Texas Tech University

Multidisciplinary Research in Transportation

Snow and Ice Control Materials for Texas Roads

VOLUME 1: Literature and Best Practices Review

VOLUME 2: Field Trials and Laboratory Study

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Performed in Cooperation with the Texas Department of Transportation

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16. Abstract
This report provides findings from a four-year research study of snow and ice control materials for winter weather roadway maintenance applications in Texas. The report is presented in two volumes. Volume 1 is a literature review and best practices review of snow and ice control materials both nationally and statewide, addressing material application and effectiveness, the availability and usability of Texas brines, durability impacts (corrosion) on infrastructure, environmental impacts and regulations, and a detailed cost analysis of TxDOT's current usage of snow and ice control materials. Volume 2 presents findings from side-by-side comparison of selected snow and ice control chemicals through field trials and laboratory testing. Key findings are (1) the effectiveness of TxDOT's maintenance response to winter weather is a direct function of TxDOT having a clearly-articulated strategy for responding to winter weather, both for typical climate and extreme winter storm events for all regions of the state; (2) geologic brines for snow and ice control include natural brine, manufactured brine, and produced brine related to oilfield operations, and all three must be tested and approved to be considered for widespread use; (3) TxDOT's current snow and ice control chemicals include granular road salt, salt brine, MeltDown 20®, and MeltDown Apex™, all of which are chlorides, and, notwithstanding TxDOT's comparatively low application rates and application frequencies, may potentially cause long-term infrastructure durability impacts; (4) environmental regulations and literature suggest minimal added risk to the environment associated with TxDOT's current usage of snow and ice control chemicals; (5) under typical Texas winter weather and road conditions, at manufacturer's recommended application rates, granular road salt performed comparably to or better than MeltDown 20® at lower cost per lane mile and similarly, salt brine performed comparably to MeltDown Apex™ with the added benefit that salt brine does not create a slick pavement surface for anti-icing when applied at temperatures above freezing; and (6) cost savings associated with TxDOT's snow and ice operations can be achieved through standardized selection of materials, improved operational efficiency, better risk management practices, and use of performance-based models for snow and ice control.

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CHAPTER 1
INTRODUCTION

1.1 The Research Problem

1.1.1 Purpose

This report, in two volumes, presents findings from a four-year research study on snow and ice control materials for winter weather roadway maintenance applications in Texas. The purpose of this research was to provide Texas Department of Transportation (TxDOT) roadway maintenance professionals with the information they need to know in order to evaluate, select, procure, apply, and otherwise implement snow and ice control materials and achieve satisfactory results in their respective areas of Texas.

1.1.2 Significance

Texas is fortunate not to have several months of harsh winter weather each year like many northern states do. Nevertheless, major storms such as the 2011 Groundhog Day Blizzard during Super Bowl XLV revealed the importance of being adequately prepared before snow and ice strike. TxDOT maintenance and operations personnel are responsible to keep Texas roadways open and safe during winter storm events. This responsibility can be met through clear understanding of service expectations, careful planning and preparation, and effective communication both internally within TxDOT and externally with the traveling public.

One key element of TxDOT's winter weather maintenance strategy is the effective use of snow and ice control materials. Historically, sanding has been the winter weather roadway maintenance strategy of choice in Texas, both because of Texas' mild winters in most geographic areas of the state and because sanding is a very visible low-cost approach to managing pavement friction. In the past 5 to 10 years however, some TxDOT districts have shifted to the use snow and ice chemicals, predominantly road salt (NaCl) or magnesium chloride ($MgCl_2$) with or without additives. However, the choice of chemical has not always been based on a quantitative assessment.

The citizens of Texas expect TxDOT to keep Texas roadways safe and open for movement and people and commerce in all seasons of the year. The findings presented in this report on the selection, procurement, application, and management of snow and ice control materials support TxDOT's goal of achieving an effective maintenance response, statewide, to winter storms.

1.1.3 Scope

The focus of this project is on common snow and ice materials used by TxDOT in its maintenance operations, as well as on alternative products such as natural brines. The research considered all major aspects of snow and ice control materials including effectiveness, availability, impact on infrastructure durability (corrosion), environmental concerns and regulations, and cost.

1.2 TxDOT-sponsored Winter Weather Research

1.2.1 Prior Research

TxDOT has recognized the need to promote effective winter weather roadway maintenance in all areas of the state. In early 2011, TxDOT sponsored two major winter weather research studies:

- Project 0-6669, Best Practices for Emergency Operations
- Project 5-9044, Winter Weather Management and Operations Training Curriculum Development and Instruction

Project 0-6669 focused on identifying actionable practices relative to winter weather operations (Perkins, et al. 2012). The research objective was to develop a winter weather operations manual that could be used by TxDOT districts vulnerable to weather related emergencies.

Project 5-9044 consisted of two curriculum development and training programs (Lawson, et al. 2012). The first program created a 6-hour training course on management of winter weather events and delivered management training to 845 TxDOT maintenance professionals statewide. The second program created a 12-hour training course on winter weather operations and delivered train-the-trainer events to TxDOT training vendors who, in turn, offer the operations training to TxDOT maintenance personnel on a recurring basis.

1.2.2 TxDOT Project 0-6793

In January 2012, TxDOT sponsored 0-6793, “Snow and Ice Chemicals for Texas Roads,” which is the research described in this report. This study was initially scheduled to be completed in 20 months but was subsequently modified to include two additional years of field and laboratory data collection. The work plan included seven functional tasks.

1.2.2.1 Task 1. Characterize the application and effectiveness of snow and ice control chemicals. The objective of Task 1 was to identify and classify the types of snow and ice control chemicals which can be used for Texas roads and winter weather conditions. This included the effectiveness, as a function of application, of the major snow and ice chemicals currently used by TxDOT (e.g. NaCl, $MgCl_2$, and $MgCl_2$ with additives) as well as natural brines. This task also included limited evaluation of abrasives to provide a basis for comparison.

