt/abrasives mixes at moderately or much higher application rates than straight chemical does not lead to corresponding improvements in friction or pavement conditions. The implication of these results is that the presence of abrasives is detrimental to the effectiveness of chemicals in the mix.
- Results of this project demonstrate that during storm periods when anti-icing operations are successful, i.e., when anti-icing operations have either prevented or have mitigated the hazards of snowpack, straight abrasives applications provide no consistent or apparent benefit in braking friction, traction, or pavement condition.

As mentioned, further direct conclusions from the field evaluation are the recommendations for anti-icing practice given in the preceding chapter.

While the implementation of anti-icing practices should be thought of as a means for systematically maintaining roads during winter storms, and using resources optimally to do so, it should not automatically be thought of as an improvement that will always result in reduced overall costs. Most importantly, anti-icing techniques provide the potential and capability for maintaining roads in the best condition possible during winter storms consistent with the level of effort expended. The secondary issue of savings depends on the current practice: for example, what level of service it supports, what materials it uses, whether it is more deicing than anti-icing, and what information sources it uses. In this project the experiments generally compared different anti-icing operations. This is because in general the conventional operations at the sites made good use of informational sources, were prompt, were not wasteful, and were performed basically according to an anti-icing strategy. As such, the study generally does not demonstrate cost savings as much as it reveals optimal techniques for improving road safety.

For those considering the implementation of anti-icing operations, a comparison of the desired and current operations *and* level of service is important. This is because a level of service can be chosen through the activity of the operations, and, conversely, the activity of the operations can be designed to fit the level of service. Speculating from the results of this study, and considering a high level of service, the following guidance can be given regarding material use and effectiveness:

- A change to an anti-icing practice from a practice that relies on applications of salt/abrasives mixes for chemical treatments will generally result in both far less chemical use and improved pavement conditions, when the anti-icing techniques have only to support the same level of service.
- A change to an anti-icing practice from a practice that relies on applications of salt/abrasives mixes for chemical treatments will generally result in less chemical use and improved pavement conditions, when the anti-icing techniques must support a higher level of service.
- A change to an anti-icing practice from a practice that uses excessive amounts of chemical alone will generally result in less material use and no change in pavement conditions, when the anti-icing techniques have only to support the same level of service.
- A change to an anti-icing practice from a practice that uses minimal amounts of chemical alone can result in more material use and improved pavement conditions, when the anti-icing techniques must support a higher level of service.
- A change to an improved anti-icing practice from a currently implemented anti-icing practice can result in more or less chemical use and in improved pavement conditions, when the new anti-icing techniques have only to support the same level of service.

Whether operations should be conducted more for *preventing* snowpack, or for *mitigating* its bond with pavement, will be a question facing those who are involved in fine-tuning anti-icing operations.

8.4 RECOMMENDATIONS FOR FURTHER WORK

This evaluation has observed that motorists are often exposed to rapid changes and prolonged reductions in friction during snowstorms. It has resulted in recommendations for changes to current practice based upon analysis of these observations and the associated snow and ice control operations. Many of these recommendations were recognized or even well known prior to this project, and were merely confirmed by the evaluation. Others are new recommendations that are confidently based upon observations of different storms and sites, and that should provide relief to motorists if carried out. The recommendations and considerable additional guidance are included in the companion manual of practice.[1] Thus, the fundamental recommendation for further work beyond this study is the implementation of practices recommended in the manual.

While the recommendations contained in the manual [1] are comprehensive, they derive from anti-icing strategies developed using preliminary guidance and their implementation during a variety of operations and combinations thereof. To date, there has been no rigorous confirmation of the effectiveness and cost-efficiency of anti-icing practice as detailed in the manual. A prudent course for further work would be to pursue validation of the manual's guidance through independent observations and documentation. Because implementation of the guidance can vary widely from agency to agency, a validation conducted with a number of agencies, chosen to cover a range of implementation approaches, climatic regimes, and operational techniques, would be appropriate.

A validation of the manual's guidance would also provide baseline documentation for further work that examines potential extensions to the recommended practice. Based upon the knowledge gained in the T&E 28 evaluation, additional work to extend the manual's scope can be outlined as follows:

- Examine the level of service required to achieve anti-icing effectiveness, focusing on recommendations for anti-icing operations at lower service levels.
- Determine the ability to conduct effective anti-icing operations where budget constraints prevent the use of sophisticated equipment or information systems, e.g., where fully deployed RWIS is not available, in order to demonstrate how winter maintenance forces with conventional tools can make immediate improvements in operations.
- Investigate the effect of rural vs. urban conditions and maintenance practices on anti-icing effectiveness.
- Examine anti-icing operations over full-patrol sections or operating districts, as opposed to relatively short test sections, in order to fully document labor and operational costs and the impact of practicable cycle times on effectiveness.
- Evaluate the proper role of abrasives operations as a complementary strategy to anti-icing, i.e., examine the effectiveness of abrasives when anti-icing operations are aborted due to unexpected storm or road conditions, or when the assigned level of service allows greater variability in road conditions. Use a friction measurement device that provides more than single-direction hard braking friction values (i.e., a variable-slip multidirectional system) to determine the road and operational conditions in which abrasives may provide significantly improved traction or increased safety, focusing on small improvements that may have been undetectable in this evaluation. Examine the actual improvement in traction provided by abrasives vs. the perceived improvement.
- Determine the effects of solid chemical gradation and solid chemical prewetting rates on anti-icing effectiveness.
- Investigate the effect of the slope and shape of chemical freezing-point depression curves on anti-icing effectiveness. In laboratory studies, examine the physical nature of the bond between snow/ice and pavement when a chemical freezing-point depressant is introduced, the migration and dilution of the chemical, the volume of snow and ice in the vicinity of the bond that is affected by the chemical, and the effect of temperature and chemical dilution on bonding and disbonding. Develop and test field practices based upon the physics of bonding and disbonding.
- Examine the effect of open-graded surface courses on anti-icing chemical application rates, both in laboratory and field work.
- Clarify the ability of pre-storm and early storm treatments to mitigate friction losses early in snowstorms.
- Demonstrate the impact of spreader performance on material loss and anti-icing effectiveness.
- Evaluate the effectiveness of anti-icing treatments for preventing preferential bridge-deck icing. Establish guidelines for pre- and post-storm longevity of chemical residues for bridge applications.
- Evaluate chemical application rates for precipitation other than snowfall, especially freezing rain.
- Determine the best approaches for integrating anti-icing and other winter maintenance practices into intelligent transportation systems in both urban and rural environments. Examine the impact of providing road condition and traction/friction information to drivers and the potential for improved safety.

Finally, further work should include evaluation of an agency's ability to fine-tune an anti-icing operation to meet specific performance goals associated with a level of service. For example, it may be possible to set and meet performance goals such as "packed snow or icy conditions no more than 5 percent of the time during a winter season." Such a goal could be designed to reflect an appropriate balance between factors such as public safety, reduction in economic losses due to winter storms, concerns regarding environmental impact and infrastructure damage, and operational costs. Exploration of such balances are likely to be possible with the future implementation of systematic anti-icing practices, and would truly initiate the engineering of such practices to meet specific goals of sustainable transportation.

APPENDIX A. INSTRUCTION MANUAL FOR EXPERIMENTS

TABLE OF CONTENTS

1. INTRODUCTION

The project is Federal Highway Administration (FHWA) Test and Evaluation Project No. 28, "Anti-Icing Technology." It is part of the FHWA Strategic Highway Research Program (SHRP) implementation program. It will implement existing technologies that were tested and reviewed under SHRP project H-208, "Development of Anti-Icing Technology." Participants are the State highway agencies of California, Colorado, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Hampshire, New York, Ohio, Oregon, Washington, and Wisconsin.

The project includes a 2-winter, 15-State, experimental anti-icing study, and an analysis of the experimental anti-icing data. The experimental program will comprise field operations and experiments conducted by State highway agency personnel, and the data analysis will consist of statistical analysis conducted by the Cold Regions Research and Engineering Laboratory. An experimental design was conducted for the project to develop a set of definitions, recommendations and requirements for conducting the experiments and collecting data. In particular, the experimental design was developed to provide data that will allow the effectiveness of treatments to be statistically analyzed, differences between the effectiveness of treatments to be quantified, the conditions under which anti-icing is effective to be established, and objective conclusions to be reached.

The experiments will be conducted at the different sites using different anti-icing and conventional treatments, and during a variety of storm events that will reflect the random nature of storms at each individual site and at the different geographical locations over the two-winter period of the study. The experimental design considered first the individual site experiments in order to set requirements for obtaining data that will allow analysis of data at the site, and second the collective data from the individual sites in order to allow objective conclusions to be made from a multiple site and treatment comparison.

The effectiveness measures for the study are based on pavement surface measurements and observations, i.e., measurements of the coefficient of friction, and observational records of the snow or ice cover on the pavement. Other data will be recorded to establish weather, pavement and traffic conditions throughout a storm in order to investigate correlations between the effectiveness measures and the conditions. Cost measures will be recorded as well, in order to establish the costs of achieving effectiveness.

This manual includes information and instructions for documenting the experiments of the project. It has been developed as a training aid for the project, and will be distributed and presented at training sessions held in each participating State during October and November 1994. A companion manual for the project, *Preliminary Recommendations for Anti-Icing Practices, A Guide for the Maintenance Manager*, will be distributed and presented as well.

2. EXPERIMENTAL BACKGROUND AND INSTRUCTIONS FOR MEASUREMENT/OBSERVATION PERSONNEL AND SUPERVISORS

2.1 Anti-Icing Treatment Strategy

At an individual site, an **anti-icing treatment strategy** will be developed and repeated throughout the winter season for each experimental storm.

The strategy may include different anti-icing application rates and/or treatments for different storm types and conditions, and may include anti-icing treatments in combination with snow plowing and removal operations, sensible deicing treatments, etc. The strategy should otherwise be "fixed" as soon as possible for **each dominant storm type** expected at the site in order that the effectiveness of the selected strategy be documented for several storms.

The anti-icing strategy should be developed with road safety as a priority.

2.2 Experiments

During a **single storm,** an **experiment** will consist of :

- **Anti-icing operations** on a **test section.**
- **Conventional operations** on a **control section.**
- **Documentation** of the operations.
- Data collection, i.e., **measurements and observations.**

Several experiments will therefore be conducted at an individual site over the course of a winter storm season.

2.3 Test and Control Sections

- Anti-icing operations will be conducted on the "**test section.**" (Anti-icing treatments should be applied uniformly along the test section.)
- Conventional operations will be conducted on the "**control section.**"

The test section is the entire highway section at the site over which the anti-icing operations are performed. A control section is the entire highway section at the site over which conventional operations are performed. Relative to the test section, the control section can be the parallel roadway in a divided highway, or it can be a continuous section in the same direction of a divided or undivided highway.

2.4 Measurements and Observations

The data collection will consist of **friction measurements** and **pavement surface observations** of the **wheel paths of the driving lanes** of test and control **measurement** sections. **Precipitation observations** will be made at the same time.

2.5 Test and Control Measurement Sections

- The **test measurement section** will consist of **subsections of the test section** that are **uniform** with regard to pavement cross-section, flatness, traffic, and other conditions.

- The **control measurement section** will consist of **subsections of the control section** that are **uniform** with regard to pavement cross-section, flatness, traffic, and other conditions.

For example, a test measurement section may be an otherwise continuous and uniform section of the test section, without short stretches of the highway containing culverts, bridges, steep grades, and underpasses.

The test measurement section must be chosen such that the uniform treatment application is not made significantly non-uniform by discontinuous traffic patterns, and it must be chosen so that it is not significantly contaminated by adjacent different treatments (e.g., from on-ramps).

The test section can be considerably longer than the test measurement section if necessary or convenient, and the control section can be considerably longer than the control measurement section as well. These distinctions are made so that the treatments can be applied over a length of highway that is operationally feasible and convenient, and so that friction measurements and pavement surface observational records can be made in a timely fashion under reasonably uniform conditions over only a part of the treated section.

It will be advantageous to select the test and control measurement sections within the test and control sections so that a complete measurement cycle or pass of the friction measurement vehicle takes as little time as is feasible for successful measurements.

2.6 How Many Measurements?

- **Test measurement section:** at least **seven friction measurements** will be made at **random locations** during each pass of the friction vehicle.

- **Control measurement section:** at least **seven friction measurements** will be made at **random locations** during each pass of the friction vehicle.

- **Pavement condition and precipitation observations** will be made at the same time.

The **medians of the coefficients of friction** of each pass will be the **primary measures of effectiveness** for the anti-icing and conventional treatments.

2.7 How Often?

- Measurement and observation passes will generally be made at 30-min intervals until the end of the operations. We recommend the following guidelines:

  – **For storms of duration less than 4 h**: Complete one pass of the test and control loop (i.e., both the anti-icing and deicing sampling sections) every 30 min until the end of snow and ice control operations.

  – **For storms of duration between 4 and 10 h**: Complete one pass of the test and control loop every 30 min for the first 4 h, then every 1 h until the end of snow and ice control operations.

  – **For storms of duration greater than 10 h**: Complete one pass of the test and control loop every 30 min for the first 4 h, then every 1 h when pavement conditions are changing significantly or every 2 h when they are not, until the end of snow and ice control operations.

- The **initial pass** should be made just after the initial application of the anti-icing treatment, and/or before any frozen precipitation.

An additional observation will be made to **judge** if the driving lane of the test measurement section or the driving lane of the control measurement section provides better **auto handling traction**, or if there is no perceivable traction difference between the two. This judgment will be recorded after a complete pass of the observation vehicle over both the test and control measurement sections. The observer will base his or her judgment of the average traction of the test measurement section vs. the average traction of the control measurement section.

If for some reason friction measurements cannot be made, the observations and judgments should be made as described here and according to the time guidelines given above.

2.8 Baseline Friction Measurements

- **Baseline friction measurements** of the test and control measurement sections will be made under non-winter wet pavement conditions prior to the winter storm season.

Specifically, 40 to 50 friction measurements will be made at random locations during multiple passes of the friction measurement vehicle over the test measurement section, and 40 to 50 friction measurements will be made at random locations during multiple passes of the friction measurement vehicle over the control measurement section.

- Measurements should be made **in the wheelpaths of the driving lane**.
- They should be conducted **by each operator** of the friction measurement vehicle, **recorded on Weather and Pavement Condition Log sheets** along **with weather and pavement condition data,** and sent to the project point of contact.

2.9 Documentation of Experiments

The following documentation is required for each storm, as soon as possible after the storm:

1. Copies of all **weather and pavement temperature forecasts** available on hardcopy, including storm forecasts made prior to arrival of storm and forecasts made throughout the duration of long storms.
2. All **RWIS data** collected for storm (i.e., 12 h prior to arrival of storm or beginning of freezing precipitation, throughout the duration of the operations, and 3 h following end of operations) from test and control section sensors, or nearby sensors if none are located within test or control sections.
3. All **other weather data** for storm and site usually obtained by State agency.
4. Completed **Weather and Pavement Condition Logs**.
5. Completed **Anti-Icing Decision Chronology Logs**.
6. Completed **Truck/Operator Activity Logs**.
7. **Traffic counts** on the driving lane every 1/4 or 1/2 h. When traffic speed data is collected, this should be sent as well. Data available at 1-h intervals will be acceptable.
8. **Checklist** of documentation.

A checklist of documentation for a storm follows this page. A Weather and Pavement Condition Log, precipitation and pavement condition definitions for the Weather and Pavement Condition Log, and an Anti-Icing Decision Chronology Log follow the checklist. A Truck/Operator Activity Log is included in the next section.

CHECKLIST OF DOCUMENTATION FOR A STORM,
FHWA Test And Evaluation Project No. 28

STATE/SITE ID: ____________ STORM DATE: ______________________________________
YOUR NAME: __________________ PHONE/FAX NUMBERS: ___________________________
COMMENTS: ____
____

The following documentation is required for each storm, as soon as possible after the storm. Please fill in the table below for each storm when submitting data. **Keep a copy for your records.**

1. Copies of all **weather and pavement temperature forecasts** available on hardcopy, including storm forecasts made prior to arrival of storm and forecasts made throughout the duration of long storms.
2. All **RWIS data** collected for storm (i.e., 12 h prior to arrival of storm or beginning of freezing precipitation, throughout the duration of the operations, and 3 h following end of operations) from test and control section sensors, or nearby sensors if none are located within test or control sections.
3. All **other weather data** for storm and site usually obtained by State agency.
4. Completed **Weather and Pavement Condition Logs.**
5. Completed **Anti-Icing Decision Chronology Logs.**
6. Completed **Truck/Operator Activity Logs.**
7. **Traffic counts** on the driving lane every 1/4 or 1/2 h. When traffic speed data is collected, this should be sent as well. Data available at 1-h intervals will be acceptable.
8. **Checklist** of documentation.

	Date sent	Check this column if data will be sent later	Check this column if data is not and will not be available
Weather forecasts			
Pavement temperature forecasts			
RWIS data			
Other weather data			
Weather and Pavement Condition Logs			
Truck/Operator Activity Logs			
Anti-Icing Decision Chronology Logs			
Traffic counts			

Supervisors and operators should ensure that all proper safety measures are followed during the field operations, and are not compromised by the documentation requirements stated here.

WEATHER AND PAVEMENT CONDITION LOG

STATE/SITE ID: _______

FOR TEST AND CONTROL LOOP PASS NUMBER ___ OBSERVER: ____________________ DATE: ______________

TIME	SECTION		PRECIPITATION								FRICTION (corrected)	PAVEMENT CONDITION									COMMENTS
	test	control	light rain	rain	freezing rain	sleet	light snow	snow	blowing snow	none		dry	damp	wet	slush	loose snow	packed snow	frost	black ice	glaze ice	

TRACTION JUDGMENT (check one after driving test and control loop):

___ CONTROL SECTION BETTER ___ NO DIFFERENCE ___ TEST SECTION BETTER

INSTRUCTIONS FOR WEATHER AND PAVEMENT CONDITION LOG,
FHWA Test and Evaluation Project No. 28

1. ***Note State and site ID, your name, and date.***

2. ***Note the pass number.*** One log form is for a single pass of the test and control loop. The initial pass should be made just after the initial application of the anti-icing treatment, and/or before any frozen precipitation. Passes will generally be made at 30-min intervals until the end of the operations. More specifically, we recommend the following as guidelines for the period of measurements and observations.

- **For storms of duration less than 4 h**: Complete one pass of the test and control loop every 30 min until the end of snow and ice control operations.
- **For storms of duration between 4 and 10 h**: Complete one pass of the test and control loop every 30 min for the first 4 h, then every 1 h until the end of snow and ice control operations.
- **For storms of duration greater than 10 h**: Complete one pass of the test and control loop every 30 min for the first 4 h, then every 1 h when pavement conditions are changing significantly or every 2 h when they are not, until the end of snow and ice control operations.

3. ***Make at least seven measurements of friction*** using the Coralba at random locations ***along the test measurement section in the driving lane wheelpaths. Note the approximate time of the measurements*** (specify a.m. or p.m. or use a 24-h clock) ***and the "corrected" friction values. Check appropriate column for the section.*** At each location ***check the most applicable box for precipitation based on your observation.*** At each location ***check the most applicable box for pavement condition in the driving lane wheelpaths based on your observation.*** Use definitions provided for precipitation and pavement condition observations. ***Write any comments that apply. Note direction of travel under comment column*** if the section includes two directions of travel.

4. ***Make at least seven measurements of friction*** using the Coralba at random locations ***along the control measurement section in the driving lane wheelpaths. Follow the documentation instructions noted above for the test section*** measurements and observations.

5. After each pass of the test and control loop, ***judge if the driving lane wheelpaths of the anti-icing sampling section or the driving lane wheelpaths of the deicing sampling section provide better auto handling traction***, or if there is no perceivable traction difference between the two sections, and ***note your judgment.*** Base your judgment on your "feel" or perception of the average traction of the anti-icing sampling section vs. the average traction of the deicing sampling section. Make judgment independent of observations and friction data.

Supervisors and operators should ensure that all proper safety measures are followed during the field operations, and are not compromised by the documentation requirements stated here.

DEFINITIONS FOR WEATHER AND PAVEMENT CONDITION LOG,
FHWA Test and Evaluation Project No. 28

PRECIPITATION DEFINITIONS

Light rain. Liquid droplets small in size falling at a rate insufficient to result in standing water (puddling) or visible run-off from a road.
Rain. Liquid precipitation falling at a rate sufficient to result in noticeable flow from a road surface or along a road gutter.
Freezing rain. Supercooled droplets of liquid precipitation falling on a surface whose temperature is below or slightly above freezing, resulting in a hard, slick, generally thick coating of ice commonly called glaze or clear ice. Non-supercooled raindrops falling on a surface whose temperature is well below freezing will also result in glaze.
Sleet. A mixture of rain and snow which has been partially melted by falling through an atmosphere with a temperature slightly above freezing.
Light snow. Snow falling at the rate of less than 13 mm/h (1/2 in/h); visibility is not affected adversely.
Snow. Snow falling at the rate of 13 mm/h (1/2 in/h) or greater; visibility may be reduced.
Blowing snow. Snow picked up by the wind from already deposited accumulations and transported across a road. Sometimes called a "ground blizzard."
None. No precipitation and no blowing snow.

PAVEMENT CONDITION DEFINITIONS

Dry. No wetting of the pavement surface.
Damp. Light coating of moisture on the pavement resulting in slight darkening of portland cement concrete (PCC), but with no visible water drops.
Wet. Road surface saturated with water from rain or meltwater, whether or not resulting in puddling or runoff.
Slush. Accumulation of snow that lies on an impervious base and is saturated with water in excess of its freely drained capacity. It will not support any weight when stepped or driven on, but will "squish" until the base support is reached.
Loose snow. Unconsolidated snow, i.e., snow lacking intergranular bonds, that can be easily blown into drifts or off of a surface.
Packed snow. The infamous "snowpack" or "pack" that results from compaction of wet snow by traffic or by alternate surface melting and refreezing of the water that percolated through the snow or that flowed from poorly drained shoulders.
Frost. Also called hoarfrost. Ice crystals in the form of scales, needles, feathers, or fans deposited on surfaces cooled by radiation or by other processes. The deposit may be composed of drops of dew frozen after deposition and ice formed directly from water vapor at a temperature below 0°C (32°F) (sublimation).
Black ice. Popular term for a very thin coating of clear, bubble-free, homogeneous ice that forms on a pavement with a temperature at or slightly above 0°C (32°F) when the temperature of the air in contact with the ground is below the freezing point of water and small slightly supercooled water droplets deposit on the surface and coalesce (flow together) before freezing.
Glaze ice. A coating of ice thicker than so-called black ice that is formed from freezing rain, from freezing of ponded water, or from poorly drained meltwater. It may be clear or milky in appearance, and generally is smooth, although sometimes it may be somewhat rough.

ANTI-ICING DECISION CHRONOLOGY LOG

STATE/SITE ID: ____________ DATE: ______________________________

Na.m.ES OF DECISION MAKER(S): ____

12 midnight	12 noon
1 a.m.	1 p.m.
2 a.m.	2 p.m.
3 a.m.	3 p.m.
4 a.m.	4 p.m.
5 a.m.	5 p.m.
6 a.m.	6 p.m.
7 a.m.	7 p.m.
8 a.m.	8 p.m.
9 a.m.	9 p.m.
10 a.m.	10 p.m.
11 a.m.	11 p.m.

INSTRUCTIONS FOR ANTI-ICING DECISION CHRONOLOGY LOG,
FHWA Test and Evaluation Project No. 28

1. ***Note State and site ID, your name(s), and date.*** If the storm covers multiple days, use multiple forms.

2. For each significant decision made regarding the anti-icing operations, ***note briefly the decision made and reasons for making the decision*** in the appropriate hour block.

3. DOCUMENTATION OF TEST AND CONTROL OPERATIONS FOR OPERATORS AND SUPERVISORS

Document all operations, i.e.,

- Type, proportions or concentration, and application rate of each major chemical component of **all chemical treatments**.

- **Snow plowing operations**.

- Type and application rate of any **abrasives** that are placed.

- Any other operations.

TRUCK/OPERATOR ACTIVITY LOG

STATE/SITE ID: ____________

TRUCK ID: __________ SPREADER: ______________________________ DATE: ____________

DATE OF LAST CALIBRATION: ______________ OPERATOR(S): ______________ PAGE ______ OF ______

START TIME	SECTION		METHOD OF TREATMENT check all that apply			PASS NO.	LANE(S) BEING TREATED check all that apply		MATERIAL AND APPLICATION RATE DATA (for chemical and abrasive treatments)		COMMENTS
	test	control	plowing	chemical	abrasives		driving	passing	material(s) applied	application rate(s)	

INSTRUCTIONS FOR TRUCK/OPERATOR ACTIVITY LOG,
FHWA Test and Evaluation Project No. 28

1. ***Note State and site ID, your name(s), and date.*** The date should correspond to the first start time entry if the log sheet covers both before and after midnight.

2. ***Note the number or other ID of the truck.*** Each truck used in the operations should have log sheets that pertain only to that truck.

3. ***Note the spreader information***, if applicable, i.e., the make and model of the spreader and the type of spreader control.

4. ***Note the date of the last calibration of the spreader.***

5. ***Note a page number when multiple pages are used for the truck log.***

6. For each pass, ***note the starting time. Specify a.m. or p.m. or use a 24-h clock.***

7. ***Check whether the pass is for the test or control section.***

8. ***Check the method(s) of treatment.*** Make sure this information is completed for all treatments of all trucks used in the operations.

9. ***Note the pass number for the truck.***

10. ***Check the lane(s) being treated.***

11. When the treatments are chemical and/or abrasive treatments: (1) ***note specifically the material(s) that are being applied*** and (2) ***note the application rate(s) as accurately as is possible.*** Specify each component of a mixture independently. Make sure this information is completed for all chemical or abrasive treatments of all trucks used in the operations.

12. ***Note any comments.***

Supervisors and operators should ensure that all proper safety measures are followed during the field operations, and are not compromised by the documentation requirements stated here.

APPENDIX B. SITE SURVEY RESPONSES

Responses to a site survey are in the tables of this appendix. The responses were provided by personnel in each State, and were completed before or during the first winter of the project. An abbreviated test matrix for the 10 sites that have data contained in this report is included in table 3 of chapter 3.

The responses include the following:

- Names of survey respondents and project personnel.
- Descriptions of typical winter storm and icing events.
- Location of maintenance station relative to the site location.
- Details of the test and control sections and the treatment equipment.
- Descriptions of the RWIS installations and the weather and pavement condition forecasting services.
- Information regarding traffic count installations.
- Identification of friction measurement equipment.
- Strategy of conventional operations for control section.
- Anticipated anti-icing strategy for test section.

The first column in each table contains the survey items, while each remaining column contains the corresponding responses from the State and/or site identified in the top row. The following list identifies each site and the table in which the survey response is contained:

- California, I-5, Mt. Shasta, Siskiyou County: Table 64.
- Colorado, I-70, Glenwood Canyon: Table 64.
- Iowa, I-35, Des Moines: Table 64.
- Kansas, U.S. 81, Cloud County: Table 65.
- Maryland, U.S. 219, Garrett County: Table 65.
- Massachusetts, I-95 and I 93, Boston Metro Area: Table 65.
- Minnesota, I-35, Downtown Duluth: Table 66.
- Missouri, U.S. 71 at Archie in Cass County: Table 66.
- New Hampshire, Route 10, Hanover: Table 66.
- New York, Route 104 Research Site, Webster: Table 67.
- Nevada, U.S. 395, Panther Valley: Table 68.
- Ohio, Franklin County, I-71: Table 68.
- Ohio, Madison County, I-70: Table 68.
- Oregon, Portland, I-5 I-405 Loop: Table 69.
- Washington, I-90, King County: Table 69.
- Wisconsin, I-43, Green Bay: Table 69.

Table 64. Site survey responses: California, Colorado, and Iowa.

1. STATE AND SITE DESIGNATION	**California, I-5, Mt. Shasta, Siskiyou County**	**Colorado, I-70, Glenwood Canyon**	**Iowa, I-35, Des Moines**
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Kathy Coots: (916) 926-2504; Clyde Aker: (916) 842-2723; Gene Freeman: (916) 235-0702, (916) 842-7076; Levi Toolanen: (916) 235-0702, (916) 467-3794; John Gut: (916) 926-3044.	Wayne Lupton, Del French: (303) 945-3840.	Cy Quick, Resident Maintenance Engineer: (515) 225-3322; Charles Pickett, Highway Maintenance Supervisor III: (515) 225-3322
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	20 storms per winter, ranging in length from a couple hours to a couple days. Another 30 times per winter, the road is wet and temperature drops below 32°F, creating an icing event.	Blank	24 storms per season: Storms vary from a trace to 9 in with 1/2 in being normal. Temperatures vary from -7 to 36°F. Most storms begin as light snow and increase in intensity and include blowing snow and drifting. Wind speeds vary from 3 to 35 mi/h. Two icing events per season: Most icing events occur either early or late in the season. However, in 1993-1994, freezing events occurred in December and January. Temperatures during icing events vary from 32 to 34°F.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	3.5 mi south on I-5 from test and control section to station.	Maintenance Station is 1 mi from site.	12493 University Avenue, Clive, Iowa is located 1-3/4 mi north of the north end of the 4.07-mi-long northbound test section of I-35.
5. TEST SECTION INFORMATION			
5.1 Test section boundaries and length:	NB I-5 from PM 9.5 to PM 11.5. Total of 2 mi. Approximately 1 mi north and south of Central Mount Shasta Interchange (Lake St.).	Interstate 70 from MM 116.3 to 118.8, westbound. Length is 2.5 mi.	Northbound I-35 from milepost 68.13 to milepost 72.2. The test section runs from a crossover south of Iowa 5 interchange, northerly through a second interchange with a county/city street and proceeds northerly to the Ashworth Road overpass which is just south of the interchange with I-80/I-235. Total length is 4.07 mi.
5.2 Pavement surface course:	Asphalt concrete.	Asphalt - no bridges, two interchanges - one at each end.	AC over PCC.
5.3 Width and number of lanes:	Two lanes, 12-ft-wide.	Two lanes, 12 ft each.	Two 12-ft lanes.
5.4 Width and number of shoulders:	4-ft shoulder on left, 10-ft shoulder on right.	Two shoulders 2-½ ft and 7 ft.	Left shoulder 6 ft. Right shoulder 10 ft.
5.5 Are shoulders to be treated?	No.	No.	No.
5.6 Total lane-miles of treatment:	4.	5.	8.14 lane-mi.
5.7 RWIS pavement sensor locations within test section:	None. Weather station and pavement sensors are located about 2-1/2 mi north of the test section on Black Butte Summit.	No.	A surface sensor is located on the Raccoon River Bridge in the right lane 0.4 mi north of beginning of test section.
5.8 Winter ADT:	Annual ADT = 22,300.	Varies from 8,000 to 10,000.	22,000.
5.9 Other information:	Blank	Blank	Automatic traffic recorder located at milepost 70 northbound. I-35 traffic travels over four bridges northbound in the test section.

Table 64. Site survey responses: California, Colorado, and Iowa (continued).

	California	Colorado	Iowa
6. CONTROL SECTION INFORMATION			
6.1 Control section boundaries and length:	SB I-5 from PM 11.5 to PM 9.5 (total of 2 mi). Approximately 1 mi north and south of Central Mount Shasta Interchange (Lake St.).	Same as test, but eastbound.	Southbound I-35, from milepost 68.13 to milepost 72.2. The control section runs from Ashworth Road overpass to the crossover south of Iowa 5. Total length is 4.07 mi.
6.2 Pavement surface course:	Asphalt concrete.	Asphalt.	AC over PCC.
6.3 Width and number of lanes:	Two lanes, 12-ft-wide.	Two lanes 12 ft each.	Two 12-ft-lanes.
6.4 Width and number of shoulders:	4-ft left shoulder, 10-ft right shoulder.	Two shoulders 2-½ ft and 7 ft.	Left shoulder 6 ft. Right shoulder 10 ft.
6.5 Are shoulders to be treated?	No.	No.	No.
6.6 Total lane-miles of treatment:	4.	5.	8.14 lane-mi.
6.7 RWIS pavement sensor locations within control section:	None. Weather station and pavement sensors are located about 2-1/2 mi north on Black Butte Summit.	MM 117.75 and MM 118, eastbound driving lane.	None.
6.8 Winter ADT:	Annual ADT = 22,300.	8,000 to 10,000.	22,000.
6.9 Other information:	Blank.	Blank	I-35 traffic travels over four bridges, southbound in the control section. Automatic traffic recorder located at milepost 70, southbound.
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS			
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	For test section: Three-axle GMC boot truck with 3,000-gal tank and Mid Tech spray bar (TASC 6000) spreading liquid "anti-icer" at 35 gal/lane-mi. Calibration at Redding Shop with water. For control section: Dump truck with tailgate sander, calibrated, with spread rate of about 125 lb/lane-mi of salt.	Equipment for test will be an Epoke SW2000 liquid spreader and a Bearcat liquid spreader. Equipment for control will be V box salt and sand spreader. Calibrate beginning of season. Spot-check rest of season.	Test section - Epoke SW2000 Liquid Spreader, hydraulically driven from a road wheel, operated from a control box in the cab. Epoke calibrated by dealer. Dry spreaders are Frink, Swenson, and Monroe and are operated from the cab. Dry spreaders are calibrated for each truck to approximate 250 lb/lane-mi; control section - dry spreaders.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	Two- and three-axle dump trucks. Swensen, Fontaine, Air Flo, and Tarrant Bin spreaders. Dickey-John, Hydra Tack and Interpac controls with yearly calibration by lb/distance. Tailgate sanders described above.	The V box spreaders will be calibrated at maximum 500 lb/lane-mi.	Test section - Dry spreaders are Frink, Swenson, and Monroe and operated from the cab. Dry spreaders are calibrated for each truck to approximate 250 lb/lane-mi; control section - dry spreaders.
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	4 yd^3 and 10 yd^3, two- and three-axle trucks with snowplows equipped with carbon-tipped blades. If snowpack forms, four- and six-wheel motorgraders.	Frink reverse-cast plows with carbide blades.	Snowplows are Frink and Henderson. Motorgraders were not available during this test period. Cutting edges on snowplows are carbon blades.
7.4 Storage/manufacturing facilities for anti-icing chemical:	12,000-gal storage tank at maintenance station.	10,000-gal tanks with recirculation in Glenwood Springs at MM 116 and in Dotseto at MM 134.	Salt is stored in 300- and 600-ton salt shed. Salt/sand mixture is mixed and stored in an outdoor bin. Brine is stored in a 1050-gal tank.
7.5 Other information:	Blank	Blank	None.

Table 64. Site survey responses: California, Colorado, and Iowa (continued).

	California	Colorado	Iowa
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES			
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:	Black Butte Summit, about 2-1/2 mi north of the test section.	On location at mile marker 118, sensors on control side only.	Tower is located in northeast quadrant of Iowa 5 and I-35. One bridge sensor is located on Raccoon River Bridge in northbound right lane. Second bridge sensor is on westbound lane of Iowa 5. A surface and sub-surface sensor is in approach to bridge over I-35 in westbound lane.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc.	Surface Systems, Inc.	Surface Systems, Inc.
8.3 Types of weather and pavement sensors at or near site:	Surface temp, chemical factor, subsurface temp, air temp, wind speed and direction, precipitation, humidity.	One sub-surface probe, two pavement sensors - eastbound, all ambient condition sensors.	Surface sensors and sub-surface sensors.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	Asphalt concrete.	Blank	Northbound I-35 is PC bridge deck -- westbound Iowa 5 are in PC bridge deck and PCC approach.
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	Workstation is in office of maintenance station - available 24 h.	Full 24-h availability, work station at Hanging Lake Tunnel complex.	Main IBM PC is at Resident Maintenance Engineer's office at University Shop location. Portable PCs are available to supervisor and Resident Maintenance Engineer for 24-h availability.
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	National Weather Service - Redding, CA. Scancast provided by Surface Systems, Inc. for Black Butte.	Surface Systems, Inc. Scancast, television stations.	Surface Systems, Inc. - Scancast Pavement Forecasts and weather forecasts; and "Freeze-notis," weather forecasts - Both 24-h forecasts. Freeze-notis is once per day. Surface Systems, Inc. is twice per day.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	Scancast provided by Surface Systems, Inc.	Surface Systems, Inc. Scancast.	Surface Systems, Inc. -- Scancast pavement forecasts - 24-h forecasts twice per day (at noon and 3 a.m.).
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	Mostly for scheduling, somewhat for determining when additional salt may be warranted.	Call out trucks when there is snow and ice alert.	Freeze-notis weather forecasts are supplemented with Surface Systems, Inc. Scancast and weather forecasts to predict start and duration of storms.
8.9 Level of confidence that decision makers have in forecasts:	Fairly high level for scheduling.	Pavement forecasts progressively getting better. Atmospheric forecasts need improvement.	Fairly high level of confidence.
8.10 Other information:	Blank	Blank	An occasional night patrol may be used when weather forecasts conflict. Highway Patrol also notifies of sudden storms.

Table 64. Site survey responses: California, Colorado, and Iowa (continued).

	California	Colorado	Iowa
9. TRAFFIC COUNT INSTALLATIONS			
9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:	Weigh in motion (WIM) station able to give breakdown of all of above plus weight per axle.	Traffic counts for location with monthly reports. No speed information. No break down of distributions.	Hourly traffic counts are obtained for volume and classification of vehicles. Speed information is available when requested from the main office by computer through an automatic polling process.
9.2 Location(s) in or relative to test and control sections:	Traffic count only station approximately 1 mi north of test area. WIM station in the test and control areas.	MM 119.	1.3 mi north of Grand Avenue in both northbound and southbound directions at Station 202+88 (milepost 70) under the Fuller Road Bridge.
9.3 Other information:	Blank	Blank	None.
10. FRICTION MEASUREMENT			
10.1 Version number (2 or 3) of Coralba friction meter(s):	1991, #3465	3.	C-MU.
10.2 Make and model of friction measurement vehicle(s):	Dodge Spirit 1993, four-door.	1992 Chevy pick-up 1/2-ton 2-WD, 1986 Ford F150.	1989 GMC Sierra S.L. 1500.
10.3 Make and model of tires on friction measurement vehicle(s):	Goodyear P 185 70 R 14 M&S F32-S All-Weather Radials.	Goodyear All-Season F32-S.	Goodyear All-Weather Radials - P225/75/15.
10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?	No antilock system.	One does, one doesn't.	Yes - two-wheel.
10.5 Other information:	Blank	Blank	None.
11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION			
11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Pavement monitors/RWIS to supervisor (or acting supervisor) to operators.	Telephone, radio.	Forecasts are obtained after noon and used by shop supervisors to evaluate the need to send crews/keep crews due to impending storm. Operators decide independently and with supervisors whether or not to apply material during storms.
11.2 Chemical(s), abrasives or mixtures used on control section:	Salt and cinders, and mixtures of both.	< 3/8 in crushed aggregate with 5 percent salt.	Granular salt, sand with some calcium chloride added to inhibit sand from freezing, a salt/sand mix.
11.3 Initial treatment, timing, and application rate:	About 125 lb/lane-mi salt when road wet and pavement temp near or below 32°F.	Application after road is icy. Timing as needed. 500 lb/lane-mi (approx.).	No initial treatment. Materials are applied after the start of the storm at the rate of 250 lb/lane-mi.
11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:	Road/weather conditions. Scancast info.	When road ices up.	Not applicable.
11.5 Further treatments, timing, and application rate:	As necessary.	As needed.	Materials are applied after the start of the storm as needed at the rate of 250 lb/lane-mi.
11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:	Road/weather conditions.	Length of storm, condition of road.	The Equipment Operators decide independently and also with supervisors whether or not to apply material.
11.7 Plowing strategy:	Plow when there is snow on the road.	Plow surface as accumulation warrants it.	Continuous plowing of roadway and some shoulder plowing to reduce drifting.
11.8 Other information:	Blank	Blank	None.

Table 64. Site survey responses: California, Colorado, and Iowa (continued).

	California	Colorado	Iowa
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION			
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Pavement monitors/RWIS to supervisor (or acting supervisor) to operators.	Hanging Lake Tunnel staff to contact operators and relay current and forecast conditions. Operator decides when to apply chemicals.	Forecasts are obtained after noon and used by shop supervisors to evaluate the need to send crews or keep crews due to impending storm.
12.2 Chemical(s), abrasives or mixtures used on test section:	Liquid magnesium chloride with PCI rust inhibitor ("anti-icer"). Cinders if needed, but not often.	Magnesium chloride.	Brine applied within 1 h before start of storm; granulated salt; sand with calcium chloride to inhibit freezing of sand; salt/sand mixture within an hour before start and during storm at initial anti-icing treatment.
12.3 Initial anti-icing treatment, timing, and application rate:	35 gal/lane-mi of "anti-icer" liquid magnesium chloride with PCI rust inhibitor when road is wet and road surface near or below 32°F.	2 h prior to accumulation. 30 gal/lane-mi application rate (approx.).	Application of sodium chloride brine within 1 h before the start of the storm provided the temperature is 20°F or above.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	Road/weather conditions.	Temperature of pavement. Forecast of pavement temperature and weather conditions. Actual weather conditions. Visual inspection.	Two weather forecasts are used; supervisor's experience, the National Weather Service, T.V./radio, cross communication between snow removal areas from supervisors in adjacent areas.
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	As necessary.	Deicing application as needed at approx. 80 gal/lane-mi. Use of sanding abrasives when needed.	During storms at 20°F or greater. During the storm additional applications may be made using brine if temperature is 20°F or greater or using salt or salt/sand mixture above 20°F or using sand above or below 20°F.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	Road/weather conditions.	RWIS conditions and forecasts. Visual inspection.	Two weather forecasts; supervisor's experience, the National Weather Service, T.V./radio, cross communication between snow removal areas, observations, driveability of roadway, operator's experience.
12.7 Plowing strategy:	Plow when there's snow on the road.	Plow surface as accumulation warrants it. Removal of snow against type 4 in control and test section.	Continuous plowing of roadway and some shoulder plowing to reduce drifting.
12.8 Other information:	Blank	Blank	None.
13. NAMES OF PROJECT PERSONNEL			
13.1 Primary decision maker(s):	Kathy Coots.	Wayne Lupton, Del French.	Blank
13.2 Personnel for friction measurements and pavement surface observations:	Gene Freeman, Levi Toolenan, John Gut.	Phillip Anderle, Pat Hawkins.	Blank
13.3 Control section operators:	Various.	Patrol 12.	Blank
13.4 Test section operators:	Various.	Patrol 42.	Blank
13.5 Other personnel and description of role in project:	Blank	Blank	Blank
14. ADDITIONAL COMMENTS AND INFORMATION	Blank	Blank	Blank

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, °C = (°F-32)/1.8

Table 65. Site survey responses: Kansas, Maryland, and Massachusetts.

1. STATE AND SITE DESIGNATION	Kansas, U.S. 81, Cloud County	Maryland, U.S. 219, Garrett County	Massachusetts, I-95 and I 93, Boston Metro Area
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Roger Alexander: (913) 823-3754; David Kopsa: (913) 243-2559; Harry Brown: (913) 527-2520.	Nevin C. Bittner, Dwayne Bittner: (301) 746-8141, (301) 746-8142.	John F. Wollenhaupt: (617) 648-6100, x448; John Cummings: (617) 648-6100, x447.
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	The snowfall varies from 6 in to 44 in with 22 in the norm. The temperature varies from -26 to 86°F with normal lows of 20°F and normal highs of 45°F. The number of winter events is 12. Three basic conditions for storms and/or icing occur: rain changing to freezing rain then snow, light snow changing to heavy snow (13 in in 24-h period), and snow blowing and drifting. Mean wind speed 12 mi/h with speeds to 40 mi/h and peak gusts to 60 mi/h.	Last year Garrett County received 181 in of snow. Several storms, sleet and freezing rain and snow mixed were received. Most storms are accompanied with high winds 40-70 mi/h. Temperature ranges in general from 15-30°F with occasional lows of 0 - 15°F below zero. Record low is 46°F below zero. The average number of storms is 40. Most storms last for 2 to 3 d. Average snow depth per storm is 4 in.	22 storms/yr. Minor icing occurs frequently. Most storms are coastal with duration of 3 to 10 h. Storms during Jan-Feb-Mar are most frequent.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	206 E. 17th Street, Concordia, KS 66901. Control section is located 5 mi south of sub-area. Test section is located 2 mi north of sub-area.	Keysers Ridge Shop for test section. Oakland Shop for control section.	The maintenance section to be used as a base of operations is the "Apache Pass" Depot at the junction of Route 28 and I-95.
5. TEST SECTION INFORMATION			
5.1 Test section boundaries and length:	The length is 8 mi and extends from the north city limits of Concordia north to the U.S. 81/KS-148 junction. Reference point 204 to 212.	U.S. 219, northern limits of Accident, Maryland to Deep Creek Lake Bridge north abutment.	Test Section boundaries are beginning at Route 28 and I-95 north approximately 5.5 mi to Essex County line at Montrose Ave. turn-around. Then return southbound to Route 28 and I-95 junction (Apache Pass). A round trip of approximately 11 mi.
5.2 Pavement surface course:	Asphalt.	Bituminous Concrete.	Pavement surface is Standard Type I-1 Bituminous Concrete Asphalt.
5.3 Width and number of lanes:	Two 12-ft lanes.	12 ft - two lanes.	12 ft wide - three lanes and breakdown.
5.4 Width and number of shoulders:	Two 8-ft shoulders.	10 ft - two lanes.	10 ft wide - two shoulders.
5.5 Are shoulders to be treated?	No.	No.	No.
5.6 Total lane-miles of treatment:	17.	9.5 mi.	33 lane-mi.
5.7 RWIS pavement sensor locations within test section:	At the Republican River Bridge, reference point 204.81.	None.	No - all information will be coming from thermal mapping results.
5.8 Winter ADT:	3795.	Blank	120,000 to 150,000.
5.9 Other information:	Test section is located north of the control section.	1.1 mi of three-lane roadway, 0.20 mi of four-lane roadway.	Highway is divided with Jersey Barrier.

Table 65. Site survey responses: Kansas, Maryland, and Massachusetts (continued).

	Kansas	Maryland	Massachusetts
6. CONTROL SECTION INFORMATION			
6.1 Control section boundaries and length:	The length is 7 mi and extends from the U.S. 81/U.S. 24 junction north to the south city limits of Concordia. Reference point 190 to 197.	U.S. 219, south abutment of Deep Creek Lake Bridge to intersection of MD 39 in Oakland.	I-93 - Roosevelt Circle, 5 mi north - turn-around. Return to pit. Staging unit is at I-93 and Rt. 28 in Reading. Straight salt to be used in that area.
6.2 Pavement surface course:	Asphalt.	Bituminous Concrete.	Type I-1 State Top-Standard.
6.3 Width and number of lanes:	2-12 ft lanes.	12 ft - two lanes.	Four lanes and breakdown.
6.4 Width and number of shoulders:	2-8 ft shoulders.	10 ft - two lanes.	10 ft width - two shoulders.
6.5 Are shoulders to be treated?	No.	No.	No.
6.6 Total lane-miles of treatment:	14.	11.3.	40 mi.
6.7 RWIS pavement sensor locations within control section:	None.	None.	No.
6.8 Winter ADT:	3,490.	Blank	130,000 to 170,000/d.
6.9 Other information:	Control section is located south of test section and 8 mi south of RWIS site.	0.9 mi three-lane roadway.	Heavy traffic through both control and test areas.
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS			
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	1988 Ford L9000 10-yd^3, dump truck w/Epoke SW 4500 spreader; salt brine 28.7 gal/64.7 lb/2 lane-mi, prewet salt 213 lb/2 lane-mi.	Swenson spreader, control with Dickey John system. Manual calibration.	Chemical is calcium chloride to be spread out of an Epoke trailer spreader unit. Standard control unit.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	1986 INC 5-yd^3, dump truck w/Swenson stainless steel spreader w/hydraulic controls, 1250 lb/2 lane-mi. 1989 Ford 7-yd^3 dump truck w/Fiberglass products spreader w/electric over hydraulic controls, 1500 lb/2 lane-mi.	Swenson spreader, control with Dickey John system. Manual calibration.	Standard six-wheel spreader with automatic controls, 300 lb/lane-mi standard calibration.
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	For snowplows use 6 in x 3/4 in tungsten carbide cutting edges and for graders use 8 in x (5/8 in to 7/8 in) flame-hardened curved single-bevel cutting edges.	Champion grader 720 A. International 2500 dump trucks. Vaulk Snowplow - Vaulk cutting edge with carbon edges.	Standard steel plow cutting edges on standard plows. No wheels and shoes on plows.
7.4 Storage/manufacturing facilities for anti-icing chemical:	Anti-icing chemical is liquid salt brine. Manufactured in stock tank and stored in 1,900-gal tank.	Salt domes.	Storage Unit is at "Apache Pass," Rt. 28 and I-95. Two 10,000-gal storage tanks on concrete base.
7.5 Other information:	Blank	Blank	Chemical will be delivered by tanker.

Table 65. Site survey responses: Kansas, Maryland, and Massachusetts (continued).