1.2.2.2 Task 2. Determine the availability, storage requirements and transport issues related to natural brines. Task 2 characterized natural brines as a potential snow and ice control chemical for Texas roads. This required evaluation of the availability of natural brine suppliers or potential suppliers for the state of Texas, review of storage requirements for these products, and consideration of transport issues including mode of transport, time of transport, and cost. Durability concerns associated with corrosion, and environmental concerns and regulatory issues associated with the use of these brines were also addressed.

1.2.2.3 Task 3. Evaluation of infrastructure durability impacts due to anti-icing and de-icing operations. The primary objective of Task 3 was to evaluate possible adverse impacts to the durability of highway infrastructure caused by de-icing and anti-icing operations on Texas roads. These durability concerns include corrosion of steel reinforcement and scaling of surfaces of concrete structures, and also corrosion of infrastructure exposed to these chemicals such as steel bridge girders, expansion joints and supports, and also snow and ice control equipment.

1.2.2.4 Task 4. Evaluate the environmental impact and regulations with relation to the current and future use of salts and brines to control snow and ice on Texas roads. Task 4 consisted of a comprehensive review of the relative environmental impacts of anti-icing and de-icing salts including natural brines. Research also evaluated the current state and future direction of environmental regulations covering the use of these salts and brines in Texas. In addition, this task evaluated environmental impacts associated with selected, commonly-used abrasives.

1.2.2.5 Task 5. Field trial to compare effectiveness of snow and ice control chemicals. The objective of Task 5 was to obtain a comparative "head-to-head" determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions. Task 5 is the part of project 0-6793 that was expanded and extended two additional years. Subtasks included:

<u>Winter 2013-14 (Modification 2)</u>

- Subtask 5.1 Identify and Establish Field Research Site
- Subtask 5.2 Storm Monitoring and Data Collection
- Subtask 5.3 Data Analysis and Reporting

<u>Winter 2014-15 (Modification 3)</u>

- Subtask 5.4 Laboratory Test Program to Evaluate Snow and Ice Control Chemicals
- Subtask 5.5 Update Field Research Site for Winter 2014-15
- Subtask 5.6 Winter 2014-15 Storm Monitoring and Data Collection
- Subtask 5.7 Data Analysis and Reporting

The field and laboratory work performed for Task 5 represented a major research effort for this project. Volume 2 of the 0-6793 report presents the findings from Task 5.

1.2.2.6 Task 6. Perform a comprehensive cost analysis of the use of snow and ice control materials. Task 6 consisted of an analysis of the life-cycle costs of selected snow and ice control materials used in Texas. This analysis considered both the short-term cost factors (e.g., purchase, processing, storage, transport, and application) and long-term factors (e.g., potential damage to equipment and roadways) of these materials.

1.2.2.6 Task 7. Production of deliverables. The objective of Task 7 was to produce the deliverables associated with the project including the research report and products.

Project 0-6793 considered all major aspects of TxDOT's typical snow and ice control materials including their effectiveness, availability, impact on infrastructure durability (corrosion), environmental concerns and regulations, field performance, and cost. Research Tasks 1 through 4, and Task 6, were performed in 2012-2013 in accordance with the initial project agreement, and findings from these tasks are reported in Volume 1 of the research report. Research Task 5 spanned 2012-2015 as per the modified project agreement, and findings from Task 5 are reported in Volume 2 of the research report. Collectively, this work serves to quantify and qualify the relative merits of common snow and ice materials used in TxDOT's maintenance operations.

1.3 Organization of the Research Report

As has been noted, the 0-6793 research is reported in two volumes, each with its own appendixes. This volume, VOLUME 1, is essentially a literature and best practices review. Organized into six chapters, VOLUME 1 reports findings from research Tasks 1 through 4 and from research Task 6.

Except for the introduction, each chapter in VOLUME 1 directly addresses a particular research task. Chapter 1 provides a statement of the research problem and an overall introduction to research project 0-6793. Chapter 2 summarizes a comprehensive review of technical literature on snow and ice control materials used in the United States including the effectiveness of these materials in relation to type of application (Task 1). Chapter 3 discusses the availability and potential usability of brines for snow and ice control including natural brines, manufactured brines, and oilfield brines (Task 2). Chapter 4 discusses the durability impacts of snow and ice chemicals on infrastructure, both based on review of the literature and on a limited experimental program (Task 3). Chapter 5 summarizes the known environmental impacts and regulations associated with application of snow and ice chemicals, nationally and in Texas (Task 4). Finally, Chapter 6 provides a detailed cost analysis of TxDOT's current usage of snow and ice chemicals (Task 6).

Chapter 2 through 6 each begins with an introduction specific to the research task. The chapters then describe method (where appropriate) and provide data, analyses, and discussion of results. These chapters conclude with a summary of findings, and as such, the individual chapters in VOLUME 1 provide a focused statement of outcomes for the subject research task. Again, the research summarized in VOLUME 1 was performed in 2012-13 and the report reflects findings for that time period.

The companion volume, VOLUME 2, and focuses on field trials and laboratory testing. VOLUME 2 is organized into eight chapters and reports findings from research Task 5 and the *overall* project summary and conclusions. Chapter 1 of VOLUME 2 provides a statement of the research problem and an overall introduction to Task 5 for project 0-6793. Chapter 2 describes the field research test site near Canyon, Texas. Chapter 3 presents the research method for Task 5 including storm response, field data collection, data presentation, and analyses. Chapter 4 of VOLUME 2 summarizes all field data obtained for the three winter seasons and identifies the subset of data judged of sufficient quality and reliability to be usable for subsequent analysis. Chapter 5 presents anti-icing results from the field test site, focusing on selected liquid snow and ice control chemicals. Chapter 6 presents de-icing results from the field test site, focusing on granular products. Chapter 7 summarizes results from laboratory testing performed for the study. Chapter 8 summarizes overall findings from the research project including conclusions, recommendations, limitations, and topics for further study.