	Kansas	Maryland	Massachusetts
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES			
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:	RWIS site is located in test section at reference point 204.81 Republican River Bridge.	N/A.	Rt. 128 Woburn - Burlington line and Rt. 128 and Rt. 1.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc.	N/A.	Vaisala Inc.
8.3 Types of weather and pavement sensors at or near site:	Atmospheric sensors include: relative humidity/air temperature sensor Thies/Surface Systems, Inc. #1.100.51.551/052-44018-2.5; precipitation sensor, optical infrared Surface Systems, Inc. #OPS; wind speed/direction sensor, RM Young #05103; surface sensor, Surface Systems, Inc. #16201D; and sub-surface temperature probe, Surface Systems, Inc. #S16UG-D. System installed December 1993.	N/A.	WAA-15 anemometer working in conjunction with WAV-15 wind vane, HMP-35D humidity and air temperature sensor, DRD-11A precipitation sensor, DRD-12 roadway surface condition temperature sensor, DTS-126 subsurface temp sensor. All attached to Milos computer system.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	Asphalt approach to bridge, and concrete bridge deck.	N/A.	Regular Type I-1 Bituminous Concrete Pavement.
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	No limits. Sub-area at Concordia, Area Office at Mankato and District Office at Salina.	N/A.	Computers will be installed in Boston office control station and at Arlington office snow and ice control station.
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	24-h forecast by Surface Systems, Inc., live weather radar through WSI, including forecast period required, zone forecasts from NWS, and weather channel on T.V. and local radio information from NWS.	National Weather Service, Weather Brief Program, local T.V./radio.	Weather Service Forecasting, Inc. A weather forecasting service will also be used with our thermal mapping and RWIS station sensors.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	Surface Systems, Inc. Scancast provided at 4 a.m. and 3 p.m. daily with updates on changes.	N/A.	Weather Service Forecasting Inc. used with RWIS and thermal mapping units.
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	Used to split crew for 24-h operation, normal 8 a.m. to 8 p.m., then 8 p.m. to 8 a.m. Use forecast and road condition to determine required treatment practice.	For prediction for size of storm and possible duration and possible start of storm and type.	RWIS data is not available at this time - current forecasts are only service used for snow and ice operations at this time.
8.9 Level of confidence that decision makers have in forecasts:	Major events (4 in more snow) fairly good, lesser events about 50 percent accurate.	Minimal.	Fairly confident in forecasts so far.
8.10 Other information:	Use nightwatch to check road conditions and weather system.	A partial system is used after normal work hours to provide reality monitoring of weather conditions.	Blank

Table 65. Site survey responses: Kansas, Maryland, and Massachusetts (continued).

	Kansas	Maryland	Massachusetts
9. TRAFFIC COUNT INSTALLATIONS			
9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:	Report can include two vehicle groups (Class 1-7 and Class 8-13) with counts and speed by hour of the day.	A traffic counter is located between the test and control section on U.S. 219.	Not sure at this time as to traffic counters and information - will fill in later.
9.2 Location(s) in or relative to test and control sections:	Continuous traffic counter located on U.S. 81 2.5 mi south of Belleville on U.S. 81. This is 6 mi north of the test section.	Between test section and control section.	Not sure - traffic counters should be located in both areas as of this time.
9.3 Other information:	Information provided by Bureau of Transportation Planning.	Blank	Blank
10. FRICTION MEASUREMENT			
10.1 Version number (2 or 3) of Coralba friction meter(s):	3.	2.	C-Mu.
10.2 Make and model of friction measurement vehicle(s):	1991 Pontiac 6000, 4-dr. Sedan.	Ford 1993 F-350 4x4.	Chevrolet 1/2-ton pickup Cheyenne.
10.3 Make and model of tires on friction measurement vehicle(s):	Goodyear F 32-S All-Weather Radial (steel-belted).	LT 235-85R 16 Goodyear.	FHWA - standard tires for testing.
10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?	No.	Yes - 4x4.	Yes, two-wheel - disconnected.
10.5 Other information:	Blank	Blank	Blank
11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION			
11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Have not used forecasts to begin treatment. Rely on operator visual observations or management observations to begin treatment.	From monitors to RME, ARME, HTM (decision makers) to team leaders and operators.	Weather service calls Snow and Ice Engineer Cummings. He makes decision to commence operations.
11.2 Chemical(s), abrasives or mixtures used on control section:	Chemical used is medium salt ASTM type I grade 1. Abrasive used is sand with 100 percent passing #4. Mixture of sand and fine salt from 8:1 to 1:1.	Mixture of sand/stone/salt 80/10/10; 65/10/25; 40/10/50; 100 salt. Rate of 200 lb/lane-mi.	Straight salt - icing we might use 50-50 sand/salt.
11.3 Initial treatment, timing, and application rate:	Slick spots develop and blowing snow will not add to the problem. Retreatment is possible at 2- to 3-h cycles. Application rate is 1000-2000 lb/2-lane-mi.	Generally, shortly after storm has started. Always start with 50 percent sand/stone and 50 percent salt mix and then shift to storm needs. 200 lb/lane-mi.	300 lb/lane-mi. As storm begins.
11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:	Visual observations.	Visual conditions of pavement as operator reported. Type of material determined by decision maker from experience.	Weather service to date. RWIS will be also used for test.
11.5 Further treatments, timing, and application rate:	Storm determines treatment by snowfall, wind speed, temperature at normal application rate. For blowing and heavy snow, treat vitals only. For ice, entire routes are treated 100 percent.	Determined by operators with review by team leaders and decision makers. All material changes made by decision makers as well as application rates.	Further treatments will be ordered usually at storm's end.
11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:	Visual observations.	Notification of need from operators; team leaders; or actual visit to road sections.	Weather forecasts - temperature readings - time of day - etc.
11.7 Plowing strategy:	Begin plowing when snow depth reaches 1 in. On two-way two-lane, plow from the center line out, including the paved shoulder.	Continuous plowing of roadway and shoulder areas. Plowing stops only if waiting for treatment to act.	When snow starts reaching depths of 1 in, all plows called out - plows will be placed on stand-by as soon as storm is received by forecasters.
11.8 Other information:	Blank	Trucks generally have 28 lane-mi except in known severe weather areas - sections will be shorter.	Blank

Table 65. Site survey responses: Kansas, Maryland, and Massachusetts (continued).

	Kansas	Maryland	Massachusetts
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION			
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Forecast used to determine state of readiness. Use pavement sensors, radar and forecast to determine treatment.	Same as control.	Monitors will be connected to computer system being monitored by snow and ice personnel who will be in contact with operators by radio and telephone.
12.2 Chemical(s), abrasives or mixtures used on test section:	*No Abrasives*. Liquid salt brine, prewetted salt at spreader spinner and medium salt.	40 percent sand, 10 percent stone, 50 percent salt per load at 200 lb/lane-mi app. rate.	Liquid calcium chloride - no abrasives - no salt.
12.3 Initial anti-icing treatment, timing, and application rate:	Treat 1 to 2 h before precipitation expected. Use liquid salt brine or prewetted salt. Brine rate is 60 lb to 195 lb/2 lane-mi and prewetted salt rate is 185 lb to 1000 lb/2 lane-mi.	Test section initial treatment by patrol generally just prior to or at first indication of snow. Rate 200 lb/lane-mi, timing as needed per pass.	Prior to storms beginning - application rates to be worked out.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	Forecast from combination of sources, pavement temperature forecast, RPU site data, radar and visual observations. Retreatment is possible at 2- to 3-h cycle.	Operator on patrol.	Weather forecast - thermal mapping computer and RWIS system - all in conjunction.
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	Surface condition will determine the treatment strategy. Vitals will be retreated as deemed necessary by operator and/or supervisor. Treatment rate up to 1000 lb/2 lane-mi.	Generally the operator assigned to section with reviews by team leader and decision maker on site.	If no storm (just icing) then applications will be every 2 h etc. as needed.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	Visual observations, friction measurements, weather forecasts and pavement conditions.	Same as 12.5	Forecasts and information from RWIS system.
12.7 Plowing strategy:	Begin plowing when snow depth reaches 1 in. On two-way two-lane, plow from the center line out, including paved shoulder.	Continuous plowing of roadway and shoulders, except when waiting for treatment to work.	When snow gets to point of plowing, all anti-icing will be stopped; anti-icing will be started again at end of storm.
12.8 Other information:	Blank	Blank	Blank
13. NAMES OF PROJECT PERSONNEL			
13.1 Primary decision maker(s):	David Kopsa, Supv., and Charles Wright, EO III.	Paul D. McIntyre, Robert C. Bowan, James A. Smith, Ron Hockman, Merle Frazee.	John Cummings - Snow and Ice Engineer, Dist. 4.
13.2 Personnel for friction measurements and pavement surface observations:	Andrew Asch, Lance Boyer and Bruce Coons, Mark Lyles with supervision by Harry Brown.	James Spear, Phil Fisher, Dwayne Bittner, Nevin Bittner.	John F. Wollenhaupt - Project Coordinator - Head of Testing - with staff.
13.3 Control section operators:	Max Bell, David Vopat and Richard Ramsey, Jim Krager.	Carl Kight, Dan Leroy Upole.	Private contractors to operate tanker trucks (to be named).
13.4 Test section operators:	Max Tate, Bruce Tracy.	Ken Sukow, William Murphy.	Private contractors to operate test trucks (to be named).
13.5 Other personnel and description of role in project:	Leland Tice, Mankato, Area Engineer; Marvin Wagner, Mankato, Area Superintendent; and Roger Alexander, Salina, Dist. Maint. Engr.	Cheryl Darby - Compiling Information, Dwayne Bittner - Overview of Project, Nevin Bittner - Overview of Project.	Peter Gaffater - Asst. to Project Coordinator.
14. ADDITIONAL COMMENTS AND INFORMATION	(1) Data Collectors, Belleville Const. Office, P.O. Box 81, Belleville, KS 66935-0068. (2) See items 7.1 and 7.2.	Blank	Other test personnel to still be named. Any information still needed, call John Wollenhaupt at (617) 648-6100, ext 448.

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, °C = (°F-32)/1.8

Table 66. Site survey responses: Minnesota, Missouri, and New Hampshire.

1. STATE AND SITE DESIGNATION	**Minnesota, I-35, Downtown Duluth**	**Missouri, Route 71 at Archie in Cass County**	**New Hampshire, Route 10, Hanover**
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Dean Cummins.	Bill Billings: (816) 241-0246; Ivan Corp: (816) 889-3350.	Stephen Gray: (603) 448-2654.
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	The estimated average number of events requiring the application of chemicals is 18. Almost all of the events are snowfalls with one or two frostings of bridge decks.	Snow, ice, sleet or a combination thereof. We expect 10 to 12 events.	NH experiences wide variety of storms. A typical winter will see snow, sleet, freezing rain or rain. Snowstorms vary in intensity, but usually have at least one major snow event with accumulations in the 16 in to 24 in range. The estimated number of events would be approximately 35 to 40.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	The Nopeming Truck Station is located approximately 10 mi south of the test and control site.	2 mi west of Route 71 in Archie, MO.	The patrol shed that maintains this section is located on Etna Road in Lebanon, approximately 6.7 mi from the test site.
5. TEST SECTION INFORMATION			
5.1 Test section boundaries and length:	Test section (both northbound and southbound) beginning at MP 256.270 and ending at MP 259.599.	Route 71 from the Bates/Cass county line northbound 5 mi to "half-way" turn-around. From log point 29.77 north to log point 24.77 in Cass County on Route 71.	The test section is a 5.04-mi stretch of Rt. 10 in the Town of Hanover. Site starts at the compact line by River Crest Road and proceeds north for 5 mi to a point just south of the Lyme/Hanover town line.
5.2 Pavement surface course:	Asphalt and portland cement concrete.	Concrete base with asphalt overlay.	Hot bituminous concrete.
5.3 Width and number of lanes:	12 ft lanes and two lanes in each direction.	Two lanes both 12 ft wide.	Two - 12-ft-wide lanes.
5.4 Width and number of shoulders:	Inside shoulder: 3 to 7 ft, outside shoulder: 10 ft.	Two shoulders inside 4 ft, outside 10 ft.	Two - 8-ft-wide shoulders.
5.5 Are shoulders to be treated?	No.	No.	Yes.
5.6 Total lane-miles of treatment:	Approximately 12 lane-mi.	10.	10.08 lane-mi.
5.7 RWIS pavement sensor locations within test section:	Located at MP 255.811 between the test and control section on the northbound. Two in bridge deck and one in the approach.	Route 71 over Grand River on south end of bridge in the lanes of traffic and the bridge approach.	Located 3.60 mi north of the compact line or the southerly terminus of the test section.
5.8 Winter ADT:		6,104.	Southern section = 7,800, northern section = 4,100.
5.9 Other information:	Automatic Traffic Recorder #102 located between test and control section at MP 255.8 in both northbound and southbound.	Blank	Blank

Table 66. Site survey responses: Minnesota, Missouri, and New Hampshire (continued).

	Minnesota	**Missouri**	**New Hampshire**
6. CONTROL SECTION INFORMATION			
6.1 Control section boundaries and length:	Control section beginning at MP 252.303 and ending MP 255.802.	From "half-way" turn-around 5 mi south to the Bates/Cass county line on Route 71. From log point 24.77 south to log point 29.77 in Cass County on Route 71.	Beginning at Hanover/Lyme town line and running north for 3.5 mi to Lyme Common.
6.2 Pavement surface course:	Asphalt and portland cement concrete.	Concrete base with asphalt overlay.	Hot bituminous concrete.
6.3 Width and number of lanes:	12-ft lanes with two lanes in each direction.	Two lanes, 12 ft wide.	Two - 12-ft-wide lanes.
6.4 Width and number of shoulders:	Inside should be 3 to 7 ft and outside 10 ft.	Two - 4 ft inside, 10 ft outside.	Two - 8-ft-wide shoulders.
6.5 Are shoulders to be treated?	No.	No.	Yes.
6.6 Total lane-miles of treatment:	Approximately 13.6 mi.	10.	7.0 mi.
6.7 RWIS pavement sensor locations within control section:	Located at MP 255.811 between the test and control sections northbound. Two in bridge deck and one in the approach.	One sensor on bridge deck.	None.
6.8 Winter ADT:		6184.	4100.
6.9 Other information:	Blank	Blank	Blank
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS			
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	CONTROLS: Liquid Spreader - Nido - Nido 90; Prewetting Spreader - Bristol - Dickey Johns; Dry Spreader - Swenson - Dickey Johns; Dry Spreader - Schmidt.	Dickey Johns ICS 2000 calibrated to spread 5-6 gal of $CaCl_2$ per ton of abrasive/salt mix. Henderson Chief cinder bed on Ford 800 dump truck. Sand salt mix - 1:1 calibrated at 400 lb/lane-mi on control and 200 lb/lane-mi on test section.	Test - Epoke SW2000 liquid spreader, ground-oriented controls, calibrated at dealer. Control - HIWAY 5-yd^3 sand/salt spreader. Control to control belt speed is in cab, gate opening set manually.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	Abrasives occasionally used in Control Sections. Dry Spreader - Swenson - Dickey Johns.	Henderson Chief cinder bed on Ford 800 dump truck. Sand/salt mix - 1:1 calibrated at 400 lb/lane-mi on control and 200 lb/lane-mi on test section.	Test - Liquid spreader not capable of distributing abrasives, if needed will have to move unit in. Sanding units not usually calibrated.
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	On trucks flame-hardened flat steel blades without shoes are used. No graders are used in either test or control sections.	Snowplows are manufactured by Missouri Highway and Transportation Department. Snowplow is mounted on a Ford 800 dump truck. The motor grader is a Fiat-Allis. All use carbon-tipped cutting blades.	Test and control sections will use FRINK SK 430 plows with carbide cutting edges.
7.4 Storage/manufacturing facilities for anti-icing chemical:	Salt, Salt/CMA mixtures are stored in three-sided wooden sheds. Liquid CMA is manufactured and stored in heated building at the Nopeming Truck Station.	$CaCl_2$ is stored in large enclosed poly tank. Salt/sand stored in salt storage building.	Storage of liquid potassium acetate will be at Patrol Shed located in Lebanon.
7.5 Other information:	Blank	Blank	Blank

Table 66. Site survey responses: Minnesota, Missouri, and New Hampshire (continued).

	Minnesota	Missouri	New Hampshire
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES			
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:	Located at MP 255.811.	On bridge over Grand River on Route 71.	Located on Rt. 10, 3.6 mi from southern terminus of test section.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc.	Surface Systems, Inc.	CRREL-operated weather station.
8.3 Types of weather and pavement sensors at or near site:	Blank	Two - surface temp and precipitation sensors. One - sub-surface sensor.	Air temp., wind speed and direction, relative humidity, pavement temperature at surface and 18 in down, and precipitation indicator.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	Outside of both test and control. Concrete pavement and concrete bridge deck.	N/A.	N/A.
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	RWIS workstations at District Headquarters and Maintenance Station. 8 h during work day and during storms.	RWIS workstation located at 5117 E. 31st St., Kansas City, MO. Decision maker has unrestricted access to workstation.	Information transmitted to CRREL - accessibility is 24 h/d by District 2 and hired weather forecaster.
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	Surface Systems, Inc. - Scan Weather Forecast; Wells - Weather Forecast; NWS-Forecast.	Surface Systems, Inc. Weather or Not Forecasting Service.	North Winds Weather will provide immediate to 5-d site-specific weather forecasting. Forecast will include timing of events (start, end) type of precipitation, accumulation and other pertinent data.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	None.	Surface Systems, Inc.	No provider of pavement forecasting. Raw data available to District Office and North Winds Weather, however forecasting is not anticipated at this time.
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	During the week, the Surface Systems, Inc. is used for scheduling shifts. Otherwise, pavement conditions determine snow and ice control operations. RWIS data are used to determine when and amount of chemical application.	Combine both forecasts and go with worst-case scenario. Staff the RWIS workstation 2-3 h in advance of storm and monitor the pavement sensors.	At present, NHDOT does not have RWIS data. Forecasts are used to alert crews of possible call out, type of treatments and duration of storm. Actual calling of crews not made until storm commences.
8.9 Level of confidence that decision makers have in forecasts:	The decision makers have a fair level of confidence in the weather forecast.	Track record indicates forecasts are correct 60-70 percent of the time.	Present forecast is rated fair. It is hoped that North Winds Weather will improve this situation.
8.10 Other information:	Blank	Blank	Blank
9. TRAFFIC COUNT INSTALLATIONS			
9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:	The automatic traffic recorder records only hourly traffic counts in each direction.	N/A.	Counters will provide two way information in 15-min increments of speed and traffic count. Do not have the ability to distinguish cars and trucks.
9.2 Location(s) in or relative to test and control sections:	The automatic traffic counter is located approximately 80 ft south of the RWIS.	N/A.	Test Section: 1.78 mi north of compact line and approximately 500 ft south of Pinneo Hill Road. Control Section: 1.92 mi north of Hanover town line.
9.3 Other information:	Blank	N/A.	Blank

Table 66. Site survey responses: Minnesota, Missouri, and New Hampshire (continued).

	Minnesota	Missouri	New Hampshire
10. FRICTION MEASUREMENT			
10.1 Version number (2 or 3) of Coralba friction meter(s):	Versions 2 and 3.	Blank	3.
10.2 Make and model of friction measurement vehicle(s):	1991 Plymouth Acclaim Sedan and 1989 Chevrolet 1/2-ton pick-up.	1992 Dodge Dynasty.	1993 Plymouth Sundance.
10.3 Make and model of tires on friction measurement vehicle(s):	Goodyear F32-S Radial Sedan P185/70/R14 pick-up P225/75/R15.	Goodyear F32-S Radials.	Goodyear F32-S.
10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?	Yes, with two-wheel system.	No.	Not anti-lock system.
10.5 Other information:	Blank	Blank	Blank
11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION			
11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Forecast is relayed to Supervisors by dispatchers. They, in turn, dispatch operators.	Data received from RWIS Workstation monitoring personnel. Data relayed to decision maker, which are interpreted and relayed to field personnel.	Weather report received in District Office and relayed to patrolman, who would then decide call-out time for equipment operator.
11.2 Chemical(s), abrasives or mixtures used on control section:	Sodium chloride - Sand.	Sand, salt, $CaCl_2$.	Straight salt or sand treated with salt.
11.3 Initial treatment, timing, and application rate:	Sodium chloride is put down as soon as possible after snow starts to accumulate. Application rate is determined by road condition and temperature.	Ideally, 20-30 min prior to frozen precipitation at calibrated rates of 400 lb/lane-mi.	Sleet/freezing rain: salt 300 lb/lane-mi, apply sand as needed. Snow temp above 20°F: salt 250 lb/lane-mi, apply sand as needed. Snow temp below 20°F: if dry pavement and snow blowing off no salt. If icing occurs, apply salt at 250 lb/lane-mi.
11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:	Supervisor uses forecast, road sensors and air temperature.	Presence of moisture and forecast for freezing temp furnished by RWIS.	Training and experience of working foreman and each section is looked at prior to ordering treatment.
11.5 Further treatments, timing, and application rate:	Supervisor uses braking action to determine further treatments and instructs operators as to timing and application rate. Observer uses friction meter to determine need for retreatment. He then notifies supervisor who determines time and application rate.	Continue monitoring conditions, reapply if conditions warrant.	Continual plowing throughout storm. Application of abrasives on hills and corners of traction. Final clean up involves an additional salt application of around 200 lb/lane-mi.
11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:	Same as 11.5.	See 11.4.	Training and experience of foreman.
11.7 Plowing strategy:	When build-up occurs, we use a train of plows and plow snow to the right. Then, continuous plowing occurs during snow event.	Plow when 1/2 in accumulation occurs on driving surface and continues until surface is clear.	Through storm to keep roadways scraped down as close as possible.
11.8 Other information:	We do not use shoes on our plows.	Blank	Blank

Table 66. Site survey responses: Minnesota, Missouri, and New Hampshire (continued).

	Minnesota	Missouri	New Hampshire
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION			
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Forecast is relayed to Supervisors by dispatchers. They, in-turn, dispatch operators.	Same as for Control.	Weather forecasts to District Office and then information relayed to site manager and patrol foreman.
12.2 Chemical(s), abrasives or mixtures used on test section:	80 percent Salt - 20 percent CMA mixture and liquid CMA for prewetting. Liquid CMA also used for anti-icing.	Sand salt and $CaCl_2$.	Liquid C-92 - sand as needed for traction.
12.3 Initial anti-icing treatment, timing, and application rate:	Blank	Ideally, 20-30 min before anticipated frozen precipitation occurs at calibrated rates of 200 lb/lane-mi.	Initial treatment of between 1/3 and 1/2 gal/1000 ft^2 of C-92 applied prior to commencement of winter event. In icing conditions application rates might be up to 1 gal/1000 ft^2.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	Air and road temperatures plus forecasted beginning of event are all factored in prior to decision to anti-ice.	See 11.4.	Weather forecast for site, temperature of pavement sensors, and experience of patrol foreman.
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	Observers are used during events to determine further treatments.	Based on RWIS information and operator experience.	Intermediate applications of C-92 or abrasives as needed.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	Same as 11.5.	See 12.5.	Friction test readings, pavement sensors, site manager and patrol foreman's experience.
12.7 Plowing strategy:	Same as 11.7.	Plow when 1/2 in accumulation occurs, continue until pavement is cleared.	Continual plowing throughout the winter event.
12.8 Other information:	Same as 11.8.	Blank	Blank
13. NAMES OF PROJECT PERSONNEL			
13.1 Primary decision maker(s):	Ed Fleege, Dean Cummins, Duane Butterfass.	Ivan Corp.	Field: Bill Estey, Patrolman, Warren Lathrop, Site Manger, Steve Gray, District Office.
13.2 Personnel for friction measurements and pavement surface observations:	Ed Fleege, Brad Bohlmann, Cindy Lillegaard, Larry Zywicki.	Monica Higgins, Kurt Becker, Bill Billings.	Warren Lathrop - Site Manager, Bill Estey - Patrolman.
13.3 Control section operators:	Willis Finifrock, Jeff Hall, Dan Sobczak, Cliff Mackey.	Charles McLanahan, Richard Evans.	Private truck owned by John Wing - operated by Robert Packard. State truck occasionally operated by Warren Burbank.
13.4 Test section operators:	Willard Quiram, Tom Jacobson, Jack Janousek, Monica Hendrickson.	Charles McLanahan, Richard Evans.	Wayne Brown.
13.5 Other personnel and description of role in project:	Al Bostrom and Bob Derfler are back-up Supervisors for Duane Butterfass, sub-area Supervisor.	Barbara Flannagan - RWIS Workstation Monitor.	Peter Thompson - Equipment, Bob Lyford - Data Collection of Traffic Recorders, Dan Williams - Area Supervisor, Barry Curren.
14. ADDITIONAL COMMENTS AND INFORMATION	Blank	Blank	Blank

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, °C = (°F-32)/1.8

Table 67. Site survey response: New York.

1. STATE AND SITE DESIGNATION	**New York State Department of Transportation, Route 104 Research Site, Webster, New York, "N.Y. 104."**
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Gene Taillie, Project Manager, office: (716) 586-4514 or (716) 265-6803; mobile: (716) 733-5548. Mark Fuller, Asst. Project Manager, office: (716) 265-6800; mobile (716) 733-5547.
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	The mechanisms driving winter weather storms in the area of the research site, "NY 104" are lake effect and synoptic storms. The mix in this area is approximately 50 percent lake effect storms and 50 percent synoptic storms. During the snow and ice season (mid-November through mid April) it would be common to have in excess of 75 storm events. A storm event is any condition requiring chemical, mechanical, or a combination of both to maintain trafficable highways. The general classification of storm and/or icing events during the snow and ice season for lake effect and synoptic storms includes the categories: rain storm, sleet storm, ice storm, wet snowstorm, and dry snowstorm. Atmospheric conditions encountered at the NY 104 Research Site during any general storm classification can include one or all of the following: rain, sleet, freezing rain, popcorn snow, wet snow, dry snow, hail, high winds, high humidity, low humidity, warming trends, and prolonged sub-zero temperatures. For the purposes of this project, a storm is any condition that requires the application of chemical or abrasive, the use of mechanical means to remove snow or ice, or a combination of both on the research section of highway. As a result, the duration of a single storm may range from a few hours to several days and encompass one or all of the conditions described above. A storm for purposes of this matrix will be classified by the predominate precipitation/condition associated with it, but this could be misleading due to the tremendous number of changing conditions that could surround storms of similar type. It is suggested that each storm be viewed independently during the time it occurs, all the unique conditions that occur during its duration are considered, and in perspective with the entire winter. Without this approach, to view a single storm classification with its endless combination of conditions and variations, could be tremendously misleading in terms of what is effective in either an anti-icing or de-icing approach.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	New York State Department of Transportation, Webster Sub-Station, 840 Salt Road, Webster, New York.

Table 67. Site survey response: New York (continued).

<table>
<tr><th></th><th>New York</th></tr>
<tr><td>5. TEST SECTION INFORMATION</td><td></td></tr>
<tr><td>5.1 Test section boundaries and length:</td><td>The main line test section of highway lies east and west, bordered by Monroe Wayne Co. Line Road on the east and Bay Road on the west. Total length of the main line test section is 6.952 mi. The service road test section of highway lays east and west, bordered by Route 250 on the east and Five Mile Line Road on the west. Total length of the service road test section is 2.263 mi. The ramps test section of highway lays east and west, bordered by Monroe Wayne Co. Line Road on the east and Bay Road on the west. Total length of the ramps test section is 3.434 mi.</td></tr>
<tr><td>5.2 Pavement surface course:</td><td>Main Line: The main line test section of highway contains 1.900 mi of portland concrete beginning at Bay Road, mile marker 104-4303-5231, and ending at Five Mile Line Road, mile marker 104-4303-5251. The main line test section of highway also contains 4.756 mi of bituminous asphalt beginning at Five Mile Line Road, mile marker 104-4303-5251, and ending at Monroe Wayne Co. Line Road, mile marker 104-4303-5303. Service Road: The service road test section of highway contains 2.263 mi of bituminous asphalt beginning at Five Mile Line Road, mile marker 104-4303-5251, and ending at Route 250, mile marker 104-4303-5274. Ramps: The ramps test section of highway contains 3.434 mi of bituminous asphalt beginning at Bay Road, mile marker 104-4303-5231, and ending at Monroe Wayne Co. Line Road, mile marker 104-4303-5303.</td></tr>
<tr><td>5.3 Width and number of lanes:</td><td>Main Line - Two lanes, each lane 12 ft wide. Service Road - Two lanes, each lane 12 ft wide. Ramps - One to two lanes, each lane 12 ft wide.</td></tr>
<tr><td>5.4 Width and number of shoulders:</td><td>Main Line: Two shoulders. Left shoulders range from 4 to 6 ft wide. Right shoulders range from 10 to 12 ft wide. Service Road: No shoulders. Ramps: Two shoulders. Left shoulders range from 0 to 6 ft wide. Right shoulders range from 0 to 10 ft wide.</td></tr>
<tr><td>5.5 Are shoulders to be treated?</td><td>No, not intentionally.</td></tr>
<tr><td>5.6 Total lane-miles of treatment:</td><td>Main Line: 13.312 lane-mi. Service Road: 4.526 lane-mi. Ramps: 3.434 lane-mi.
21.272 total lane-mi.</td></tr>
<tr><td>5.7 RWIS pavement sensor locations within test section:</td><td>Sensor No. 1 located at mile marker 104-4303-5250 and is installed in the driving lane with a pavement surface course of portland cement concrete. The physical placement of the sensor is half way between the center of the driving lane and the left wheel track. Sensor No. 2 located at mile marker 104-4303-5246 and is installed in the driving lane with a pavement surface course of bituminous asphalt. The physical placement of the sensor is half-way between the center of the driving lane and the left wheel track. A total of nine additional sensors are located 2.183 mi west of the research site on the Irondequoit Bay Bridge. The location and numeric designation of each sensor is listed below.
<table>
<tr><th>Sensor #</th><th>Location</th><th>Structure</th><th>Surface Type</th></tr>
<tr><td>1</td><td>Westbound Passing Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>2</td><td>Eastbound Driving Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>3</td><td>Eastbound Center Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>4</td><td>Westbound Approach</td><td>Highway</td><td>Portland Concrete</td></tr>
<tr><td>5</td><td>Westbound Center Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>6</td><td>Westbound Driving Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>7</td><td>Eastbound Passing Lane</td><td>Bridge Deck</td><td>Portland Concrete</td></tr>
<tr><td>8</td><td>Eastbound Approach</td><td>Highway</td><td>Portland Concrete</td></tr>
<tr><td>9</td><td>Subprobe</td><td>Highway</td><td>Portland Concrete</td></tr>
</table></td></tr>
<tr><td>5.8 Winter ADT:</td><td><table>
<tr><th>Location</th><th>Direction of Travel</th><th>Mile Marker</th><th>Count</th></tr>
<tr><td>Research Trailer</td><td>Eastbound</td><td>104-4303-5250</td><td>23,429</td></tr>
<tr><td>Five Mile Line Road</td><td>Eastbound</td><td>104-4303-5246</td><td>22,273</td></tr>
<tr><td>Salt Rd./Phillips</td><td>Eastbound</td><td>104-4303-5282</td><td>12,592</td></tr>
</table></td></tr>
<tr><td>5.9 Other information:</td><td>Blank</td></tr>
</table>

Table 67. Site survey response: New York (continued).

	New York
6. CONTROL SECTION INFORMATION	
6.1 Control section boundaries and length:	The main line control section of highway lies east and west, bordered by Monroe Wayne Co. Line Road on the east and Bay Road on the west. Total length of main line is 6.952 mi. The service road control section of highway lies east and west, bordered by Route 250 on the East and Five Mile Line Road on the west. Total length of service road is 2.273 mi. The ramps control section of highway lies east and west, bordered by Monroe Wayne Co. Line Road on the east and Bay Road on the west. Total length of ramps is 3.201 mi.
6.2 Pavement surface course:	Main Line: The main line control section of highway also contains 5.25 mi of bituminous asphalt beginning at Monroe Wayne County Line Road, mile marker 104-4303-5303, and ending at Five Mile Line Road, mile marker 104-4303-5251. The main line control section of highway contains 1.900 mi of portland cement concrete beginning at Five Mile Line Road, mile marker 104-4303-5251, and ending at Bay Road, mile marker 104-4303-5231. Service Road: The service road control section of highway contains 2.273 mi of bituminous asphalt beginning at Route 250, mile marker 104-4303-5274, and ending at Five Mile Line Road, mile marker 104-4303-5251. Ramps: The ramps control section of highway contains 3.201 mi of bituminous asphalt beginning at Monroe Wayne County Line Road, mile marker 104-4303-5303, and ending at Bay Road, mile marker 104-4303-5231 .
6.3 Width and number of lanes:	Main Line - Two lanes, each lane 12 ft wide. Service Road - Two lanes, each lane 12 ft wide. Ramps - One to two lanes, each lane 12 ft wide.
6.4 Width and number of shoulders:	Main Line: Two shoulders. Left shoulders range from 4 to 6 ft wide. Right shoulders range from 10 to 12 ft wide. Service Road: No shoulders. Ramps: Two shoulders. Left shoulders range from 01 to 6 ft wide. Right shoulders range from 01 to 10 ft wide.
6.5 Are shoulders to be treated?	No, not intentionally.
6.6 Total lane-miles of treatment:	Main Line: 13.904 lane-mi. Service Road: 4.546 lane-mi. Ramps: 3.201 lane-mi. 21.651 total lane-mi.
6.7 RWIS pavement sensor locations within control section:	Sensor No. 3 located at mile marker 104-4303-5250 and is installed in the driving lane with a pavement surface course of bituminous asphalt. Sensor No. 4 located at mile marker 104-4303-5246 and is installed in the driving lane with a pavement surface course of portland cement concrete. A total of nine additional sensors are located 2.183 mi west of the research site on the Irondequoit Bay Bridge. The location and numeric designation of each sensor is listed below. Sensor # — Location — Structure — Surface Type 1 — Westbound Passing Lane — Bridge Deck — Portland Concrete 2 — Eastbound Driving Lane — Bridge Deck — Portland Concrete 3 — Eastbound Center Lane — Bridge Deck — Portland Concrete 4 — Westbound Approach — Highway — Portland Concrete 5 — Westbound Center Lane — Bridge Deck — Portland Concrete 6 — Westbound Driving Lane — Bridge Deck — Portland Concrete 7 — Eastbound Passing Lane — Bridge Deck — Portland Concrete 8 — Eastbound Approach — Highway — Portland Concrete 9 — Subprobe — Highway — Portland Concrete
6.8 Winter ADT:	Location — Direction of Travel — Mile Marker — Count Research Trailer — Westbound — 104-4303-5246 — 24,740 Five Mile Line Road — Westbound — 104-4303-5250 — 22,726 Salt Rd./Phillips — Westbound — 104-4303-5282 — 13,028
6.9 Other information:	Blank

Table 67. Site survey response: New York (continued).

	New York
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS	
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	The anti-icing research that began as SHRP H-208 in 1991 and continues as FHWA Project No. 28 today has resulted in an evolutionary process taking place with the spreader and prewetting equipment used by NYSDOT. To meet the requirements of the project changes to all standard configurations on spreaders and prewetting systems have been made by both manufactures and Department employees. This is true of both the equipment that existed in the department as research began in 1991, and that subsequently purchased directly for the project. The modifications range from minor refinements to major redesign efforts. Absolutely nothing used in terms of spreaders or prewetting equipment remains "box stock." These modifications are significant to note so that evaluations of equipment effectiveness for anti-icing or de-icing operations are weighted fairly and the findings placed in the proper perspective. The in-house calibration policy for spreader equipment used on the FHWA Project will attempt to calibrate all equipment prior to the start of the project and approximately every 30 d thereafter.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	The equipment used for chemical treatment is the same equipment used for abrasive treatment.
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	All plows and wings attached to trucks are equipped with a set of carbide blades protected by a steel cover blade. The plows and wings are also equipped with leveling shoes. Graders and snow blowers are not normally used on the research section of highway. If extreme conditions dictate their use, it will be noted at that time, as with the types of equipment as they are supplied to the research site by the department.
7.4 Storage/manufacturing facilities for anti-icing chemical:	The storage facility for solid anti-icing materials is a 1,500-ton domed facility. The fine (FC) salt is covered with tarps inside the domed structure. The traditional road salt is stored inside the dome uncovered. The ice control sand is generally stored outside, uncovered. When the ice control sand and traditional road salt are combined into a "mix" it is stored inside the dome when possible. The 32 percent concentration liquid calcium chloride is stored in a 2,500-gal tank and pumped into the single and/or twin 80-gal spreader saddle tanks as needed.
7.5 Other information:	See included samples of: traditional road salt, fine (FC) salt, and ice control sand. The mixing ratio of traditional road salt and ice control sand to produce the "mix" is 3 parts sand to 1 part salt.

Table 67. Site survey response: New York (continued).

	New York
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES	
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:	Production Surface Condition Analyzer (SCAN) System: Irondequoit Bay Bridge, Irondequoit/Webster New York. Pre-Production Surface Condition Analyzer (SCAN) System: Route 104/Five Mile Line Road, Webster, New York.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc. (SSI), 11612 Lilburn Park Road, St. Louis, MO 63146.
8.3 Types of weather and pavement sensors at or near site:	Near the NY 104 Research Site Production SCAN System: 1 - Theis air temperature sensor 1 - Theis relative humidity sensor 1 - R.N. Young wind-speed sensor 1 - WIVIS precipitation classifier 1 - Sub-probe sensor 8 - Surface sensors These sensors determine: ATMOSPHERIC DATA ATMOSPHERIC TEMPERATURE - The atmospheric temperature is the air temperature at the Remote Processing Unit (RPU). WIND DIRECTION - Wind direction is presented as three separate values: average, maximum, and minimum. The wind direction minimum indicates one extreme of the wind direction sweep, while wind direction maximum indicates the other extreme of wind direction sweep. Wind direction average represents the direction from which the wind was blowing the majority of the sample period. The average is the mean of 60 1-s samples over a 1-min period. WIND SPEED - The average wind speed indicates the average speed of the wind sampled over a 1-min period of time. A gust is the maximum wind speed measured over the sample period of time. The sampling procedure is to average the wind speed each 4 s and collect 15 4-s averages in the 1-min time interval. The largest of these 15 values is considered the gust value. RELATIVE HUMIDITY - Relative Humidity (RH) is the percentage of moisture that is present in the air. RH ranges from 10 percent to 100 percent. DEW POINT TEMPERATURE - The Dew Point Temperature is that temperature at which the air becomes saturated when cooled. PRECIPITATION - The precipitation sensor determines the presence or absence of precipitation. If precipitation is detected by the sensor, it is indicated by the display of a "Y". Lack of detection of precipitation is indicated by the display of an "N".

Table 67. Site survey response: New York (continued).

	New York
8.3 Types of weather and pavement sensors at or near site (continued):	PRECIPITATION TYPE AND INTENSITY - The Weather Identifier portion of the WIVIS reports the type of precipitation, the intensity, the precipitation rate, and the accumulation for the day. The sensor determines precipitation type and precipitation rate directly, then derives intensity and accumulation. The WIVIS can separate precipitation into rain, drizzle, snow and precipitation-type-not-distinguishable. The intensity is derived from the precipitation rate value, which falls into one of the National Weather Service intensity classes (light, moderate, or heavy). Precipitation type and intensity are combined to form the current precipitation status. Valid status entries are: R+ Heavy rain R Moderate rain R- Light rain S+ Heavy snow S Moderate snow S- Light snow P+ Heavy precipitation, type not distinguishable P Moderate precipitation, type not distinguishable P- Light precipitation, type not distinguishable L Moderate drizzle L- Light drizzle CL Clean sensor The measurement technique involves shining a light beam between a source and a receiver and allowing precipitation to fall through this beam. The light beam passing through falling snow or rain produces a characteristic "shadow" that can be related to the type of precipitation and the rate of precipitation. The amount of light energy at a given wavelength passing through the precipitation is a function of transmitted light at different wavelengths; the WIVIS can determine the precipitation type as rain, drizzle, or snow and ascertain the precipitation rate. PRECIPITATION RATE - The precipitation rate is a snapshot of the rate at a point in time. The rate is stored in the computer to the nearest one-thousandth and displayed in SCG as four digits. For values under 1.000 in/h, the rate appears in thousandths; for values between 1.000 and 9.999 in/h, the rate appears in hundredths. Snowfall is converted to water equivalent and the rate represents the rate of liquid equivalent in in/h. Because of the fluctuation of precipitation rates over short periods of time, the snapshot value is actually the average precipitation rate for the last complete 30-s compute cycle. The WIVIS is continually computing this average. Every 30 s, the RPU collects the latest value from the WIVIS and stores it for the next transmission to the CPU. DAILY PRECIPITATION ACCUMULATION - Starting at midnight each day, the RPU sets its Precipitation Accumulator to zero and starts summing the rainfall amount or snowfall liquid equivalent amount for the next 24-h period. Each 30 s the RPU computes the amount of water that would accumulate in that 30 s based upon the precipitation rate. The amount is then added to the previous value of the precipitation accumulation, thereby keeping a running sum of precipitation from the start of the day. This accumulation value is stored in units of a thousandth of an inch.

Table 67. Site survey response: New York (continued).

	New York
8.3 Types of weather and pavement sensors at or near site (continued):	SURFACE DATA SURFACE TEMPERATURE - The surface temperature is the temperature of the road surface at the sensor. The color shade of the sensor is approximately the same as the surrounding pavement surface when it is wet. The material used to fabricate the sensor has thermal characteristics similar to material used for pavement. These two factors ensure that temperature readings of the sensor simulate the temperature of the surrounding pavement very closely. SURFACE CONDITION - The surface condition is the state of the roadway surface. The actual state is based upon the information provided by the surface sensor plus atmospheric conditions such as the state of the precipitation sensor at the dew point temperature. CHEMICAL FACTOR - The Chemical Factor is a relative indication of chemical presence in the moisture on the surface. It is dependent on the amount of chemical and the amount of moisture present on the surface. Chemical Factor is presented on a relative scale ranging from 5 to 95 and is displayed in increments of 5. When the status indicates that moisture is present on the pavement and the pavement temperatures are below 50°F, the Chemical Factor will be displayed as a numerical value. When the surface reflects no moisture or the surface temperature is 50°F or higher, the Chemical Factor is not displayed. A decreasing Chemical Factor corresponds to a decrease of chemical or an increase in the amount of moisture on the surface sensor. SUB-SURFACE TEMPERATURE - The sub-surface temperature is the temperature at or near the interface between the subgrade and the material below the subgrade. The sub surface probe is located 17 in below the pavement surface and directly below one of the surface sensors. This temperature represents the reservoir of heat or the lack of sub-surface heat in the material that supports the roadway. The temperature is critical for the Scancast model, because it permits calculation of the heat into or out of the pavement from below.

Table 67. Site survey response: New York (continued).

	New York
8.3 Types of weather and pavement sensors at or near site (continued):	At the NY 104 Research Site Pre-Production SCAN System: 1 - Theis air temperature sensor 1 - Theis relative humidity sensor 1 - R.N. Young wind-speed sensor 1 - WIVIS precipitation classifier 2 - Sub-probe sensor 4 - Surface sensors These sensors determine: ATMOSPHERIC DATA ATMOSPHERIC TEMPERATURE - The atmospheric temperature is the air temperature at the Remote Processing Unit (RPU). WIND DIRECTION - Wind direction is presented as three separate values: average, maximum, and minimum. The wind direction minimum indicates one extreme of the wind direction sweep, while wind direction maximum indicates the other extreme of wind direction sweep. Wind direction average represents the direction from which the wind was blowing the majority of the sample period. The average is the mean of 60 1-s samples over a 1-min period. WIND SPEED - The average wind speed indicates the average speed of the wind sampled over a 1-min period of time. A gust is the maximum wind speed measured over the sample period of time. The sampling procedure is to average the wind speed each 4 s and collect 15 4-s averages in the 1-min time interval. The largest of these 15 values is considered the gust value. RELATIVE HUMIDITY - Relative Humidity (RH) is the percentage of moisture that is present in the air. RH ranges from 10 percent to 100 percent. DEW POINT TEMPERATURE - The Dew Point Temperature is that temperature at which the air becomes saturated when cooled. PRECIPITATION - The precipitation sensor determines the presence or absence of precipitation. If precipitation is detected by the sensor, it is indicated by the display of a "Y". Lack of detection of precipitation is indicated by the display of an "N".

Table 67. Site survey response: New York (continued).

	New York
8.3 Types of weather and pavement sensors at or near site (continued):	PRECIPITATION TYPE AND INTENSITY - The Weather Identifier portion of the WIVIS reports the type of precipitation, the intensity, the precipitation rate, and the accumulation for the day. The sensor determines precipitation type and precipitation rate directly, then derives intensity and accumulation. The WIVIS can separate precipitation into rain, drizzle, snow and precipitation-type-not-distinguishable. The intensity is derived from the precipitation rate value, which falls into one of the National Weather Service intensity classes (light, moderate, or heavy). Precipitation type and intensity are combined to form the current precipitation status. Valid status entries are: R+ Heavy rain R Moderate rain R- Light rain S+ Heavy snow S Moderate snow S- Light snow P+ Heavy precipitation, type not distinguishable P Moderate precipitation, type not distinguishable P- Light precipitation, type not distinguishable L Moderate drizzle L- Light drizzle CL Clean sensor The measurement technique involves shining a light beam between a source and a receiver and allowing precipitation to fall through this beam. The light beam passing through falling snow or rain produces a characteristic "shadow" that can be related to the type of precipitation and the rate of precipitation. The amount of light energy at a given wavelength passing through the precipitation is a function of transmitted light at different wavelengths; the WIVIS can determine the precipitation type as rain, drizzle, or snow and ascertain the precipitation rate. PRECIPITATION RATE - The precipitation rate is a snapshot of the rate at a point in time. The rate is stored in the computer to the nearest one-thousandth and displayed in SCG as four digits. For values under 1.000 in/h, the rate appears in thousandths; for values between 1.000 and 9.999 in/h, the rate appears in hundredths. Snowfall is converted to the water equivalent and the rate represents the rate of liquid equivalent in in/h. Because of the fluctuation of precipitation rates over short periods of time, the snapshot value is actually the average precipitation rate for the last complete 30-s compute cycle. The WIVIS is continually computing this average. Every 30 s the RPU collects the latest value from the WIVIS and stores it for the next transmission to the CPU. DAILY PRECIPITATION ACCUMULATION - Starting at midnight each day, the RPU sets its Precipitation Accumulator to zero and starts summing the rainfall amount or snowfall liquid equivalent amount for the next 24-h period. Each 30 s the RPU computes the amount of water that would accumulate in that 30 s based upon the precipitation rate. The amount is then added to the previous value of the precipitation accumulation, thereby keeping a running sum of precipitation from the start of the day. This accumulation value is stored in units of a thousandth of an inch.

Table 67. Site survey response: New York (continued).

	New York
8.3 Types of weather and pavement sensors at or near site (continued):	SURFACE DATA SURFACE TEMPERATURE - The surface temperature is the temperature of the road surface at the sensor. The color shade of the sensor is approximately the same as the surrounding pavement surface when it is wet. The material used to fabricate the sensor has thermal characteristics similar to material used for pavement. These two factors ensure that temperature readings of the sensor simulate the temperature of the surrounding pavement very closely. SURFACE CONDITION - The surface condition is the state of the roadway surface. The actual state is based upon the information provided by the surface sensor plus atmospheric conditions such as the state of the precipitation sensor at the dew point temperature. SUB-SURFACE TEMPERATURE - The sub-surface temperature is the temperature at or near the interface between the subgrade and the material below the subgrade. The sub-surface probes are located at sensor numbers 1 and 2, each installed 18 in below the pavement surface directly below the surface sensor. This temperature represents the reservoir of heat or the lack of sub-surface heat in the material that supports the roadway. The temperature is critical for a Scancast model because it permits calculation of the heat into or out of the pavement from below. FREEZE POINT OF SOLUTION ON PAVEMENT - The freeze point of solution on pavement is the temperature below which ice crystals will form in the liquid present on the surface. The freeze point will fluctuate based on pavement temperature, and the introduction or reduction of precipitation and chemicals. DEPTH OF SOLUTION - The depth of solution is the depth of liquid present on the surface. ICE PERCENTAGE ON PAVEMENT - The ice percentage on pavement is the percent by volume of total liquid that is ice on the surface. (The remaining percentage by volume is presumed to be liquid.) This begins when the freezing point of the solution is reached and continues until the final freeze temperature is reached and the percentage of ice on the pavement equals 100 percent.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	Sensor # — Location — Structure — Surface Type 1 — Westbound Passing Lane — Bridge Deck — Portland Concrete 2 — Eastbound Driving Lane — Bridge Deck — Portland Concrete 3 — Eastbound Center Lane — Bridge Deck — Portland Concrete 4 — Westbound Approach — Highway — Portland Concrete 5 — Westbound Center Lane — Bridge Deck — Portland Concrete 6 — Westbound Driving Lane — Bridge Deck — Portland Concrete 7 — Eastbound Passing Lane — Bridge Deck — Portland Concrete 8 — Eastbound Approach — Highway — Portland Concrete 9 — Sub-probe — Highway — Portland Concrete
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	Location — Equipment — Availability — Staff Regional Office — PC (IBM P70) — 0800-1700 M-F — Mgt. Monroe East Residency — PC (ALR Power Flex) — 24 h/d — All Webster Sub-Station — PC (IBM P70) — 24 h/d — All Mobil — PC (IBM 700C) — 24 h/d — Mgt. Mobil — PC (IBM 700C) — 24 h/d — Mgt. Mobil — PC (IBM 700C) — 24 h/d — Mgt. Mobil — PC (IBM 700C) — 24 h/d — Mgt. Mobil — Panasonic Data Term. — 24 h/d — Mgt.