CHAPTER 2
IDENTIFICATION AND CLASSIFICATION OF SNOW AND ICE CONTROL MATERIALS

2.1 Introduction

2.1.1 Overview

This chapter summarizes technical literature about the identification and classification of snow and ice control materials suitable for application on Texas roads under Texas winter weather conditions. This includes the effectiveness of major snow and ice control materials, including natural brines, which TxDOT maintenance forces either currently use or which can be used. The term "application" as used in this report refers to how the materials are applied to the roadway, under what weather and roadway conditions, and at what rates. "Effectiveness" refers to the range of pavement temperatures, concentrations, and related factors through which these chemicals suppress the freezing point of water and thus facilitate removal of snow and ice from the roadway surface.

2.1.2 Scope and Organization

This chapter addresses Task 1 of TxDOT project 0-6793, "Snow and Ice Chemicals for Texas Roads." The overall research objective has been to quantify and qualify the relative merits of common snow and ice control chemicals used by TxDOT in its roadway maintenance operations including their effectiveness, availability, environmental concerns, environmental regulations, impact on infrastructure durability (corrosion), and cost effectiveness. Task 1 is essentially a literature review and best practices review focused on characterization of the application and effectiveness of snow and ice control materials.

The introduction presents the focus of the Task 1 research effort, authorization and scope, and the organization of the chapter. Section 2 states the method by which the work was performed including the objective and outcome of the task. Section 3 provides a national perspective on snow and ice control materials. This includes primary knowledge sources, an overview of snow and ice control materials, considerations in selection, including cost, and a summary of national trends. Section 4 presents snow and ice control materials from a Texas perspective including history, application rates, detailed usage, cost, and other considerations in selection. Section 5 presents snow and ice control materials relative to Texas weather. Climate data are presented as well. Section 6 discusses how snow and ice control materials are part of an overall strategy for winter weather roadway maintenance in Texas. Section 7 summarizes key themes from the literature review.

2.2 Method

2.2.1 Overview

The research team accomplished Task 1 through a series of literature and best practice reviews. The research method consisted of documenting and synthesizing published literature on snow and control materials and conducting interviews with subject matter experts. The outcome of this task is a descriptive summary of the application and effectiveness of the different types of snow and ice control materials used for Texas roads with respect to Texas winter weather conditions.

2.2.2 Published Literature on Snow and Ice Control Materials

A substantial body of literature exists on snow and ice control materials for roadway maintenance applications, much of this having been sponsored by and developed for northern states that experience frequent and heavy winter weather storm events. This literature includes information about the application and effectiveness of most of the snow and ice control chemicals currently used, and as such, available research represents a key source of information for this study. This literature has been evaluated, synthesized, and summarized herein.

2.2.3 Interviews with Subject Matter Experts

As the research focus was not just a general interest in snow and ice control materials but more specifically how these materials are used relative to the roadway and winter weather conditions that exist in Texas, the researchers conducted interviews with subject matter experts both statewide and nationally. Table 5.1 provides the list of interviewees.

Table 2.1 Snow and Ice Subject Matter Experts Interviewed

Subject Matter Expert (National)	Subject Matter Expert (Texas)
Bret Hodne Public Works Director The City of West Des Moines West Des Moines, Iowa	Claudia Kern Chemist Materials and Pavement Section Construction Division Texas Department of Transportation Austin, Texas
Leland D. Smithson, PE AASHTO SICOP Program Coordinator Iowa Department of Transportation Ames, Iowa	Kristina F Santos, PE Transportation Engineer Materials and Pavement Section Construction Division Texas Department of Transportation Austin, Texas

Table 2.1 Snow and Ice Subject Matter Experts Interviewed, continued

Wilfrid A. Nixon, PhD, PE Professor Dept of Civil and Environmental Engineering University of Iowa Iowa City, Iowa	John Henley Engineering Specialist Materials and Pavement Section Construction Division Texas Department of Transportation Austin, Texas
Richard "Mark" DeVries Maintenance Superintendant McHenry County Woodstock, IL	Kent Thayer MSMS/Stock Control Manager TxDOT, General Services Division Austin, Texas
Annette Dunn Winter Operations Administrator, Maintenance Iowa Department of Transportation Ames, Iowa	Scott Speer Envirotx Austin, Texas
Tina Greenfield Iowa DOT RWIS Coordinator Iowa Department of Transportation Ames, Iowa	
Xianming Shi, PhD, PE Research Professor, Department of Civil Engineering Western Transportation Institute Montana State University, Bozeman, MT	

2.2.4 Application and Effectiveness of Natural Brines

While much information is available about the application and effectiveness of common snow and ice control chemicals, limited information is available on the use of natural bines, particularly those specific to Texas. The majority of information on natural brines is covered in the brine section of this report (Chapter 3).

2.3 National Perspectives on Snow and Ice Control Materials

2.3.1 Primary Knowledge Sources

Snow and ice control materials represent one important aspect of winter weather roadway maintenance, a broad topic of both practical and academic concern. As would be expected, leadership on winter weather roadway maintenance activities, including the use of snow and ice control materials, corresponds to those geographic regions where transportation systems are most strongly impacted by winter weather.

2.3.1.1 National Leadership Winter roadway maintenance research in the United States is accomplished at both the national level and the state level. There are several national research initiatives and also some United States/Canada shared initiatives.

In 1996, the Federal Highway Administration (FHWA) presented the *Manual of Practice for an Effective Anti-icing Program-A Guide for Highway Winter Maintenance Personnel* (Ketcham, 1996) and in 2004, the National Cooperative Highway Research Program (NCHRP) presented *Snow and Ice Control: Guidelines for Materials and Methods* (Blackburn, 2004).