Table 67. Site survey response: New York (continued).

	New York
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	ACCU WEATHER Inc.: ACCU WEATHER provides forecasts in plain language text and graphic formats accompanied by plain language weather map depicting anticipated snowfall rates and locations for all of New York State. The frequency of reports is dictated by weather. National Weather Services: National Weather Services provides forecasts in plain language text format. The frequency of reports is dictated by weather. Surface Systems, Inc.: Surface Systems, Inc. provides forecasts in plain language text and graphic formats for the immediate NY 104 area. These reports are received twice daily. Their staff is on duty 24 h/d to respond to questions and update forecasts. WOKR Weather Services: WOKR Weather Services provides site-specific forecasts in plain language text and graphic formats for DOT Residencies in Region 4, accompanied by regional and state wide maps depicting snowfall rates and locations. These reports are received at least twice daily, regardless of weather conditions (more often based on weather conditions), and forecast immediate weather patterns as well as a 5-d outlook. Their staff is on duty 24 h/d to respond to questions by department staff and update forecasts.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	Surface Systems, Inc.: Provides Scancast surface forecast for the Irondequoit Bay Bridge and immediate NY 104 research area. The reports are received twice daily. Their staff is on duty 24 h/d to respond to questions by department staff and update forecasts.
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	The currently available forecast services combined with the RWIS data are used to control the timing of plowing, chemical, abrasive, or a combination of these three for snow and ice control. They are also used to determine the correct types and quantities of chemical and/or abrasive for current and/or projected atmospheric and road conditions.
8.9 Level of confidence that decision makers have in forecasts:	The level of confidence the decision maker has in a forecast is directly related to which forecast products are being utilized and for what purpose. The more site-specific the maintenance requirements are, the greater the limitations of certain portions of products become. When the strengths of each product are combined, the confidence level of making the correct decision increases. The greatest limiting factors in the decision-making process are limitations of products and the learning curve associated with new products and techniques. This learning curve and the associated confidence level in weather forecasts and the decision-making process for snow and ice control is particularly long and difficult when dealing with a subject like meteorology, which is not an exact science. As a result, the learning curve varies greatly from individual to individual and storm to storm in developing the confidence and expertise to comfortably use all the information and tools at management's disposal. The following chart is a relative indication of the strengths and confidence level of each forecast product for our purposes in the anti-icing research project. This is not an evaluation of these products as they relate to other maintenance activities or other geographic location, either locally or internationally, and is purely subjective.

Vendor	Site Forecast	Local Forecast	Regional Forecast	Statewide Forecast	Pavement Temperature
ACCU WEATHER	N/A	Low	Medium	High	N/A
Nat. Weather Serv.	N/A	Low	Medium	Medium	N/A
Surface Sys. Inc.	Medium	N/A	N/A	N/A	High
WOKR Weather	Medium	High	High	N/A	N/A

Table 67. Site survey response: New York (continued).

	New York
8.10 Other information:	There is additional meteorological information on location in the form of weather radar systems. Following is a brief description of each. Data Transmission Network Corporation (DTN): The Data Transmission Network Corporation (DTN) is a satellite-based system that is tied into National Weather Service and Kavorus for its text and weather radar images. The information is received on a satellite dish located at the East Rochester Residency, with updates of radar images every 15 to 60 min. This unit for our purposes has two main menus for weather products that are generated on a modified PC. The Short Range Weather menu contains 37 weather products, including text forecasts, U.S. satellite images, U.S. radar composites, and 18 regional radar composites. The Long-Range Weather menu contains 16 weather products, including the National Weather Service Forecasts, 3- to 5-d, 6- to 10-d, 30-d, and 90-d forecasts. This product is extremely useful in tracking storms moving into our area that are outside the range of the local C-Band radar. The limitations locally are due to the lack of a National Weather Service Radar site close enough to Rochester area to detect lake effect snow. Specifications (DTN): ANTENNA Model: 6017 Size: 29.56 in F/D Ratio: 0.6 Foc. Length 17.74 in WSI Corporation: WSI is a PC-based radar imaging software product that ties into the National Weather Service and uses the NEXRAD radar imagery. This product is currently being evaluated in a number of locations across New York State. This product holds great promise, and if it meets the needs of decision makers at remote locations, it will be installed at the Monroe East Residency, Webster Sub-Station, and all mobile laptop computers. WOKR Color Weather Radar: The C-Band radar is distributed by WOKR and is received at all residencies in Region 4, including the Webster Sub-Station. This radar has an maximum operational range of 450 mi, but is most effective for snow and ice operations, particularity lake effect snow, between 60 and 125 mi. The radar image updates every 72 s and operates via phone lines. This is extremely helpful in determining position and intensity of precipitation. It defines both leading and trailing edges of the precipitation and displays intensity in shades of color overlaid on a regional map. This is especially useful for snow and ice operations, particularly during lake effect snow. This information is also recorded in a time-lapse format for the entire winter for later playback during storm evaluation and training seminars. Specifications (WOKR C-Band Color Weather Radar): TRANSMITTER-RECEIVER-SERVO UNIT Frequency: 5450- to 5825-MHz turntable. Peak power output: 250-kW minimum at the transmitter-receiver output waveguide flanges. Magnetron type: SFD 373. Pulse width: 2.0 µs. PRF: 250 PPS. Receiver: Logarithmic. Receiver dynamic range: 78-dB minimum. Receiver bandwidth: 0.5-MHz nominal. Receiver intermediate frequency: 30 Hz. ANTENNA ASSEMBLY Type: Elevation over azimuth. Azimuth travel: 360 degrees continuous. Elevation travel: -1 to +60 degrees. PARABOLIC ANTENNA Type: Horn-fed parabolic. Diameter: 8-ft solid, +40 dB. Polarization: Linear, horizontal. Gain: 40-dB minimum. Beamwidth: 1.65-degree maximum (-3 dB points).

Table 67. Site survey response: New York (continued).

<table>
<tr><th></th><th>New York</th></tr>
<tr><td>9. TRAFFIC COUNT INSTALLATIONS</td><td></td></tr>
<tr><td>9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:</td><td>Six separate locations are equipped with inductance traffic loop sensors manufactured by G.K. Instruments to record traffic volume and speed. Four traffic loop installations (two installations eastbound and two installations westbound) are placed in both the driving lane and the passing lane at each prototype pavement sensor location near the NYSDOT/Surface Systems, Inc. research site. Two traffic loop installations (one installation eastbound and one installation westbound) are placed in both the driving lane and passing lane near Salt Road. The traffic loops record traffic every 15 min, with counts separated into 15 distinct speed bins representing 5 mi/h intervals from 0 to 71+ mi/h.</td></tr>
<tr><td>9.2 Location(s) in or relative to test and control sections:</td><td><table>
<tr><th>Location</th><th>Direction of Travel</th><th>Mile Marker</th><th>Count</th></tr>
<tr><td>Research Trailer</td><td>Eastbound</td><td>104-4303-5250</td><td>23,429</td></tr>
<tr><td>Five Mile Line Rd.</td><td>Eastbound</td><td>104-4303-5246</td><td>22,273</td></tr>
<tr><td>Salt Rd./Phillips</td><td>Eastbound</td><td>104-4303-5282</td><td>12,592</td></tr>
<tr><td>Research Trailer</td><td>Westbound</td><td>104-4303-5246</td><td>24,740</td></tr>
<tr><td>Five Mile Line Road</td><td>Westbound</td><td>104-4303-5250</td><td>22,726</td></tr>
<tr><td>Salt Rd./Phillips</td><td>Westbound</td><td>104-4303-5282</td><td>13,028</td></tr>
</table></td></tr>
<tr><td>9.3 Other information:</td><td>The G.K. traffic count equipment was upgraded in February 1994 with Diamond Traffic Products equipment. All Diamond-equipped counting stations are a modified model TT-2001-2RT-4L.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>10. FRICTION MEASUREMENT</td><td></td></tr>
<tr><td>10.1 Version number (2 or 3) of Coralba friction meter(s):</td><td>Version 3.06.</td></tr>
<tr><td>10.2 Make and model of friction measurement vehicle(s):</td><td>1992 Chevrolet Corsica.</td></tr>
<tr><td>10.3 Make and model of tires on friction measurement vehicle(s):</td><td>Goodyear 185/75R/14.</td></tr>
<tr><td>10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?</td><td>Yes, four-wheel system.</td></tr>
<tr><td>10.5 Other information:</td><td>An attempt is being made to replace the Corsica/Coralba with a different type of friction-measuring vehicle that would better lend itself to the peculiarities of the NY 104 site.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION</td><td></td></tr>
<tr><td>11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:</td><td>Flow of information:<table>
<tr><th>Resource</th><th></th><th>Mode</th><th></th><th></th><th>Resource</th></tr>
<tr><td>SSI support</td><td><---></td><td>Phone/voice <---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>WOKR support</td><td><---></td><td>Phone/voice <---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>ACCU WEATHER</td><td>---></td><td>Phone/FAX ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>DTN forecast</td><td>---></td><td>Satellite/PC ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>WOKR forecast</td><td>---></td><td>Phone/FAX ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>SSI Scancast</td><td>---></td><td>Phone/PC ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>SSI graphics</td><td>---></td><td>Phone/PC ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>DTN radar</td><td>---></td><td>Satellite/PC ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
<tr><td>WOKR radar</td><td>---></td><td>Phone/PC ---></td><td>Decision makers</td><td><---></td><td>Staff</td></tr>
</table></td></tr>
<tr><td>11.2 Chemical(s), abrasives or mixtures used on control section:</td><td>Traditional road salt, snow and ice control sand, or a combination of both.</td></tr>
<tr><td>11.3 Initial treatment, timing, and application rate:</td><td>The initial treatment is dependent on the type and intensity of precipitation, pavement condition and temperature.</td></tr>
<tr><td>11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:</td><td>Weather forecasts, radar images, pavement sensor data, Scancast, discussions with meteorologists, department/project guidelines, staff feedback, visual observations, common sense.</td></tr>
<tr><td>11.5 Further treatments, timing, and application rate:</td><td>Further treatments, timing, and application rates are dictated by previous conditions, current conditions, anticipated conditions, and department/project guidelines.</td></tr>
<tr><td>11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:</td><td>Weather forecasts, radar images, pavement sensor data, Scancast, discussions with meteorologists, department/project guidelines, staff feedback, visual observations, common sense.</td></tr>
<tr><td>11.7 Plowing strategy:</td><td>Plowing should generally begin when snow depth reaches ½-in minimum to 1-in maximum.</td></tr>
<tr><td>11.8 Other information:</td><td></td></tr>
</table>

Table 67. Site survey response: New York (continued).

	New York
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION	
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Flow of information: Resource Mode Resource SSI support <---> Phone/voice <---> Decision makers <---> Staff WOKR support <---> Phone/voice <---> Decision makers <---> Staff ACCU WEATHER ---> Phone/FAX ---> Decision makers <---> Staff DTN forecast ---> Satellite/PC ---> Decision makers <---> Staff WOKR forecast ---> Phone/FAX ---> Decision makers <---> Staff SSI Scancast ---> Phone/PC ---> Decision makers <---> Staff SSI graphics ---> Phone/PC ---> Decision makers <---> Staff DTN radar ---> Satellite/PC ---> Decision makers <---> Staff WOKR radar ---> Phone/PC ---> Decision makers <---> Staff
12.2 Chemical(s), abrasives or mixtures used on test section:	Traditional road salt, fine (FC) salt, snow and ice control sand, 32 percent concentration liquid calcium chloride, or a combination of these materials.
12.3 Initial anti-icing treatment, timing, and application rate:	The initial treatment is dependent on the type and intensity of precipitation, pavement condition and temperature.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	Weather forecasts, radar images, pavement sensor data, Scancast, discussions with meteorologists, department/project guidelines, staff feedback, visual observations, common sense.
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	Further treatments, timing, and application rates are dictated by previous conditions, current conditions, anticipated conditions, and Department/Project guidelines.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	Weather forecasts, radar images, pavement sensor data, Scancast, discussions with meteorologists, department/project guidelines, operator feedback, visual observations, common sense.
12.7 Plowing strategy:	Plowing should generally begin when snow/ice depths on the highway surface reach 1/2 in minimum to 1 in maximum. These depths are somewhat arbitrary as initial plowing is highly dependent on type and consistency of precipitation in the atmosphere and on the road surface. Because of the variables present, plowing can begin with amounts of snow/ice depths of less than 1/2 in.
12.8 Other information:	Blank

Table 67. Site survey response: New York (continued).

	New York
13. NAMES OF PROJECT PERSONNEL	
13.1 Primary decision maker(s):	Day/Night Shift: Gene Taillie, Project Manager; Mark Fuller, Assistant Project Manager; Richard Mapes, Highway Maintenance Supervisor II. Day Shift: Frank Izquierdo, Highway Maintenance Supervisor I; Albert Carmichael, Highway Maintenance Supervisor I. Night Shift: Ralph Taliento, Highway Maintenance Supervisor I.
13.2 Personnel for friction measurements and pavement surface observations:	Day Shift: Bob Walker, Research Team Leader; Barbara Bilyk, Research Team Member; Andrea Day, Research Team Member; Dan Sekula, Research Team Member. Night Shift: Tony Austin, Research Team Leader; Mark Bush, Research Team Member; Ron Novak, Research Team Member; Annette Smith, Research Team Member.
13.3 Control section operators:	Day Shift: Steve Szkapi, Construction Equipment Operator; Rick Reynolds, Construction Equipment Operator; Ray Chiccino, Construction Equipment Operator; Howard Henderson, Construction Equipment Operator; Wilfred Parsons Jr., Construction Equipment Operator; Alonzo Parker, Construction Equipment Operator. Night Shift: Alex Brown, Construction Equipment Operator; Asento Thompson, Construction Equipment Operator; John Lombardi, Construction Equipment Operator; Art Mack, Construction Equipment Operator; Cliff Vickers, Construction Equipment Operator; Herman Platino, Construction Equipment Operator; Terry Abel, Construction Equipment Operator; Jim Blankenberg, Construction Equipment Operator.
13.4 Test section operators:	Day Shift: Steve Szkapi, Construction Equipment Operator; Rick Reynolds, Construction Equipment Operator; Ray Chiccino, Construction Equipment Operator; Howard Henderson, Construction Equipment Operator; Wilfred Parsons Jr., Construction Equipment Operator; Alonzo Parker, Construction Equipment Operator. Night Shift: Alex Brown, Construction Equipment Operator; Asento Thompson, Construction Equipment Operator; John Lombardi, Construction Equipment Operator; Art Mack, Construction Equipment Operator; Cliff Vickers, Construction Equipment Operator; Herman Platino, Construction Equipment Operator; Terry Abel, Construction Equipment Operator; Jim Blankenberg, Construction Equipment Operator.
13.5 Other personnel and description of role in project:	Dewey Amsler, Statewide Snow and Ice Coordinator; Peter E. White, Regional Highway Maint. Eng., Region 4; Jerry Kerwin, Asst. Regional Highway Maint. Eng., Region 4; Louis Bechle, Resident Eng., Monroe East Residency; Jim Parshall, Asst. Resident Eng., Monroe East Residency; Dennis Wright. Safety Engineer, Region 4.
14. ADDITIONAL COMMENTS AND INFORMATION	There are additional components gathering data or capable of gathering data, installed within the research site or available for the research site that will be addressed at a later date. There are also various pieces of equipment that are being evaluated for snow and ice control that have been supplied by vendors.

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, $^{\circ}C = (^{\circ}F-32)/1.8$

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70.

1. STATE AND SITE DESIGNATION	**Nevada, U.S. 395, Panther Valley**	**Ohio, Franklin County, I-71**	**Ohio, Madison County, I-70**
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Richard J. Nelson, P.E. - (702) 688-1250; Thor A. Dyson, P.E. - (702) 688-1250.	Ned Kerstetter, Jim Block: (614) 363-1251.	Ned Kerstetter: (614) 363-1251.
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	Snowstorms, freezing rain or sleet, rain, frost. Approximately 10 storms a season; storms last approximately 24-36 h.	Freezing rain, two-four events; 1 in-2 in snow, 20°F, little blowing, < 24-h duration, approximately 10 events; high winds, less than 4 in snow, temperature < 20°F, approximately 10 events; high winds, 4 in-10 in snow, temperature < 20°F, approximately two events; > 12 in snow, 20-30°F, approximately two events.	Freezing rain, 2-4 events; 1 in to 4 in snow, 20-30°F, little blowing, < 24-h duration, approximately 10 events; high winds, < 4 in snow, < 20°F, approximately 10 events; high winds, 4 in to 10 in snow, < 20°F, approximately two events; 12 in snow or greater, 20 to 30°F, approximately one event.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	Reno maintenance station is within 1/2 mi of the test section.	Grove City outpost located at I-71 and 665. Station at site.	West Jefferson ODOT about 3 mi from site.

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
5. TEST SECTION INFORMATION			
5.1 Test section boundaries and length:	U.S. 395, milepost 25.12 to milepost 31.35, northbound, Washoe County; length of test section is 6.23 mi. Both northbound lanes on U.S. 395 receive test chemical (Freezgard) treatment; however, only the driving lane is being tested with friction equipment vehicles.	I-71 southbound, Franklin County, mile marker 98 to 91.5, length 6.5 mi. SR 665 to Madison County line.	I-70 westbound, Madison County, mile marker 80 to 86, length 6 mi.
5.2 Pavement surface course:	Portland cement concrete.	Asphalt.	Asphalt (404).
5.3 Width and number of lanes:	Two lanes each direction - 12-ft lanes.	Two lanes, 12 ft.	Three lanes, 12 ft wide, 36 ft total.
5.4 Width and number of shoulders:	One 8-ft inside shoulder, one 8-ft outside shoulder.	Two, 5 ft to 10 ft.	Right shoulder 10 ft, left 2 ft.
5.5 Are shoulders to be treated?	No.	No.	No.
5.6 Total lane-miles of treatment:	12.46 mi; however, only 6.23 mi are tested with friction equipment.	13.	18 lane-mi.
5.7 RWIS pavement sensor locations within test section:	Yes, approximately at milepost 30.00. Road sensor is located in the bridge deck (Sensor #7). Elevation is approximately 5,060 ft.	I-71 and 62 northbound driving lane. In both bridge decks northbound and southbound.	Westbound driving lane east of 29 overhead a short distance.
5.8 Winter ADT:	From the 1992 Annual Traffic Report, below are listed by month the Average Daily Traffic (ADT) total for both northbound and southbound average traffic volumes. This information is obtained from a Continuous Traffic Recorder (CTR) located on U.S. 395, north of the Panther Siding north of Reno approximately at milepost 31.00. Daily traffic volumes are monitored on a continuous hourly basis. January - 37894, February - 39545, March - 41662, April - 43189, May - 43240, June - 44225, July - 44086, August - 44205, September - 47598, October - 42400, November - 39828, December - 38747.	19,700.	17,500.
5.9 Other information:	Altitude change within test section is approximately 700 ft. 4,500-5,200 ft at Golden Valley.	Blank	Blank

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
6. CONTROL SECTION INFORMATION			
6.1 Control section boundaries and length:	U.S. 395, milepost 25.12 to milepost 31.35, southbound, Washoe County; length of control section is 6.23 mi. Both southbound lanes on U.S. 395 receive abrasives and salt treatment; however, only the driving lane is being tested with friction equipment vehicles.	I-71 northbound, Franklin County, mile marker 91.5 to 98, length 6.5 mi. Madison County line to SR 665.	I-70 eastbound, Madison County, mile marker 80 to 86, length 6 mi.
6.2 Pavement surface course:	Portland cement concrete.	Asphalt.	Asphalt (404).
6.3 Width and number of lanes:	Two lanes each direction - 12-ft lanes.	Two - 12 ft.	Three lanes, 12 ft wide, 36 ft total.
6.4 Width and number of shoulders:	One 8-ft inside shoulder, one 8-ft outside shoulder.	5-10 ft, two.	Right 10 ft shoulder, left 1 ft.
6.5 Are shoulders to be treated?	No.	No.	No.
6.6 Total lane-miles of treatment:	12.46 mi; however, only 6.23 mi are tested with friction equipment.	13.	18.
6.7 RWIS pavement sensor locations within control section:	Yes, approximately at milepost 30.00. Road sensors are located in the roadway both in the driving lane and passing lane (Sensors #5 and #6). Elevation is at approximately 5060 ft.	I-71 and 62 northbound driving lane. Both northbound and southbound bridge decks.	Eastbound far left lane.
6.8 Winter ADT:	See above (5.8).	19,700.	17,500.
6.9 Other information:	None.	Blank	Blank
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS			
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	For test section, Epoke SW2000 Liquid Spreader is used. Calibration is checked yearly with the setting kept at 35 to 45 gal/lane-mi. For the control section, 5:1 ratio of sand to salt is used.	Epoke spreader on a tandem truck. If there are problems with it, a single-axle truck with a 55-gal liquid tank and Pengwyn spreader control will be used.	Single axle dump truck with Pengwyn system plus 55-gal liquid tank using 10 gal/ton of salt. Spreader rate setting set at 4 to get 200 lb/lane-mi.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	Spreaders are Little Chiefs by Swenson. Calibration is checked at the beginning of each winter season, with setting kept at approximately 1,200 lb/lane-mi and can be adjusted from 800 to 1,500 lb/lane-mi depending on existing conditions.	Same as above.	Same as above (except not using liquid).
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	Snowplows are reversible Henke plows with a carbide-tipped blades. Motorgraders are seldom used.	11-ft carbon tip.	11-ft carbon-tip snow blades.
7.4 Storage/manufacturing facilities for anti-icing chemical:	Storage - two 6,000-gal HDPE tanks. Morgan Emultech/Utah-manufactured chemicals (Freezgard).	3,000-gal fiberglass tank for liquid calcium. Sheds for salt.	West Jefferson, Ohio (outpost).
7.5 Other information:	None.	Blank	Blank

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES			
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:	U.S. 395, milepost 30.00, Panther Valley Bridge, Washoe County.	Remote at Hillard outpost located at I-270 off Roberts Rd.	London, Ohio, ODOT garage located on SR 42 S/E.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc.; ID #79.	Surface Systems, Inc.	Surface Systems, Inc.
8.3 Types of weather and pavement sensors at or near site:	Air temperature, relative humidity, bridge deck temperature, road temperature, subsurface temperature, wind speed and direction, chemical factors, wet pavement conditions.	Dew point, surface temperature, relative humidity, wind speed and direction, and chemical factors.	Gives air temperature, dew point, relative humidity, wind direction, wind speed, surface temperature, chemical factor, sensor number, location, status.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	N/A.	N/A.	Blank
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	Central processing unit (CPU)/workstation is located in the Dispatch Center. Supervisors can dial into the system through laptop or they can call Reno Road (Dispatch Center) for information via radio 24 h/d. Supervisors then can designate field personnel as required.	Hillard outpost, just a phone call or radio call away. In the same county 10 mi from site.	London ODOT Garage, available 24 h, decision maker's main office.
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	Surface Systems, Inc., and local meteorological consultant.	Scancast, cable T.V., weather channel.	Scancast, cable T.V., weather channel.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	Surface Systems, Inc.	Scan system sensors.	Scan system sensors.
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	Local area forecasters and consultant, Weather Channel - cable, RBIs Data, Northwest Weather Net, Inc., Surface Systems, Inc. Forecasts are used to determine staffing levels in anticipation to winter storm events.	Use Scan system to determine pavement temperature, chemical content on road, air temp., etc. Also use weather forecast to prepare for storm (this is not very reliable).	Use Scan system to determine pavement temperature, chemical content on road, air temperature, etc. Also use weather forecast to prepare for storm (this is not very reliable).
8.9 Level of confidence that decision makers have in forecasts:	60-70 percent.	<50 percent on weather forecast.	<50 percent on weather forecast.
8.10 Other information:	Forecasts in the Sierra Nevada Area can change rapidly due to the mountains. Because of our location on the lee side of the Sierra Nevada, storm events can rapidly develop or disperse. A better method would be hours of advance warning before an event. For Nevada, this is approximately 6-24 h.	Blank	Blank