Environmental and regulatory agencies have questioned the environmental impacts of snow and ice control materials. In 2006, a Canadian consulting company, Levelton Consultants Limited, completed NCHRP 577 *Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts* (Levelton Consultants Ltd., 2006).

The Western Transportation Institute at Montana State University (Shi, 2013) has worked on many of the latest projects including but not limited to:

- *Evaluation and Analysis of Liquid Deicers for Winter Maintenance*, funded by the Ohio Department of Transportation (in process).
- *Understanding and Mitigating Effects of Chloride Deicer Exposure on Concrete*, funded by the Oregon Department of Transportation and USDOT RITA (2012).
- *Best Practices and Guidelines for Protecting DOT Equipment from the Corrosive Effect of Chemical Deicers, Phase I*, funded by the Washington State Department of Transportation and USDOT RITA (2013)
- *Inhibitor Longevity and Deicer Performance*, a Pacific Northwest Snowfighters Pooled Fund Study (2011)
- *Effect of Chloride-Based Deicers on Reinforced Concrete Structures*, funded by the Washington State Department of Transportation (2010)
- *Establishing Best Practices for Removing Snow and Ice from California Roadways*, funded by the California Department of Transportation (2010)
- *Evaluation of Alternate Anti-icing and Deicing Compounds Using Sodium Chloride and Magnesium Chloride as Baseline Deicers*, funded by the Colorado Department of Transportation (2009)

2.3.1.2 State DOT Leadership Winter roadway maintenance research and practice is done primarily at the State DOT level. Several states are noted for winter roadway maintenance due to their own multiple research projects or pooled-fund research projects. Figure 2.1 shows the state leaders in winter roadway maintenance.

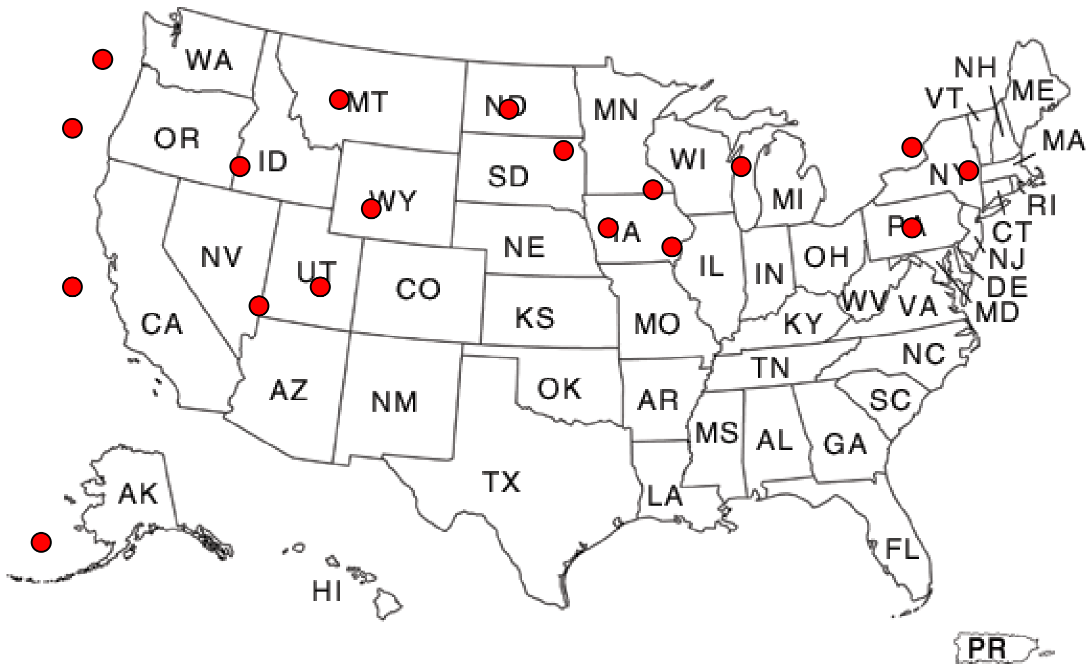


Figure 2.1. State leaders in winter roadway maintenance.

2.3.1.3 Association of Transportation Agencies and Trade Associations The complexity of winter roadway maintenance has given rise to national/international associations of transportation agencies and other trade associations. The main organizations, along with brief descriptions, are identified below.

The Pacific Northwest Snowfighters (PNS) is an association of transportation agencies, including British Columbia, Idaho, Montana, Oregon and Washington, Colorado. PNS is dedicated to ensuring the safety of winter maintenance products through structured testing and evaluation. The group established procedures for testing deicing and anti-icing chemicals and maintains specifications that these products must meet to be considered for widespread use. PNS has become a nationally recognized leader in establishing and standardizing chemical products for snow and ice control. The PNS homepage http://pnsassociation.org provides more information.

Clear Roads is an ongoing pooled fund research project #TPF-5(218) aimed at rigorous testing of winter maintenance materials, equipment and methods for use by highway maintenance crews. Minnesota is the lead state and has contracted with CTC & Associates LLC to provide administration, project management and information services. Website www.clearroads.org/ .

Aurora is an international program of collaborative research, development and deployment in the field of road and weather information systems (RWIS), serving the interests and needs of public agencies. Currently, the Pennsylvania DOT is the lead. Website www.aurora-program.org/.

The Snow and Ice Pooled Fund Cooperative Program (SICOP) was developed by the American Association of State Highway and Transportation Officials (AASHTO). The program is a collaborative research effort for testing materials related to snow and ice control. Website sicop.transportation.org/.

The Salt Institute is a trade organization to promote the use of salt. The Salt Institute has developed material specifically on the topic of snow control. Website www.saltinstitute.org/.