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
9. TRAFFIC COUNT INSTALLATIONS			
9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:	1992 Annual Traffic Report: Traffic counts are available on a monthly and annual basis from FAU 650 (McCarran Blvd. Interchange) to Parr Blvd. Interchange on U.S. 395. Total ADT's for both northbound and southbound vehicles: 41,400 (93 percent passenger vehicles and 7 percent truck vehicles). From the Annual Speed Monitoring Program Report, it states that on U.S. 395 in Reno at MP 31.80 in Washoe County, 17,762 vehicles were measured with an average speed of 56.1 mi/h, median speed of 56.4 mi/h, and the 85th percentile is 62.9 mi/h.	Installation measures speed and length of vehicle to convert to car/truck distribution. Measures each lane of traffic. Stores data in 15-min intervals. Data downloaded once a week.	Installation measures speed and length of vehicle to convert to car/truck distribution. Measured each lane of traffic. Stores data in 15-min intervals. Data downloaded once a week.
9.2 Location(s) in or relative to test and control sections:	The CTR is located within the test section on U.S. 395, north of the Panther Siding, north of Reno at milepost 31.00 (approx.).	Located on I-71, 1-1/2 mi south of SR 62, which is inside the test section.	Located on I-70 1/2 mi east of the SR 29 interchange, which is in both sections on WB and EB sides.
9.3 Other information:	None.	No phone lines, data downloaded by person going to site.	No phone lines. Data downloaded by person going to site.
10. FRICTION MEASUREMENT			
10.1 Version number (2 or 3) of Coralba friction meter(s):	Two.	2.	2.
10.2 Make and model of friction measurement vehicle(s):	Chevrolet W/T 1,500.	89 Reliant, Plymouth.	89 Reliant, Plymouth.
10.3 Make and model of tires on friction measurement vehicle(s):	Goodyear P234/75RIS Mud and Snow, F32-S All-Weather Radials.	Goodyear, F32-S	Blank
10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?	Yes, two-wheel system.	No, two-wheel system.	No - two-wheel system.
10.5 Other information:	NDOT has expanded the use of Coralba friction meters to other maintenance supervisors.	Blank	Blank

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION			
11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Daily conference call(s) with maintenance administration, supervisors and meteorological consultants are performed. Weather reports from RWIS are posted for all maintenance personnel to review.	Decision makers have remote computer available for sensor data. Operators have radios in vehicles for contact with supervisors.	Decision makers have remote computer available for sensor data. Operators have radios in vehicles for contact with supervisors.
11.2 Chemical(s), abrasives or mixtures used on control section:	Abrasives/salt; premixed at 5:1 ratio.	Straight salt.	Salt.
11.3 Initial treatment, timing, and application rate:	Initial treatment is just prior to road surface turning white. Operators can adjust abrasives and salt, anywhere from 800 to 1,500 lb/lane-mi - this varies based on need.	As needed for de-icing. 400 to 600 lb/mi depending on conditions.	As needed for de-icing, 400 to 600 lb/2-lane-mi depending on conditions.
11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:	Operator's judgment is used; first application occurs just as road turns white and/or road sensors from RWIS indicate freezing pavement temperatures and trends.	Visual observation, anticipated storms, calls from patrol and sheriff. Scan system data.	Visual observation, anticipated storms, Scan system data.
11.5 Further treatments, timing, and application rate:	Treatment to continue after initial treatment as needed during storm event. Operator makes decision. Application rate: 800 to 1,500 lb/lane-mi as needed.	As needed; determined by operator. 400 to 600 lb/mi.	As needed, determined by operator.
11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:	Based on operators judgment, RWIS data, and/or road conditions.	Visual observation, Coralba friction readings, Scan sensor data.	Visual observation, Coralba friction readings, Scan sensor data.
11.7 Plowing strategy:	Two plows in tandem to clear both the passing and traveling lanes. U.S. 395 is to be plowed first - ramps and frontage roads are secondary.	Accumulation of snow and temperatures.	Approximately 1 in or more of snow accumulation or when slush buildup is excessive as determined by driver or supervisor.
11.8 Other information:	None.	Due to personnel, equipment and logistics of treatment plan, the same truck will do both the test and control sections.	Due to manpower and equipment availability and logistics of area being covered, the same truck does both the test and control section.

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION			
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Daily conference call(s) with maintenance administration, supervisors and consulting meteorologists are performed. Weather reports from RWIS are posted for all maintenance personnel.	Same as 11.1 - computers and radios.	Same as 11.1 - computer and radios.
12.2 Chemical(s), abrasives or mixtures used on test section:	Only Freezgard ($MgCl_2$) is used on test section; however, as a snowpack develops, maintenance personnel switch to conventional salt/abrasives for snow and ice control.	Salt mixed with liquid calcium.	Salt, liquid calcium chloride.
12.3 Initial anti-icing treatment, timing, and application rate:	Chemical is applied to roadway up to an hour prior to forecasting of freezing pavement or air temperatures. Approximately 35 to 45 gal/lane-mi are applied.	Hopefully, approximately 30 min before the storm, at a rate of 200 lb/mi at 1084 gal/ton of salt.	200 lb/lane-mi with 10 gal/ton of liquid calcium chloride. Approximately 30 min before storm.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	If pavement temperature is forecasted to freezing with precipitation and as it gets close to the forecasted freezing period, temperature trends are monitored to see if forecast is accurate. Radios, telephones, and laptop(s) are used to assist in the decision-making process on whether or not to apply Freezgard to the roadway.	Scancast, adjoining counties, time of day.	Scan system, weather forecasts, adjoining counties.
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	Treatment continues during a storm as needed with the monitoring of traffic, pavement conditions, and sensor readings from the RWIS. Once a pack or dangerous condition develops, application of the anti-icing treatment (Freezgard) is halted and conventional practices are instituted. The application rate of Freezgard is approximately 35 to 45 gal/lane-mi.	As needed.	As needed.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	Temperature and moisture, chemical factor, visual observation of road conditions, time of day, RWIS sensor(s) information, and operator's judgment.	Same as 11.6.	Same as 11.6.
12.7 Plowing strategy:	If snow develops on roadway, snowplows are ahead of Freezgard application equipment for effective results.	Same as 11.7.	Same as 11.7.
12.8 Other information:	None.	See 11.8.	See 11.8.

Table 68. Site survey responses: Nevada, Ohio I-71, and Ohio I-70 (continued).

	Nevada	Ohio, I-71	Ohio, I-70
13. NAMES OF PROJECT PERSONNEL			
13.1 Primary decision maker(s):	Tom Adams, Larry Burgess, Jim Boston, Joe Gnibus, and Randy Lopez.	Don Thomas.	Arnie Holley, County Supt.
13.2 Personnel for friction measurements and pavement surface observations:	Thor Dyson, Peter Booth, and Rick Washer.	Jim Block - friction, Don Thomas, Clearance Noblood.	Mick Green - friction, Arnie Holley, Jim Davis, John McSavaney, visual observation.
13.3 Control section operators:	Don Micalizzi, Anita Smith, Danny Rogers, Jim McConnell, Randy Lopex, Jim Boston, Victor Archuleta, Joe Gnibus.	Matt Snow, Doug Barber	James Buell, John McSavaney.
13.4 Test section operators:	Joe Gnibus, Jim Boston, and Randy Lopez.	Doug Barber, Matt Snow.	James Buell, John McSavaney.
13.5 Other personnel and description of role in project:	Reno Road (Dispatch Crew) reviews Surface Systems, Inc. (RWIS) computers for sensor information and informs operators/crew.	Ned Kerstetter overseeing project. Jim Robson, Tech Services - responsible for traffic data.	Ned Kerstetter - contact person, Jim Robson - Tech Services - responsible for traffic data.
14. ADDITIONAL COMMENTS AND INFORMATION	None.	Blank	Blank

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, °C = (°F-32)/1.8

Table 69. Site survey responses: Oregon, Washington, and Wisconsin.

1. STATE AND SITE DESIGNATION	**Oregon, Portland, I-5 I-405 Loop**	**Washington, I-90, King County, DOT District 1 Area 5**	**Wisconsin, I-43, Green Bay**
2. NAME(S)/PHONE NUMBER(S) OF SURVEY RESPONDENT(S)	Dick Parker: (503) 378-2318.	Mike Katzer: (206) 822-4161; Jim McBride: (206) 455-7116.	Allen C. Beyer: (414) 492-5701.
3. DESCRIPTIONS OF STORM AND/OR ICING EVENTS, AND ESTIMATED AVERAGE NUMBER PER WINTER SEASON	Frost morning ices - 10 per season. Freezing rain - 3 per season. Light snow - 2 per season.	Storm events are usually heavy rain turning to snow. Snowfall generally < 1-d duration, 6 in to 12 in, followed by a clear cold snap into low teens. Icing events are usually freeze-refreeze problems with temperatures into the 30s during the day and into the 20s at night, causing road condensation and ice on structures and in shady areas.	Winter season - November-April (approx.). Storm types - complete range from freezing rains to sleet, to snow. Temperatures range from sub-zero to above freezing. In addition to storms, there are frost occurrences, drifting snow, etc. Number of occurrences - 30 to 40 storms/yr.
4. LOCATION OF MAINTENANCE STATION RELATIVE TO SITE	4 mi north of site.	Area 5 Preston Maintenance facility is 1/2 mi from I-90 located within the test section.	Anti-icing equipment and operators work out of the Brown County Highway Department shop located approximately 8 mi from site. Anti-icing data collectors work out of the department of transportation, District 3 office, located approximately 8 mi from site.
5. TEST SECTION INFORMATION			
5.1 Test section boundaries and length:	Test section includes the top decks of the Fremont and Marquam bridges with the connecting I-5 and I-405 freeway sections (NB I-5 and SB I-405), plus the ramps leading to the top decks of both bridges: NB I-5 to top deck Fremont Br.; SB I-5 to top deck Fremont Br.; SB I-405 to WB U.S. 30; EB U.S. 30 to NB I-405; and the Kirby Street ramp to top deck of Fremont Bridge. This totals about 7 linear mi of roadway.	I-90 eastbound, milepost 18 to 31.	I-43 southbound lanes located in Brown County from Humboldt Road south to the CTH MM interchange. The driving and passing lanes will be treated, with only the driving lane being tested for friction.
5.2 Pavement surface course:	PCC deck.	PCC.	Continuous reinforced concrete pavement.
5.3 Width and number of lanes:	Two 12 ft lanes in ramp areas to five 12-ft lanes on top deck of bridge.	Four lanes, 12-ft width each.	Two - 12 ft lanes.
5.4 Width and number of shoulders:	Two - 8 ft.	10 ft right shoulder, 6 ft left shoulder.	Outside shoulder - 10 ft, median shoulder - 6 ft.
5.5 Are shoulders to be treated?	No.	No.	No.
5.6 Total lane-miles of treatment:	27.	48.	16.
5.7 RWIS pavement sensor locations within test section:	The RWIS sensors are located in the upper deck of the Fremont Bridge complex with at least one pavement sensor at each end of the structure in the test section.	I-90 just east of SR 18. One surface sensor and one subsurface sensor.	No, sensors are located in control section (NB lanes).
5.8 Winter ADT:	40,000 each way - total 80,000.	29,700.	Ranges from 9,240 to 11,270 on various segments within section (southbound only).
5.9 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
6. CONTROL SECTION INFORMATION			
6.1 Control section boundaries and length:	Control section includes the bottom decks of the Fremont and Marquam bridges with the connecting I-5 and I-405 freeway sections (SB I-5 and NB I-405), plus ramps leading to the bottom decks of both bridges: to SB I-5; bottom deck Fremont Bridge and the ramp from bottom deck Fremont Bridge to Kirby Street. This totals about 7 linear mi of roadway.	I-90 westbound, milepost 31 to 17.	I-43 northbound lanes located in Brown County from the CTH MM interchange to Humboldt Road. Only the driving lane will be tested for friction.
6.2 Pavement surface course:	PCC bridge deck.	PCC.	Continuous reinforced concrete pavement.
6.3 Width and number of lanes:	Two to five 12-ft lanes.	Four, 12 ft each.	Two 12-ft lanes.
6.4 Width and number of shoulders:	Two, 8 ft.	10-ft right shoulder, 6-ft left shoulder.	Outside shoulder 10 ft; median shoulder 6 ft.
6.5 Are shoulders to be treated?	No.	No.	No.
6.6 Total lane-miles of treatment:	27.	45.	16 lane-mi of control section (non-treatment).
6.7 RWIS pavement sensor locations within control section:	The RWIS sensors are located in the lower deck of the Fremont Bridge complex with at least one pavement sensor at each end of the structure in the control section.	None.	Yes, sensor located in the I-43 northbound driving lane, in the STH 172 interchange area.
6.8 Winter ADT:	40,000 each way, total 80,000.	29,700.	Ranges from 9,290 to 11,830 in various segments of the section (northbound only).
6.9 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
7. TREATMENT EQUIPMENT USED ON TEST AND CONTROL SECTIONS			
7.1 Chemical treatment equipment, spreader controls, and calibration policy:	Epoke SW 2000, Epoke prewet.	32,000 GVW truck with 1000-gal chemical holding tank. Epoke liquid spreader. Equipment is calibrated prior to first use and as needed through winter season.	Conventional: Truck #26, triaxle with 12 CY box, tailgate spreader with manual controls, to be upgraded to closed loop, ground-oriented automatic controls at a future date. Spreader calibrated to apply within range of 100 to 300 lb/lane-mi of sodium chloride (rock salt). Anti-ice: Truck #61, single-axle flat bed with 1500-gal brine tank. Truck will tow Epoke SW2000 Liquid Spreader calibrated to spread from 14 to 86 gal/lane-mi.
7.2 Abrasives treatment equipment, spreader controls, and calibration policy:	Epoke prewet sander, Epoke drag boxes and slip in V bottom sanders.	32, 000 to 54,000 GVW truck with either front or conventional dump bed and spinner. Spreader controls are hydraulic. Calibration is done late October and as needed during the winter.	Same as conventional, truck #26, calibrated to apply within range of 500 to 2000 lb/lane-mi of sand.
7.3 Snowplows, graders, and types of cutting edges on snowplows and graders:	Truck-mounted plows with rubber blades.	Steel or rubber bit. One 14-ft-width grader with steel or ice bits is used as needed. Two plows with steel edges, one plow with rubber edge, and additional trucks with rubber edges from Bellevue if available, 10-ft width.	Truck #26 - Reversible plow with carbide steel blade (doubled with regular blade to prevent breaking). Truck also equipped with wing plow. Grader #113 - pre-hardened Caterpillar blade.
7.4 Storage/manufacturing facilities for anti-icing chemical:	8,000-gal - above-ground tank.	One each 6500-gal storage tank.	Salt brine storage tanks and manufacturing apparatus are located at the Brown County Highway Department shop.
7.5 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
8. RWIS INSTALLATIONS, AND WEATHER AND PAVEMENT CONDITION FORECASTING SERVICES			
8.1 Locations of RWIS installations at the site, or nearest to site if outside of the test and control section boundaries:		Westbound I-90, near SR 18.	Installation is located on site at the I-43 interchange with STH 172.
8.2 Manufacturer of RWIS at or near site:	Surface Systems, Inc.	Surface Systems, Inc.	Surface Systems, Inc., St. Louis, MO.
8.3 Types of weather and pavement sensors at or near site:	The RWIS sensors are located in the upper (test section) and lower (control section) sections of the Fremont bridge complex with at least one pavement sensor at each end of the structure in each of the test and control sections.	Air temperature, pavement surface temperature, pavement sub-surface temperature, wind direction and speed, dewpoint, relative humidity, precipitation, chemical factor.	Meteorological data - Air temperature, dew point, precipitation sensor, relative humidity, wind direction (minimum, average, maximum), and wind speed (average and gusts). Roadway sensors - four sensors at site, one in I-43 NB driving lane, one in STH 172 approach lane, one in STH 172 bridge deck, and one subsurface sensor. Surface condition data recorded are pavement status (i.e., dry, wet, snow/ice alert, etc.), surface temperature, and chemical factors.
8.4 Type of pavement surface course that pavement sensors are embedded in, if outside of test or control section:	PCC bridge deck.	PCC within test section	Sensors located within control section, concrete pavement.
8.5 Location(s) of RWIS workstation(s), accessibility to decision makers, and limits on 24-h availability:	Accessible through laptop PC and maintenance district office.	10833 Northrup Way, Bellevue, WA, District 1, Area 5 Main Office. Open M-F 0730-1600. RWIS available to Maintenance Supervisor and above after normal working hours.	WDOT District 3 office and Brown County Highway Department both have terminals to access weather information; terminals are also portable and can be taken home during off-hours. These terminals can access both current data and forecasts, 24 h/d, 7 d/week.
8.6 Description and provider of weather forecasting services used for site and/or nearby highway sections:	We are acquiring a micro-forecast service.	NorthWest Weather Net by contract for area-specific forecasting.	Surface Systems, Inc. provides on-site weather data, surface conditions and 24-h forecasts, along with additional access to National Weather Service data and reports. Local media weather reports are also utilized.
8.7 Description and provider of pavement forecasting services used for site and/or nearby highway sections:	ERF company provides no pavement forecasting.	Surface Systems, Inc. installed sensors for real-time information.	Surface Systems, Inc. is weather service providing on-site pavement forecasts.
8.8 Current use of forecasts and RWIS data in conventional snow and ice control operations:	Basic planning. RWIS data are now used operationally.	Review daily forecasts from NW Weather Net and monitor real-time data from Scan system. Radical weather change updates provided to Area Supervisors via phone after normal working hours.	Use daily forecasts and current weather data to plan daily operations and provide assistance in making decisions on use of de-icing chemicals and abrasives.
8.9 Level of confidence that decision makers have in forecasts:	Moderate.	85 percent.	Forecasts have proved to be 70 to 80 percent accurate.
8.10 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
9. TRAFFIC COUNT INSTALLATIONS			
9.1 Capabilities of installation, e.g., period of reports, availability of speed information, and breakdown of traffic counts into car/truck distributions:	Hourly counts by lane are available - breakdowns for car/truck are HPMS sample - these are permanent.	Reports hourly, no speed or car/truck distributions.	Installations are capable of continuously recording traffic volumes and speed breakdowns. Separate count installations are in the northbound and southbound lanes, recording volumes at ½-h intervals in 5 mi/h increments. No car/truck distributions are being taken at this time other than by visual estimates.
9.2 Location(s) in or relative to test and control sections:	These three permanent counters are physically within the test and control sections.	Milepost 23.54 at PTR 826. Milepost 25.69 at SR 18, Oxing. Westbound within control section. Eastbound within test section - was out of service in February 1994.	One location in each of the control and test sections on I-43, southeast of CTH V.
9.3 Other information:	Blank	Blank	Blank
10. FRICTION MEASUREMENT			
10.1 Version number (2 or 3) of Coralba friction meter(s):	3.	C-MU.	Version 3.
10.2 Make and model of friction measurement vehicle(s):	1988 Chevrolet Citation.	GMC 1500 two-WD Extended Cab pickup.	1993 Chevrolet Cavalier Station Wagon.
10.3 Make and model of tires on friction measurement vehicle(s):	Project-specified Goodyear F32-S Radials.	P 235/R 75 15 Goodyear.	Goodyear F32-S, P185/75R14.
10.4 Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?	No.	Yes, two-WD.	Yes; four-wheel system.
10.5 Other information:	Backup is 1991 Dodge Dynasty with four-wheel antilock and Goodyear F32-S Radials.	Blank	

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
11. STRATEGY OF CONVENTIONAL OPERATIONS FOR CONTROL SECTION			
11.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	RWIS information is displayed at a central site. Crews are informed when icing is detected. Daily forecasting is fed to District and Section.	Modem/Fax/Phone to decision makers through 800-MHz mobile radio to operators.	Decision makers have direct access to terminals, communicating with weather information systems. This information is then communicated to the operators by direct contact, radio, or cellular phones.
11.2 Chemical(s), abrasives or mixtures used on control section:	Ethylene glycol wetted 1/4 in - #10 abrasives.	Sand/granular CG-90 10-to-1 mix.	Predominantly rock salt (sodium chloride) is used. Salt may be prewetted with liquid calcium chloride, or in extremely cold conditions, dry calcium chloride may be added to the salt. Salt-treated sand may also be used at times.
11.3 Initial treatment, timing, and application rate:	When ice is detected by RWIS or visually, treatment is initiated.	Treatment begins when either ice forms on the road or snow accumulations reach 0.25 in. Application rate is 750 lb/lane-mi. Treatments are repeated as needed to provide traction.	The treatment varies and is dependent on the type of storm, severity, temperature, etc. If it appears to be a packing-type snow, an early application of salt may be made as an anti-icing technique to prevent bonding. The salt application rate is 100 to 300 lb/lane-mi, and is dependent on conditions.
11.4 Basis of decision, and decision-making tools relied upon, for ordering initial treatment:	Eyeball.	Pre-sanding is done by monitoring temperature and experience of local conditions. Major treatments begin when ice starts to form on the pavement or there are snow accumulations.	Decisions are based on input from forecasts, current conditions, local enforcement reports, and actual conditions reported by both State and county personnel. Many decisions are also based on past experience and training.
11.5 Further treatments, timing, and application rate:	As needed.	As needed.	This again varies as explained previously. All factors are taken into account.
11.6 Basis of decision, and decision-making tools relied upon, for ordering further treatments:	Direct observation.	Visual inspection of conditions, reviewing forecasts.	Same as 11.4.
11.7 Plowing strategy:	When snow starts, plowing is initiated. If snow is packing and heavy, no abrasives are used.	Begin plowing when accumulations reach 1/2 in in the direction of major traffic flows.	Plowing is used to remove as much snow, hardpack and slush as possible, to minimize amount of chemical required to clean up pavement. If hardpack can't be removed by trucks, graders are called in to scrape. Chemical is used only to keep snow in plowable condition during storm, for cleanup after storm, or for extremely hazardous slippery conditions.
11.8 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
12. ANTICIPATED ANTI-ICING STRATEGY FOR TEST SECTION			
12.1 Line of communication from weather and pavement forecast/condition monitors, to decision makers, and to operators:	Section personnel have direct access to RWIS. Micro-forecast data will be on a dial-up or direct FAX line. ODOT radio and cellular phones are used to maintain communications.	Weather Net forecast people available 24 h/d, 7 d/week. One hard copy send to Bellevue each day with updates called in to residences or shop as needed. No access to Surface Systems, Inc. pavement monitors available to field personnel.	Decision makers have direct access to terminals, communicating with weather information systems. Any off-hour updates will be called in to district personnel from weather service. If warranted, district personnel will then notify county when to dispatch anti-ice equipment. Weather will continually be monitored by decision makers. This information is then communicated to the operators by direct contact, radios, and/or cellular phones.
12.2 Chemical(s), abrasives or mixtures used on test section:	Liquid CMA 25 percent.	None will be used during the test unless traction is needed in certain places. Then, straight sand will be applied.	Initial treatment, when conditions warrant, will be an application of the anti-ice treatment, a salt brine solution (sodium chloride and water). Conventional treatment will follow if required (11.2), using predominantly rock salt (sodium chloride). Salt may be prewetted with liquid calcium chloride, or dry calcium chloride may be added to salt if extremely cold conditions develop. Salt-treated sand may also be used if required.
12.3 Initial anti-icing treatment, timing, and application rate:	The initial anti icing application treatment is to be applied approximately 1 h prior to precipitation or icing at the equivalent rate of 100 (dry) lb (45 gal of liquid) of CMA/lane-mi.	Under snow conditions treatment hopefully will occur prior to snow sticking to the roadway. In icing conditions, it would be applied during hours when it would normally begin to freeze. Both applications would be 43 gal/mi, 101 lb/mi.	When temperatures are above 15°F, and other conditions warrant, an initial anti-ice treatment will be used. This will consist of spraying the test section with the salt brine solution in advance of the storm (approximately 2 h). The rate will be at an equivalent of approximately 100 lb/lane-mi of dry salt. On the Epoke liquid spreader, this would be a setting of 3 on the Servoset 22, which delivers 42.9 gal/mi.
12.4 Basis of decision, and decision-making tools relied upon, for ordering initial anti-icing treatment:	Section lead people will evaluate RWIS and micro-forecast and visual data.	Experience, weather report, temperature, and conditions within a 50-mi radius of test section.	The decision to apply the anti-icing treatment will be based on forecasted weather data from our weather information systems, in particular, anticipated pavement temperatures being greater than 15°F, storm type, duration, amount, temperature trends, winds, etc. Traffic conditions will also be considered (heavy peak-hour traffic may not allow for safe data collection).

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
12.5 Further anti-icing and/or deicing treatments, timing, and application rate:	Retreat will be based on visual observation, RWIS, and micro-forecast data.	Repeated applications will be applied until snow bottom begins to build, then the liquid will be suspended and straight sand applied to maintain traction. Application will be 101 lb/mi.	Additional anti-ice treatments during a storm will be considered if pavements are bared, additional precipitation is anticipated, and other weather factors considered in initial treatment are still favorable to this treatment. The application rate will be the same as the initial treatment at this time (equivalent of 100 lb/lane-mi of dry salt, or 42.9 gal/mi of solution). Otherwise, conventional deicing treatments will be used, if warranted.
12.6 Basis of decision, and decision-making tools relied upon, for ordering further anti-icing and/or deicing treatments:	As above.	Field personnel visual observations and skid test equipment; also, conductivity will be monitored with a Sobo meter.	The decision to reapply anti-icing treatment will be based on pavement condition, forecasted weather and pavement temperatures from weather information systems, and traffic patterns, much the same as our basis for decisions on the initial treatment.
12.7 Plowing strategy:	Accumulating snow will be plowed, with possible use of small amounts of abrasives.	Test and control areas will be plowed the same using two steel 10-ft plows, one 14-ft steel grader, and up to four rubber bitted plows.	Plowing is still relied upon to remove as much snow, snowpack or slush from pavement as possible to minimize amounts of chemicals needed to bare pavement. Graders may also be used to assist in this effort.
12.8 Other information:	Blank	Blank	Blank

Table 69. Site survey responses: Oregon, Washington, and Wisconsin (continued).

	Oregon	Washington	Wisconsin
13. NAMES OF PROJECT PERSONNEL			
13.1 Primary decision maker(s):	North Portland Maintenance personnel.	Phil George.	Department of Transportation, Allen C. Beyer and/or Carroll W. Halsted.
13.2 Personnel for friction measurements and pavement surface observations:	Gerry Plucar, Mike Gardner.	Mark Farmer, Section Supervisor.	Department of Transportation, Kristofer Hawley, Ken Lyman, Dick Conradt, and Jim Geurts.
13.3 Control section operators:	Varies.	C. Wolf, S. Wehmeyer, W. Kerlee.	Brown County Highway Department, John Palet (conventional truck with plow and spreader).
13.4 Test section operators:	Varies.	T. Colson, K. Bykonen, J. McBride.	Brown County Highway Department, Ric Van Vonderen (anti-ice brine truck) and John Palet (conventional truck with plow and spreader).
13.5 Other personnel and description of role in project:	Eric Brooks - training and backup - Coralba. Dick Parker - consulting and liaison.	Blank	Brown County Highway Department, Ed Kazik and Wayne De Valk, Patrol Superintendents, in charge of calling out county personnel and equipment upon notification from State personnel for anti-icing operations.
14. ADDITIONAL COMMENTS AND INFORMATION	Blank	Blank	This is a joint, cooperative effort between FHWA, who provides the funding and direction for the test; the Wisconsin DOT, who provides data collection personnel and immediate direction of the project, including initial decision-making in regards to when the anti-icing techniques will be applied; and the Brown County Highway Department, who will provide the manpower and equipment to plow and apply treatments for the winter maintenance operations on the test and control sections.

Approximate conversions to SI units: 1 in = 25.4 mm, 1 ft = 0.305 m, 1 mi = 1.61 km, 1 yd^3 = 0.765 m^3, 1 mi/h = 1.61 km/h, 1 gal = 3.785 L, 1 ton = 0.907 t, °C = (°F-32)/1.8

APPENDIX C. ADDITIONAL STORM DATA SETS

To support the cost data in chapter 6, "Cost Analysis," this appendix contains data history graphs that were not included in chapter 5, "Field Evaluation Results and Interpretation," but whose cost data were contained in chapter 6. Description of these graphs is given in section 4.2.1.

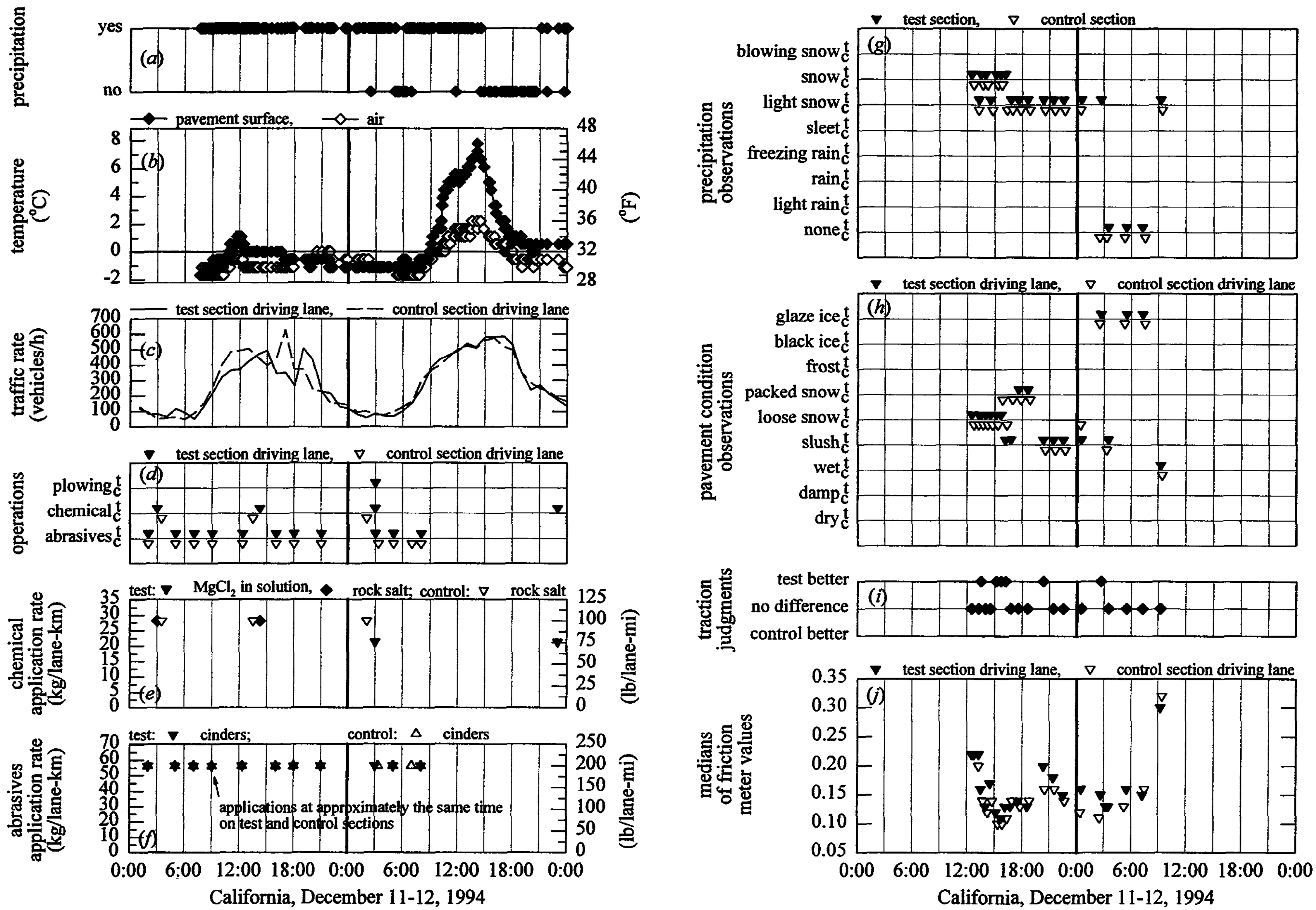


Figure 79. California, storm CA412B, December 11-12, 1994, data histories.

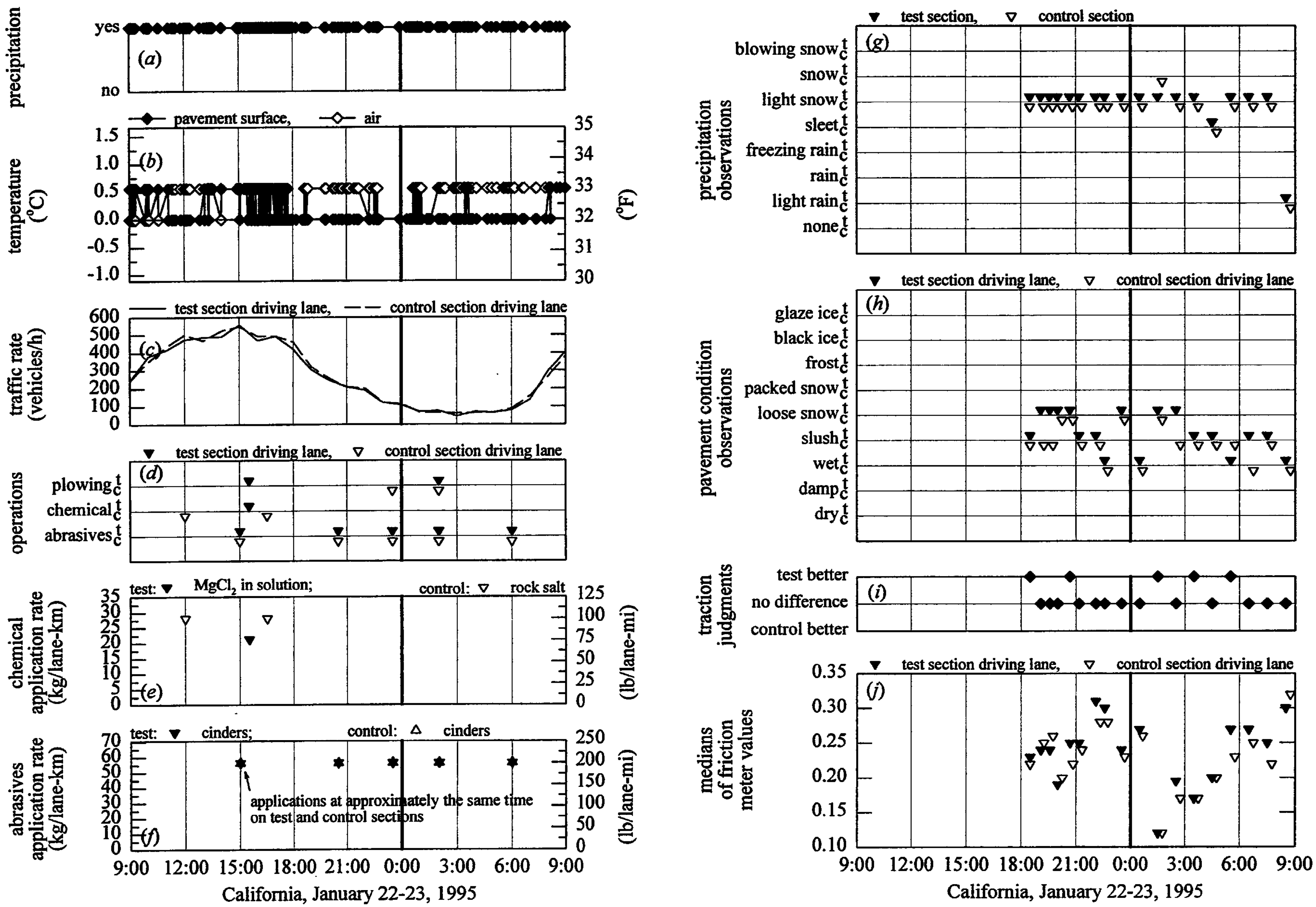


Figure 80. California, storm CA501B, January 22-23, 1995, data histories.

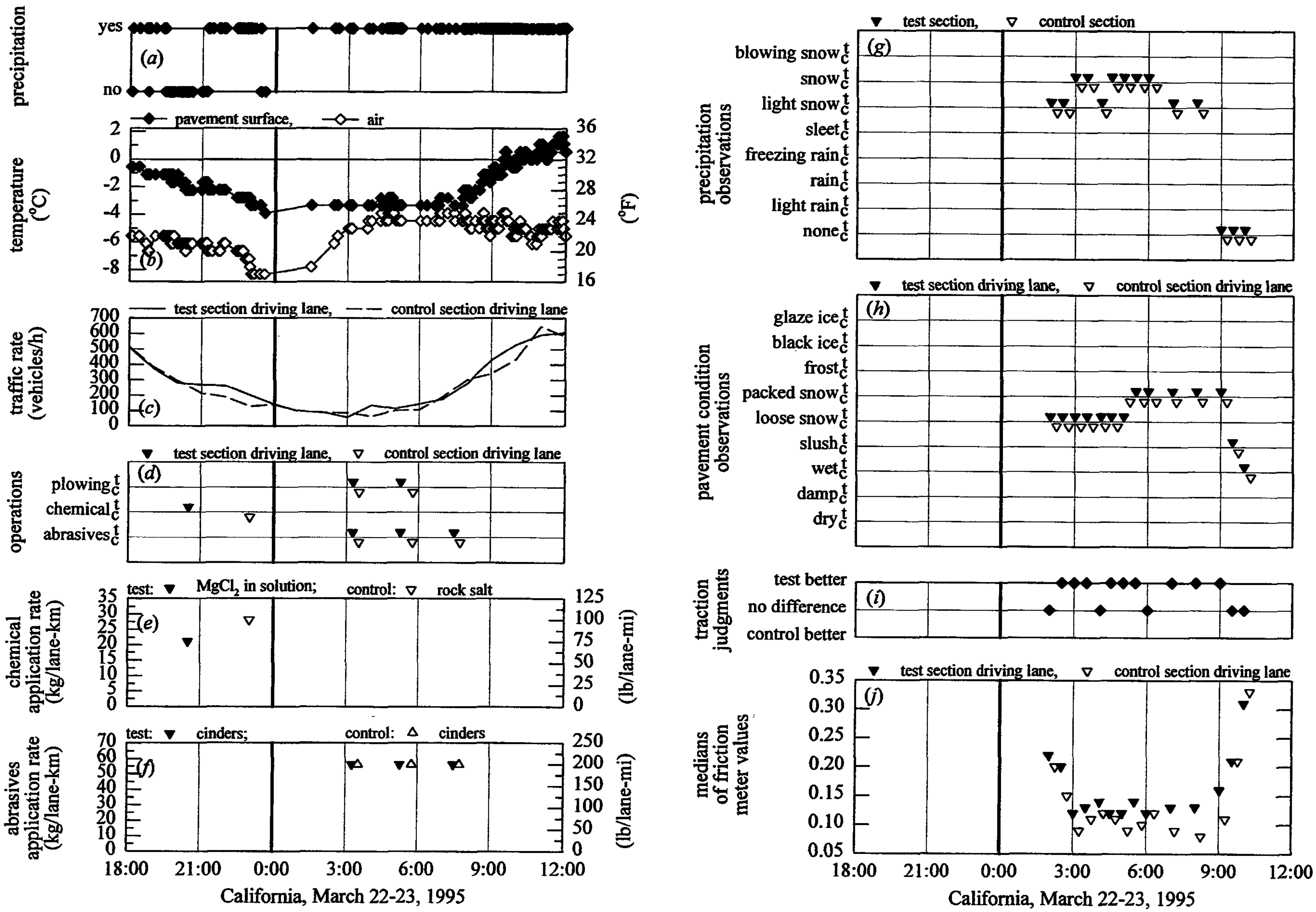


Figure 81. California, storm CA503A, March 22-23, 1995, data histories.

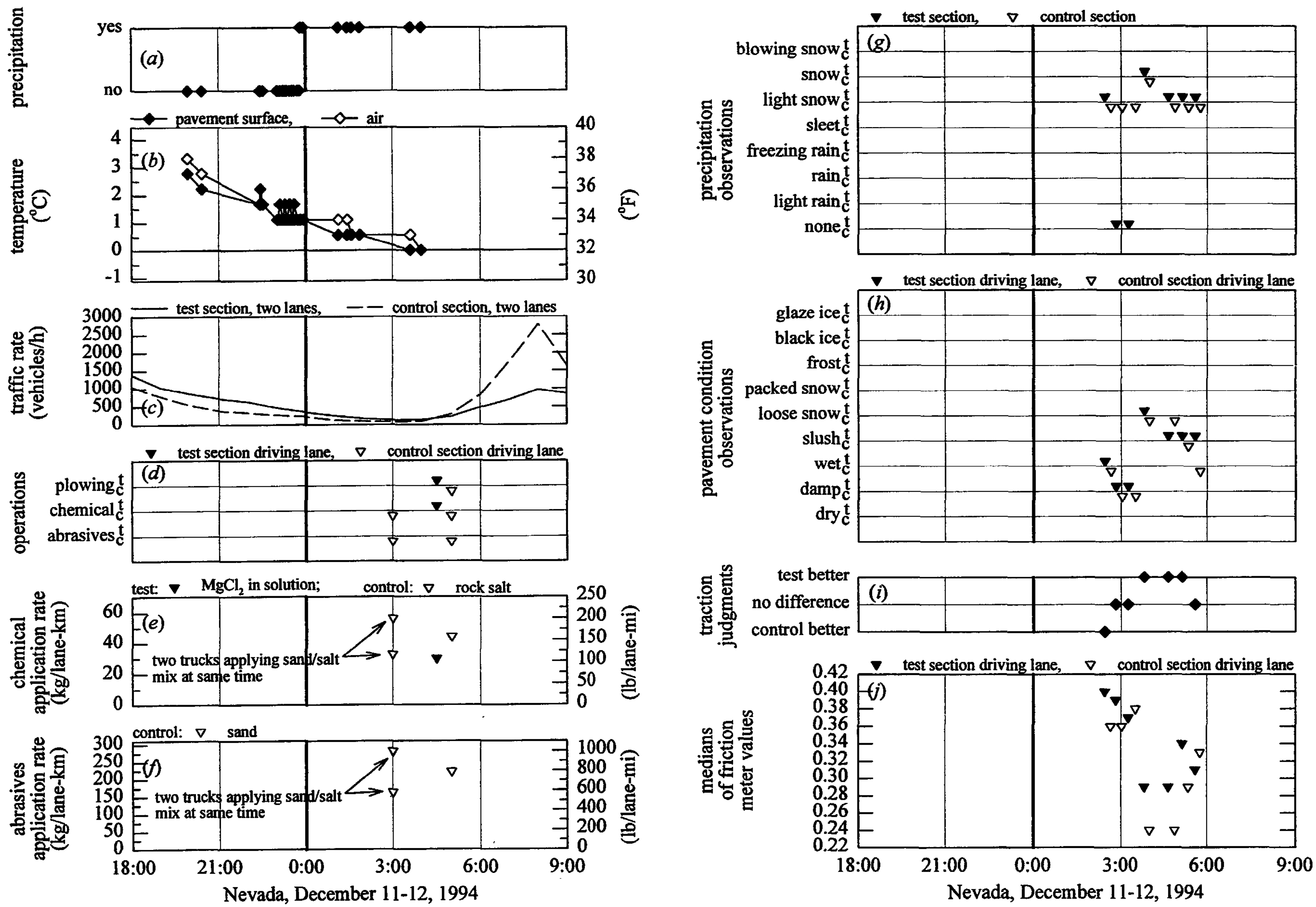


Figure 82. Nevada, storm NV412A, December 11-12, 1994, data histories.

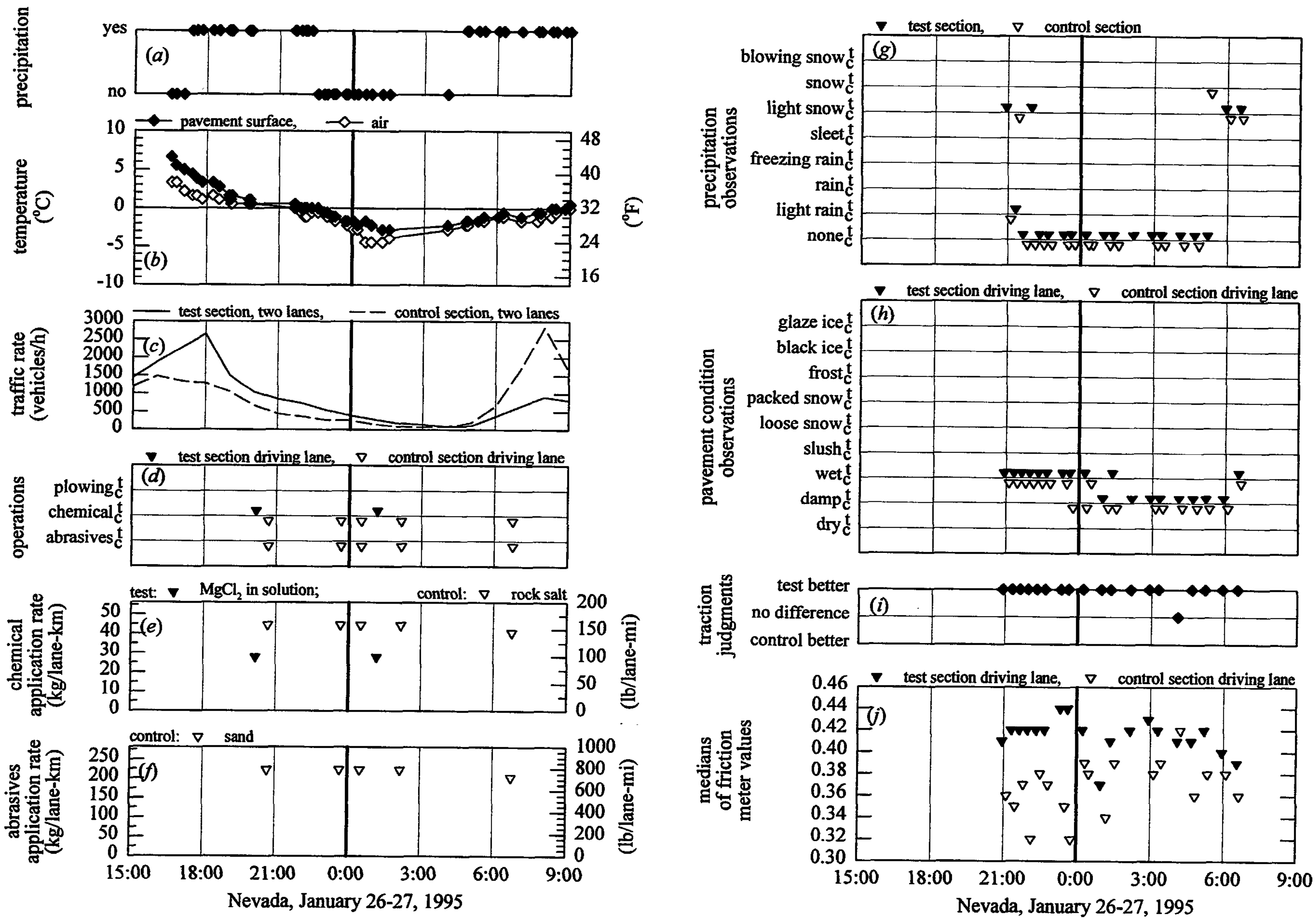


Figure 83. Nevada, storm NV501G, January 26-27, 1995, data histories.

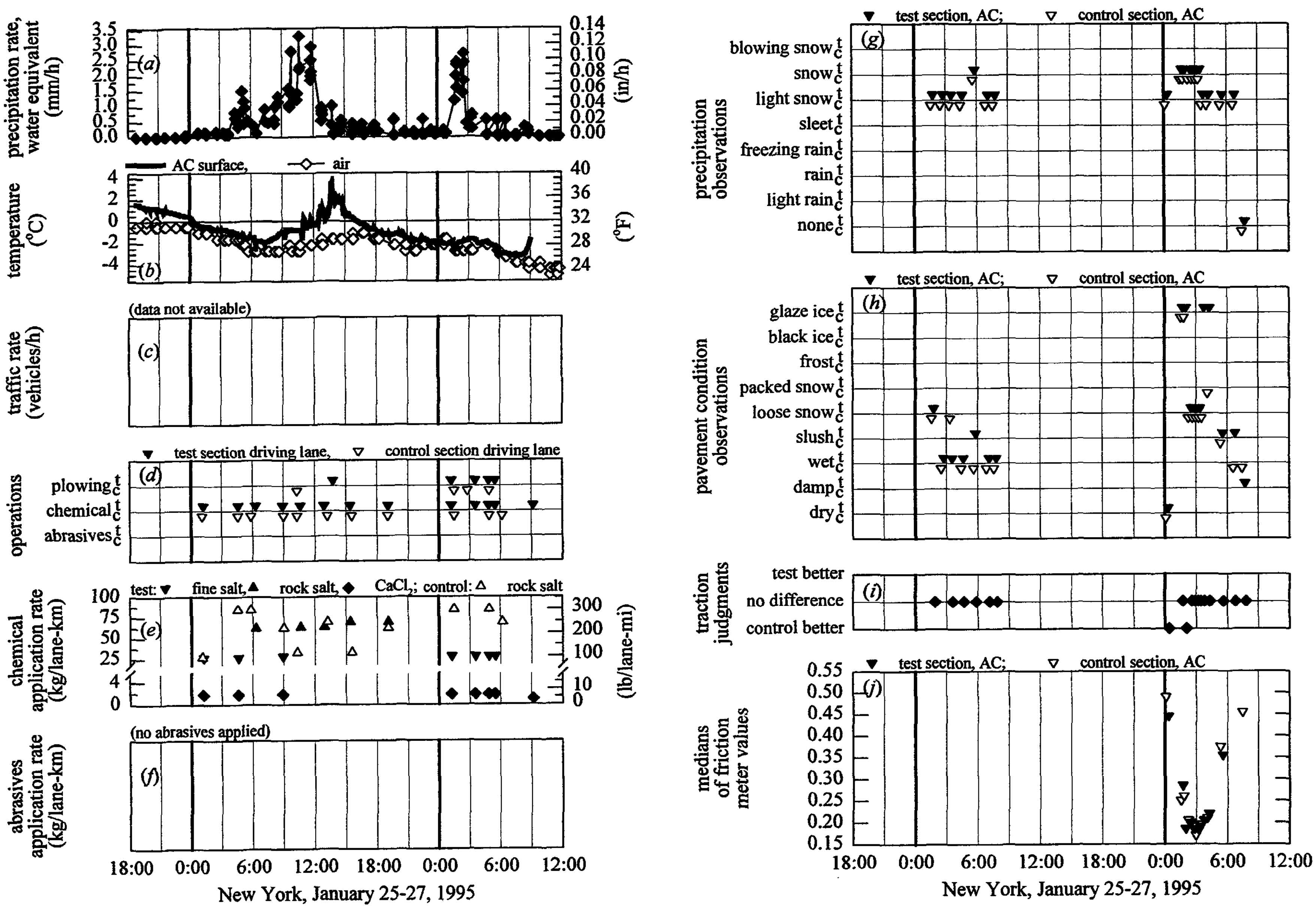


Figure 84. New York, storm NY501G, January 25-27, 1995, data histories.