2.3.2 National Data on Snow and Ice Control Materials

2.3.2.1 Types of Snow and Ice Control Materials Table 2.2 identifies the most commonly-used snow and ice control materials in the United States (Levelton Consultants Ltd., 2006). The material types can be categorized as chloride salts, organic products, nitrogen products, and abrasives. Product applications include roadways, airport runways, or as an additive. Product use is not limited to the stated product types; for example, calcium magnesium acetate can be applied directly to roadway surfaces, but due to high cost, it is commonly used as a blended product. For the purposes of Table 2.2, an additive is defined as a chemical that is combined with another chemical to make a blended product, and the chemical comprises less than half of the total blend.

Table 2.2. Common Snow and Ice Control Materials (*source*: NCHRP 577).

Material Type	Snow and Ice Control Material	Product Application
Chloride Salts	Sodium Chloride (NaCl)	Roadway
	Calcium Chloride ($CaCl_2$)	Roadway
	Magnesium Chloride ($MgCl_2$)	Roadway
	Well Brines (blends)	Roadway
Organic Products	Calcium Magnesium Acetate (CMA)	Additive/Bridges
	Potassium Acetate (KA)	Additive/Bridges/Airport Applications
	Agricultural By-Products	Additive
	Manufactured Organic Materials	Airport Applications
Nitrogen Products	Urea	Airport Applications
Abrasives	Inert granular materials, composition varies	Roadway

The most widely-used snow and ice control chemicals are chloride salts. These materials are favored due to their low cost when compared to alternative material types. Manufactured blended products are becoming increasingly used by State DOTs (Levelton Consultants Ltd., 2006). These products commonly include one or more chloride salts to improve low-temperature performance and the hygroscopic properties of the blend. Many custom-blended products also include a corrosion inhibitor (Levelton Consultants Ltd., 2006).

Corrosion is a concern with salts, and alternative products have been implemented, such as calcium magnesium acetate (CMA) and potassium acetate (KA), which have lower corrosion potential when compared to chlorides. CMA was the result of a Federal Highway Administration (FHWA) effort to find a low corrosion biodegradable substitute for sodium chloride. CMA has low corrosion but it is also costly to produce and is mainly used as an additive to other chloride salts or placed on bridges as a low corrosion alternative (Levelton Consultants Ltd., 2006). Potassium acetate is a non-chloride, high-performance product originally designed for use as a runway deicer. Due to its high cost, potassium acetate is usually used as an additive to other chloride salts or in automated bridge de-icing systems (Levelton Consultants Ltd., 2006). These products are currently used in airport applications because corrosion to aluminum aircraft is a major concern. Automated bridge de-icing systems are becoming another area of increased use for these low corrosion alternatives.

In the past decade, a very large increase in the number of manufactured blended products has been brought to the market. The Pacific Northwest Snowfighters (PNS) have the most comprehensive pre-qualified product list of manufactured blended products. This qualified product list can be seen in Appendix A.

Agricultural additives, consisting of complex sugars, are sometimes mixed with chloride salts for their corrosion-inhibiting characteristics and claims of increased overall product performance for snow and ice control. Currently, these are all proprietary products, so little is known about the actual manufacturing and refining process.

Abrasives are inert and are not used to melt snow and ice. The use of abrasives has been a longtime strategy for many agencies as a low-cost approach to improving pavement friction. However, when abrasives are placed on the road surface without significant pre-wetting, they provide at best, a very short term increase in road surface friction (Levelton Consultants Ltd., 2006). Also, as roadway traffic levels and speeds are increased, any benefit from abrasive use diminishes (Levelton Consultants Ltd., 2006).

2.3.2.2 Usage of Snow and Ice Control Materials The NCHRP conducted an agency survey to determine the products most commonly used for snow and ice control. Twenty-two states (U.S.), three provinces (Canada), and three cities responded to the survey and the information is presented in Table 2.3. Further information can be found in NCHRP Report 577 (Levelton Consultants Ltd., 2006). Table 2.3 shows the percentage of respondents followed by the number of respondents (in parenthesis).

Table 2.3. Snow and Ice Control Material Preference (*source*: NCHRP 577).

Material	1st Choice	2nd Choice	3rd Choice	4th Choice	5th Choice	6th Choice
NaCl solid	57%(16)	18%(5)	4%(1)	0	0	0
NaCl brine	11% (3)	32% (9)	7% (2)	0	4%(1)	0
Salt-based solid products plus other ingredients	4%(1)	4%(1)	0	0	0	0
Chloride-based brines plus organic additive	0	4%(1)	0	4%(1)	7%(2)	0
$CaCl_2$	7%(2)	18%(5)	18%(5)	14%(4)	0	0
$MgCl_2$	14%(4)	7%(2)	29%(8)	0	14%(4)	0
CMA	0	4%(1)	0	7%(2)	0	0
KA	4%(1)	7%(2)	0	0	0	4%(1)
Abrasives	21%(6)	18%(5)	7%(2)	11%(3)	7%(2)	4%(1)
Abrasives/NaCl mixture	4%(1)	0	0	0	0	0
Sand mixed with salt solids plus inhibitor	0	4%(1)	0	0	0	0

Chloride salts were by far the respondents' first preference. Sodium chloride (NaCl) was the most common material with 57 percent of the respondents placing granular sodium chloride as their first preference and 11 percent of respondents placing sodium brine as their first preference. Respondents noted that for the most part, sodium brine was produced in house by the agency (Levelton Consultants Ltd., 2006). In all, 79 percent of respondents considered solid sodium chloride as their first, second or third choice, and 50 percent of respondents considered sodium brine to be their first, second, or third choice. Some respondents placed both solid and brine sodium as their first choice, possibly showing that they use both as a winter weather strategy, one for anti-icing and one for de-icing. Magnesium chloride was shown to be the next most popular chemical with 14 percent of respondents claiming as their first choice and 50 percent of respondents claiming as their first, second, or third choice. Finally, 43 percent of respondents claimed calcium chloride as their first, second, or third choice. For the most part, respondents said that they use magnesium and calcium chloride with corrosion inhibitors. Many western states reported that a natural product with a combination of sodium chloride, magnesium and potassium chloride was a high preference product (Levelton Consultants Ltd., 2006).

2.3.2.3 Sources of Snow and Ice Control Materials China is currently the world's leading salt producing nation, surpassing the United States in 2005 (Kostick, 2011). According to U.S. Geological Survey (USGS) data as of 2010, 28 companies operated 60 salt-producing plants in 16 states in the US. The five leading states in the US for total salt sold are Louisiana (32 percent), Texas (21 percent), New York (15 percent), Kansas (7 percent), and Utah (5 percent). The 2010 apparent consumption (salt sold or used plus imports minus exports) was 123 million pounds, with 38 percent used for snow and ice control. The majority of rock salt is used for snow and ice control, and production fluctuates with demand (Kostick, 2011).

2.3.2.4 Storage and Handling Proper storage of solid snow and ice control material involves adequate access to the stockpile and proper protection against escape of chemicals or leachate (Levelton Consultants Ltd., 2006). Ideally, granular (solid) snow and ice control chemicals should always be stored inside to prevent runoff of salts dissolved by precipitation. Storage structures should be constructed on an impermeable pad and graded away from the center of the storage area for drainage. Storage structures should be constructed to withstand the pressure from the material and the stress of loaders pushing materials against the inside walls (Levelton Consultants Ltd., 2006).

Liquid storage details include adequate tank capacity, proper-sized pumps and hoses for quick loading, and recirculation capability to maintain product consistency should settling occur. Liquid chemical storage should include containment barriers sufficient to contain and recapture spills or the volume released from a tank rupture (Levelton Consultants Ltd., 2006).

Proper handling entails having appropriate receiving and loading equipment. When handling, the exposure effects of snow and ice control chemicals are relatively mild. Whenever there are key concerns on proprietary chemicals, these handling concerns are stated on Material Safety Data Sheets (MSDS). Most products can produce dust in their dry form and may irritate the respiratory system. Eye and skin irritation is a common concern when handling snow and ice control chemicals in liquid form. Eye, skin, and respiration protection is recommended under certain conditions (Levelton Consultants Ltd., 2006).

2.3.3 Effectiveness and Usage of Snow and Ice Control Materials

2.3.3.1 Application Strategy: Anti-Icing, Deicing and Friction Improvement Anti-icing applications consist of placing snow and ice control chemicals onto the roadway surface prior to the storm event. These chemicals depress the freezing point and prevent snow and ice from forming a bond to the roadway surface. Anti-icing also helps by weakening the bonds that are formed and allowing for easier plowing of snow and ice. Because the chemical is applied prior to receiving snow and ice, anti-icing is termed a "proactive" winter weather maintenance strategy. Anti-icing requires less chemical per lane mile when compared to de-icing, with some studies identifying the benefit as 4 to 10 times compared to de-icing (AASHTO 2003). Best practice includes brine, but pre-wet granular chemicals are sometimes used. Brine is defined as any snow and ice chemical mixed with water to form a liquid solution. This solution is then sprayed onto the roadway. Brines can be made from several snow and ice control chemicals, and can be further classified as to the type of brine, such as a sodium chloride brine, magnesium chloride brine, etc. Natural brines and manufactured brines can possibly have a combination of chlorides. The eutectic point, the lowest temperature at the optimum solution concentration for a given chemical solution, is commonly used to determine the correct dry chemical to water ratio.

De-icing is a reactive strategy in which snow and ice control chemicals are applied during or after the storm, when ice and snow have bonded on the roadway surface. De-icing operations are intended to depress the freezing point and break the bond between the ice and road surface, allowing the snow and ice to be plowed from the roadway surface. Vehicular traffic is needed to work the chemical through snow-pack or ice for de-icing operations, and this commonly occurs during storms of extended duration. De-icing is not meant to completely melt the snow and ice as the application rates for this to occur would not be considered a best practice. De-icing specifically applies to the chemicals used to break the bond between the ice and road surface and does not apply to the use of abrasives, as abrasives materials are inert. Liquid brines are not recommended for de-icing use. De-icing requires a greater application rate than anti-icing.

Abrasives increase the friction between vehicle tires and driving surface and thus are used for traction improvement. Normally abrasives are used as a reactive strategy after ice and/or snow have already bonded to the roadway. Roadway maintenance forces use many types of materials as abrasives including but not limited to crushed stone, metallurgical slag, bottom ash, and natural river sand. Abrasives are often blended with de-icing chemical such as salt; however, the amount of chemical used in the blend is small such that the intent is still traction improvement and not deicing in the formal sense. Blending with chemical helps to keep moist abrasive materials flowable (unfrozen) and helps improve workability of the stockpile.

2.3.3.2 Theoretical and Practical Effectiveness The effectiveness of each snow and ice control chemical is a function of the chemical's ability to depress the freezing point of water. Freeze point depression prevents ice and snow from bonding to the road surface in an anti-icing application. For de-icing applications, the chemical melts the snow or ice and breaks the bond between the road surface and ice to allow the snow, ice, and slush mix to be plowed from the roadway surface.

Depending on weather conditions, some materials may be more effective than others. By assessing the phase diagram of the chemicals and calculating differences in dilution factors between products at a given temperature, it is possible to gauge the performance of the material. The phase diagrams for sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride

($CaCl_2$), calcium magnesium acetate (CMA), and potassium acetate (KA) can be found in Appendix B.

Dilution of a chemical takes place from the chemical's initial concentration as it melts snow and ice to water, and subsequently reduces the concentration of the solution until it will freeze. The melting potential is a comparison tool used to gauge the effectiveness of different chemicals. It takes into account the temperature and phase curves of each chemical as described above. The equation for the melting potential is:

$$MP = \frac{BC}{EC} - 1$$

where:

MP= Melting potential of the chemical. The higher the melting potential, the better the performance, because more melting can occur before re-freeze.