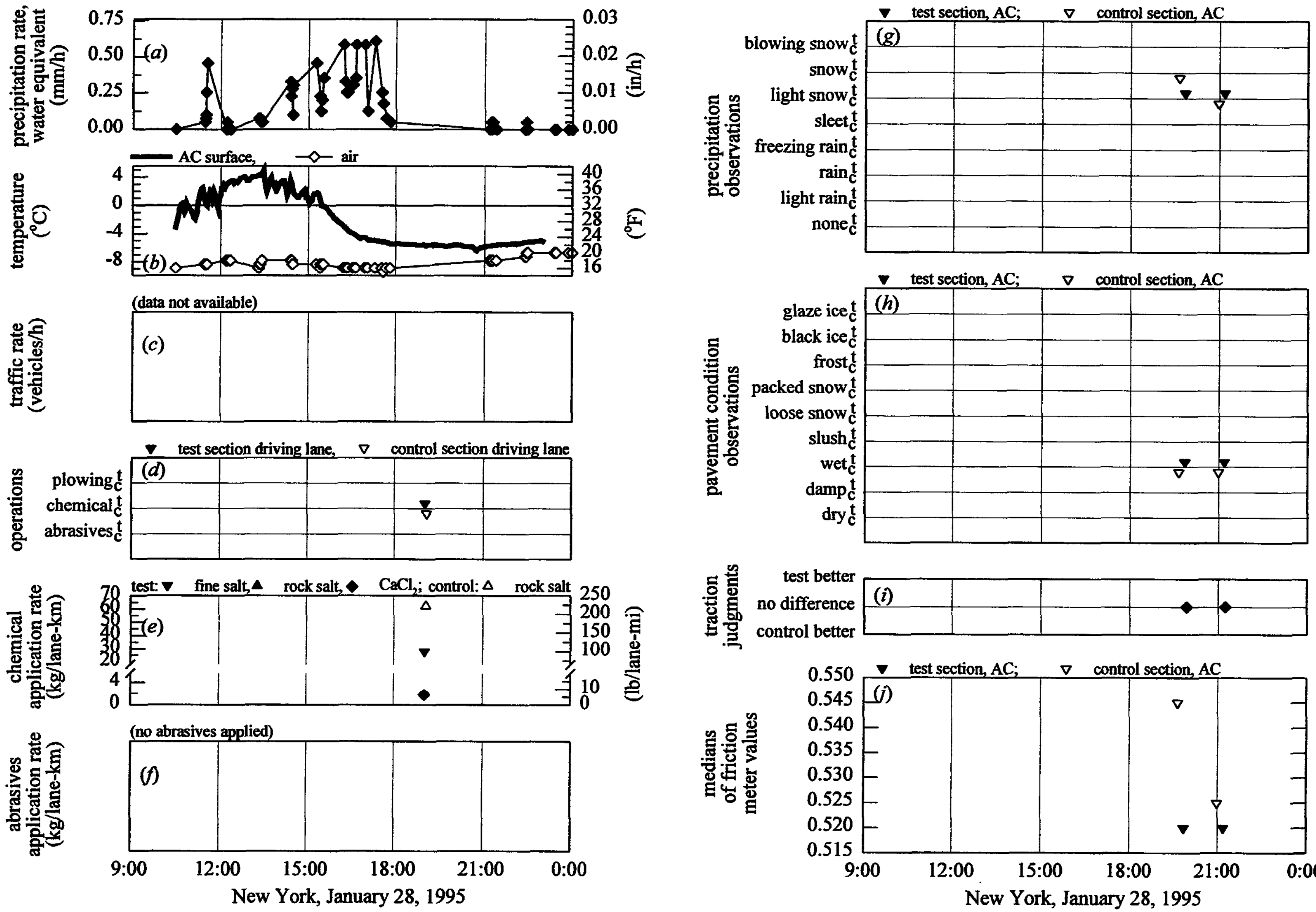


Figure 85. New York, storm NY501H, January 28, 1995, data histories.

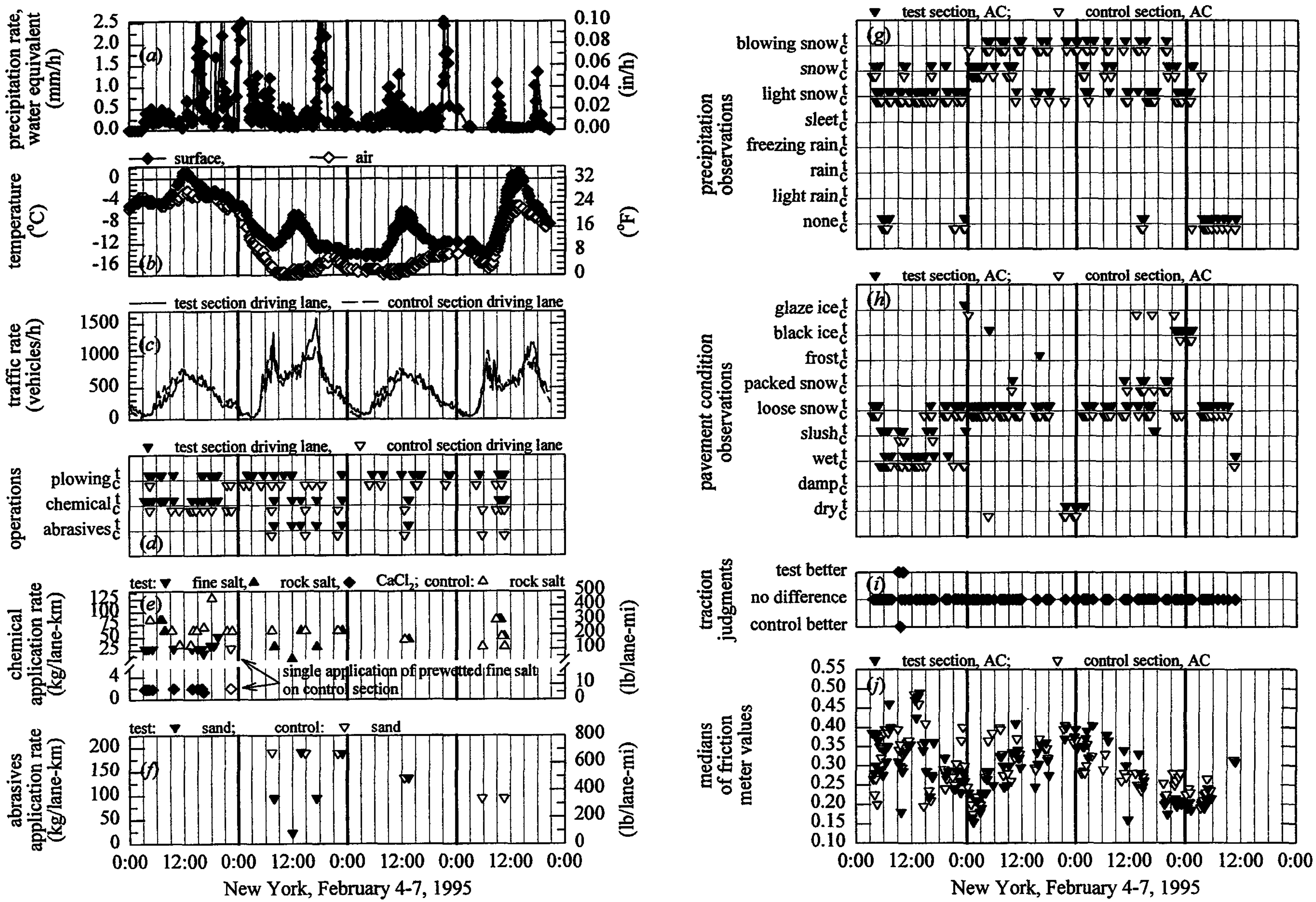


Figure 86. New York, storm NY502B, February 4-7, 1995, data histories.

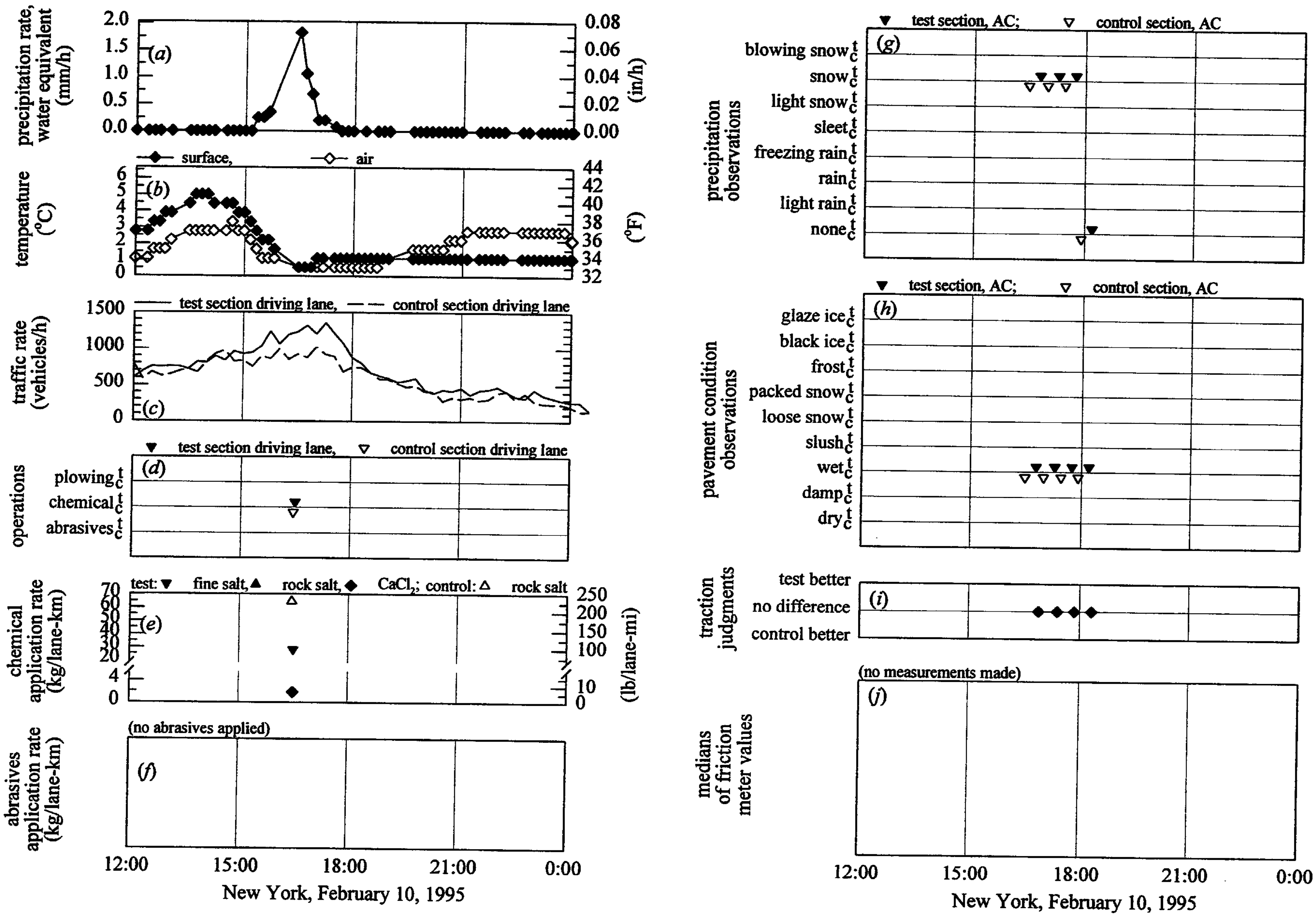


Figure 87. New York, storm NY502E, February 10, 1995, data histories.

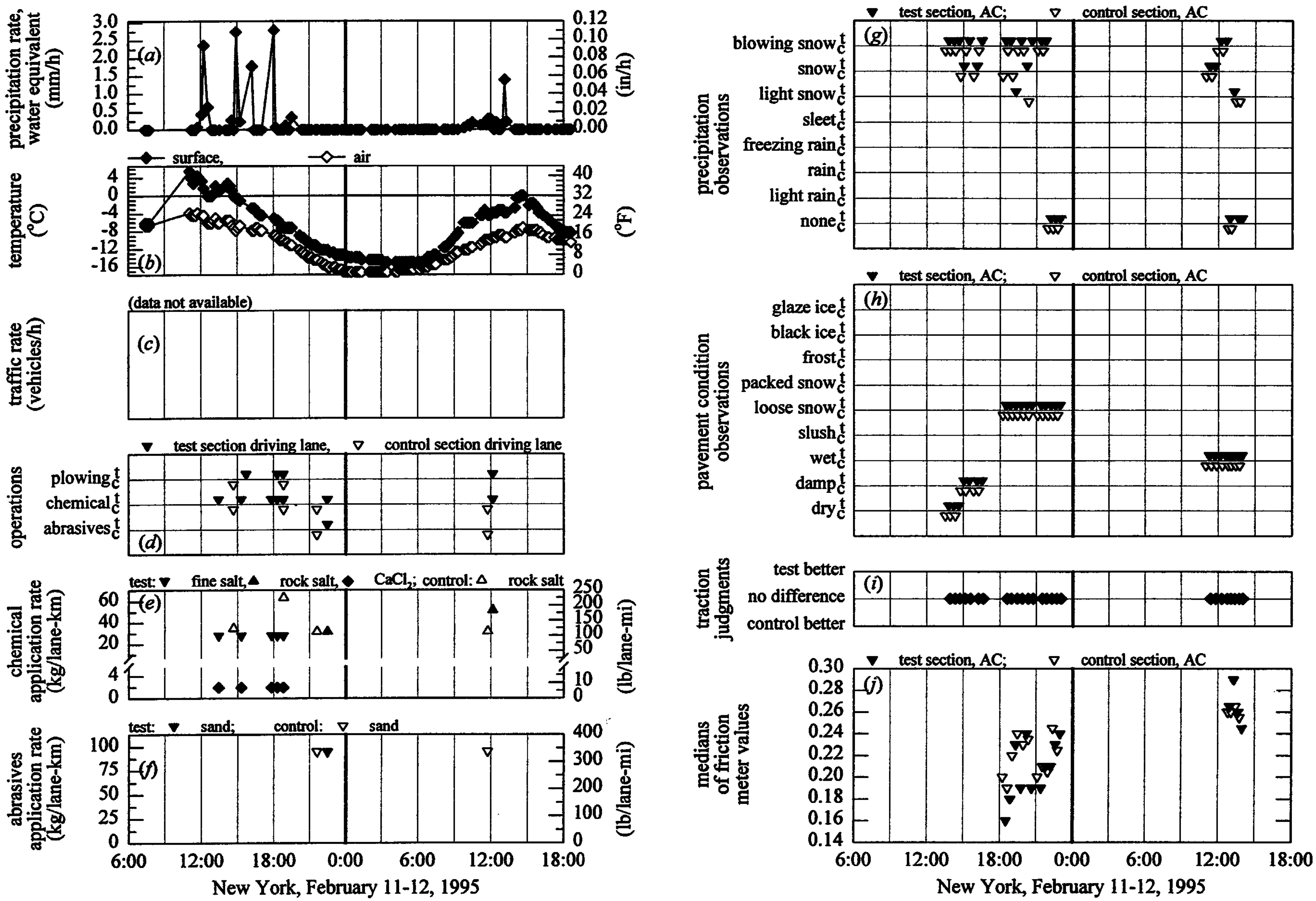


Figure 88. New York, storm NY502F, February 11-12, 1995, data histories.

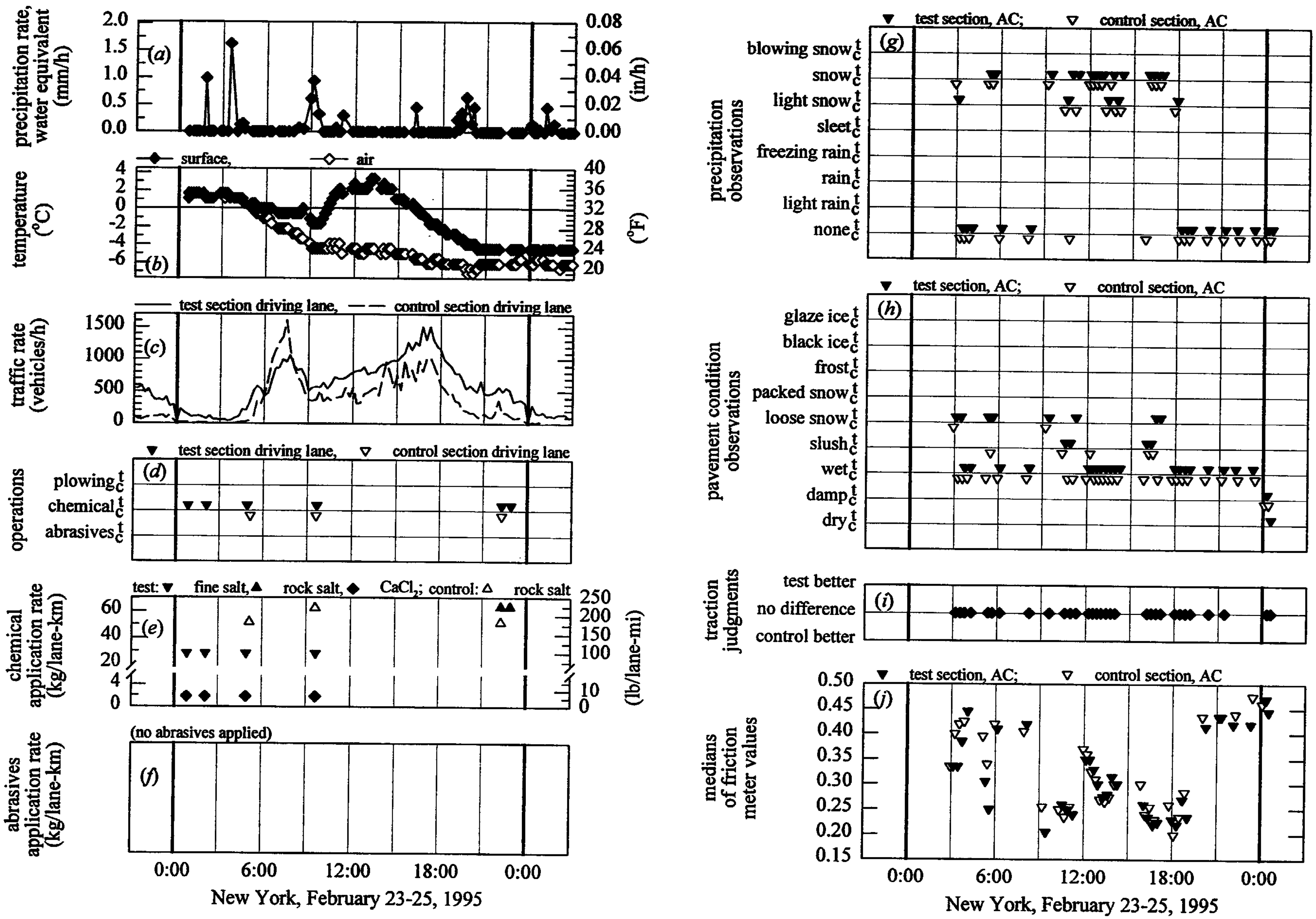


Figure 89. New York, storm NY502H, February 23-25, 1995, data histories.

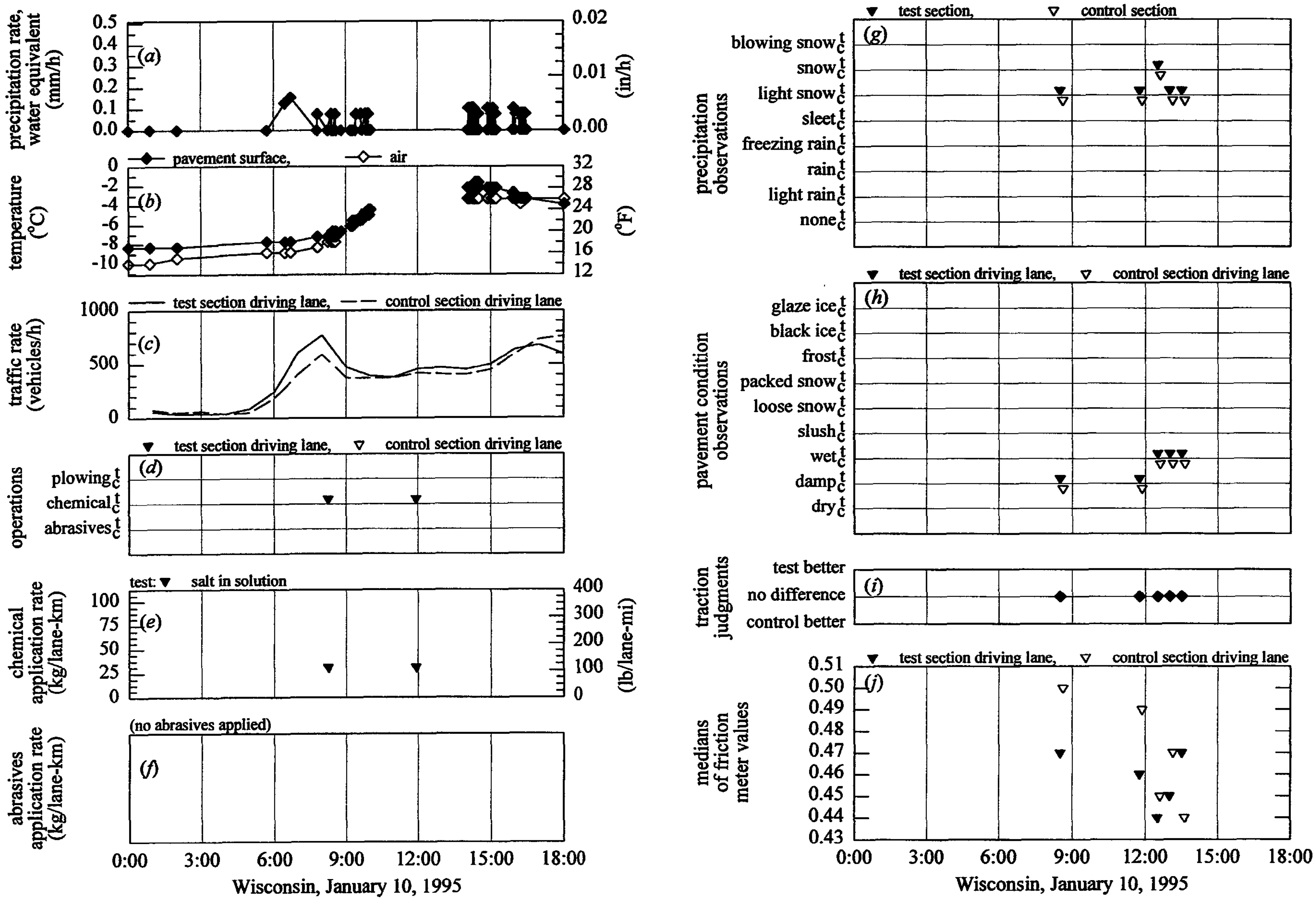


Figure 90. Wisconsin, storm WI501A, January 10, 1995, data histories.

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