BC= Beginning concentration of chemical. This is the concentration of chemical when applied to the roadway surface.

EC= Ending concentration. This ending concentration is determined from the phase diagram. This is the point when, at a given temperature, the chemical becomes diluted to the point that re-freezing of the brine will occur.

An example for melting potential comparisons for sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), calcium magnesium acetate (CMA), and potassium acetate (KA) can be found in Appendix B. Note the beginning concentrations, since changing these concentrations would change the melting potentials. Table 2.4 shows the effectiveness and application ranges for the most common types of snow and ice control chemicals used for roadway snow and ice operations. Actual application rates depend on several factors which include the application strategy (anti-icing or de-icing), pavement temperature, amount of precipitation, traffic load, and application time rates.

Table 2.4. Comparison of the Effectiveness of Snow and Ice Chemicals (*source: AASHTO)*.

Chemical Property	NaCl	$CaCl_2$	$MgCl_2$	CMA	KAc
Eutectic Temperature	-6°F	-59°F	-28°F	-17.5°F	-76°F
Lowest melting Temperature	15°F	-25°F	5°F	20°F	-13°F
Eutectic Concentration	23.3%	30%	22%	32.5%	50%
Thermodynamics	Absorbs heat when melting	Releases heat when melting	Releases heat when melting	Releases heat when melting	Releases heat when melting

2.3.3.3 Snow and Ice Control Material Application Rates Application rates for snow and ice control materials has been a topic of significant inquiry, with studies performed at both the national and state levels. In 1996, the Federal Highway Administration (FHWA) presented the *Manual of Practice for an Effective Anti-icing Program-A Guide for Highway Winter Maintenance Personnel.* This manual of practice set a guide to the current usage of snow and ice chemicals (Ketcham, 1996).

This FHWA document includes guidance on highway anti-icing operations for maintenance field personnel. Its purpose is to suggest maintenance actions for *preventing* the formation or development of packed and bonded snow or bonded ice during a variety of winter weather events. It is intended to complement the decision-making and management practices of a systematic anti-icing program so that roads can be efficiently maintained in the best possible condition. Guidance is presented in six tables for six distinctive winter weather events including: (1) light snow storm, (2) light snow storm with period(s) of moderate or heavy snow, (3) moderate or heavy snow storm, (4) frost or black ice, (5) freezing rain storm, and (6) sleet storm.

Appendix C presents these six tables which suggest the appropriate maintenance action to take during an initial or subsequent (follow-up) anti-icing operation for a given precipitation or icing event. Each action is defined for a range of pavement temperatures and an associated temperature trend. For some events the operation is dependent not only on the pavement temperature and trend, but also upon the pavement surface or the traffic condition at the time of the action. Most of the maintenance actions involve the application of a chemical in either a dry solid, liquid, or prewetted solid form.

In 2004, the National Cooperative Highway Research Program (NCHRP) published *NCHRP 526*, *Snow and Ice Control: Guidelines for Materials and Methods* (Blackburn, et al., 2004). This report further refined the usage of chemicals with factors such as type of precipitation, precipitation rate, dilution potential, cycle time, traffic load, and application (anti-icing or de-icing). NCHRP 526 presents a 6-step procedure entitled "Using Road and Weather Information to Make Chemical Ice Control Treatment Decisions." Appendix D of this report includes the NCHRP 526 attachment.

In addition to these national-level studies, various state DOTs have published guidance on material application rates. Minnesota DOT is a case in point. In 2005, the Minnesota DOT published *Minnesota Snow and Ice Control – Field Handbook for Snowplow Operators*. This easy-to-use guide provides recommended application rate ranges based on pavement temperature and weather conditions. Appendix E of this report includes selected pages from the Minnesota guide.

Published national guidance on snow and ice control material application rates appears in Table 2.5 which identifies the range of application rates for different winter maintenance treatment strategies.

Table 2.5. Application Rates for Selected Snow and Ice Control Strategies (*source*: NCHRP 577)

Strategy/ Method	Materials	Pavement Temperature Ranges	Application Rates
Anti-Icing	Liquid Chemicals, Solid Chemicals, Pre-wet Solid Chemicals	32° F to 10° F	65 – 400 Lbs/Lane Mile
De-Icing	Pre-wet Solid Chemicals, Solid Chemicals	32° F to 0° F	200 – 700 Lbs/Lane Mile
Abrasives	Pre-wet Abrasives, Dry Abrasives	No limits	500-6,000 Lbs/Lane Mile
	Abrasive/Salt Mixes	32° F to 0° F	500-6,000 Lbs/Lane Mile

The ranges are wide, but Table 2.5 captures the idea that anti-icing applications use less chemical than deicing, and abrasives require the highest application rates by far. Collectively, available documents and other published guidance present a systematic way for maintenance personnel to think about snow and ice control material application rates as they perform their winter maintenance operations.

2.3.4 Cost and Other Considerations in Selection

2.3.4.1 Cost of Snow and Ice Control Materials Snow and ice removal represents a considerable roadway maintenance cost in the United States. The average annual cost for snow and ice removal in the United States was $1.7 billion (Table 2.6) for the years 2007 through 2011. The snow and ice roadway maintenance cost per year is shown, by state, in order to demonstrate the variability between winter seasons. Table 2.6 also identifies the lane miles for each State DOT. These are the total on-system lane miles maintained by each DOT. The range in winter weather roadway maintenance cost per lane mile, or differentiation between “snowy states” and others, can also be seen in Figure 2.2. Figure 2.3 identifies the five-year average salt usage, salt price, and material sources in the United States for the 2012-2013 winter season.

Table 2.6 shows that the average cost for snow and ice removal per state ranges from $0/year (Hawaii and Florida) to $253 million/year (Pennsylvania). Texas ranks 30th with an average cost for snow and ice removal of $17.4 million/year. On a cost per lane mile basis, the range is $0/year

Table 2.6. Annual State Cost (USD) of Snow and Ice Removal.

STATE	TOTAL ON SYSTEM LANE MILES	2007 PHYSICAL MAIN-TENANCE x $1000	2007 SNOW AND ICE REMOVAL x $1000	2008 PHYSICAL MAIN-TENANCE x $1000	2008 SNOW AND ICE REMOVAL x $1000	2009 PHYSICAL MAIN-TENANCE x $1000	2009 SNOW AND ICE REMOVAL x $1000	2010 PHYSICAL MAIN-TENANCE x $1000	2010 SNOW AND ICE REMOVAL x $1000	2011 PHYSICAL MAIN-TENANCE x $1000	2011 SNOW AND ICE REMOVAL x $1000	AVERAGE SNOW AND ICE REMOVAL x $1000	RANK	AVERAGE SNOW AND ICE REMOVAL AS PERCENT OF PHYSICAL MAINTENANCE	RANK	AVERAGE SNOW AND ICE REMOVAL COST PER ON-SYSTEM LANE MILE x $1	RANK
Alabama	29,324	161,502	2,948	164,585	12	158,245	1	141,484	216	152,120	314	698	45	0	46	24	45
Alaska	11,653	62,492	24,961	71,876	24,908	72,610	27,909	32,827	25,968	33,291	28,402	26,430	21	55	9	2,268	14
Arizona	19,341	103,342	2,857	112,901	3,400	117,821	3,192	82,930	7,181	111,071	3,764	4,079	41	4	39	211	38
Arkansas	37,357	130,113	3,752	131,534	5,040	137,228	6,511	133,854	12,390	141,212	12,753	8,089	39	6	36	217	37
California	49,598	365,577	18,018	498,021	24,414	547,446	23,552	517,765	25,272	957,329	33,877	25,027	22	5	38	505	33
Colorado	22,934	149,639	40,616	114,242	68,899	101,393	57,359	242,397	66,644	277,374	57,387	58,181	11	38	12	2,537	12
Connecticut	9,838	141,462	22,116	84,469	32,744	71,838	33,522	71,355	26,444	71,565	36,246	30,214	15	38	13	3,071	5
Delaware	11,797	66,236	5,596	55,917	3,167	54,261	3,662	7,047	16,046	5,915	16,188	8,932	38	104	3	757	29
Florida	42,956	755,980	-	854,822	-	685,611	-	610,308	-	619,761	-	-	49	-	49	-	49
Georgia	48,397	151,825	281	164,897	1,098	156,094	580	126,925	230	165,853	25	443	46	0	47	9	47
Hawaii	2,492	21,676	-	30,739	-	36,969	-	38,351	-	22,188	-	-	48	-	48	-	48
Idaho	12,225	79,888	13,391	87,068	18,145	82,842	15,737	87,233	13,916	104,796	15,133	15,264	32	17	25	1,249	22
Illinois	42,097	361,892	55,702	372,626	90,348	417,500	86,247	417,500	86,247	414,327	86,247	80,958	5	20	22	1,923	17
Indiana	27,879	56,687	13,990	65,495	26,750	173,052	26,750	533,445	20,075	542,777	25,614	22,636	27	18	24	812	28
Iowa	22,740	78,506	45,830	93,353	67,477	87,774	74,905	98,548	74,963	106,005	66,602	65,955	10	71	6	2,900	6
Kansas	23,988	130,775	6,968	137,594	4,515	133,294	3,812	126,307	4,499	145,065	4,873	4,933	40	4	40	206	39
Kentucky	61,799	256,755		290,109		303,487	22,198	332,918	23,351	341,876	22,791	22,780	25	7	34	369	35
Louisiana	39,375	224,774	82	197,794	40	226,341	29	278,057	101	89,797	1,831	417	47	1	45	11	46
Maine	17,617	108,366	23,553	158,397	34,135	121,667	29,656	129,556	22,887	116,499	28,547	27,756	20	22	18	1,575	19
Maryland	14,762	122,271	48,081	130,779	46,105	116,675	52,632	112,311	124,623	159,922	70,222	68,333	9	55	10	4,629	2
Massachusetts	9,570	57,034	41,535	62,450	103,883	114,500	127,454	147,473	69,688	147,473	69,688	82,450	4	89	4	8,615	1
Michigan	27,442	201,246	63,127	199,365	81,239	192,948	81,219	207,072	57,211	172,542	79,380	72,435	7	38	14	2,640	9
Minnesota	29,306	279,950	58,157	291,805	82,368	344,285	67,935	356,697	59,108	389,511	80,586	69,631	8	21	20	2,376	13
Mississippi	27,294	76,800	281	88,990	526	101,583	435	93,170	1,533	81,729	2,523	1,060	44	1	43	39	44
Missouri	75,999	353,613	37,087	352,261	50,591	390,532	44,597	388,416	46,697	427,078	32,545	42,303	14	11	31	557	32
Montana	25,049	59,241	18,912	63,688	21,903	64,764	24,966	77,260	20,245	75,062	29,541	23,113	23	34	17	923	26
Nebraska	22,474	85,279	22,816	88,340	23,925	101,512	31,221	78,670	43,246	85,505	28,172	29,876	16	35	16	1,329	21
Nevada	13,360	91,317	5,512	84,899	10,260	89,267	16,100	59,577	21,125	65,558	15,289	13,657	33	19	23	1,022	25
New Hampshire	8,410	128,597	23,587	150,519	35,049	120,100	34,294	2,667	27,327	2,667	27,327	29,517	17	424	1	3,510	4
New Jersey	8,480	175,072	15,079	96,908	17,471	185,605	24,805	242,810	27,076	160,123	29,243	22,735	26	14	29	2,681	8
New Mexico	29,160	96,518		120,178		147,028	4,400	75,048	4,456	38,759	2,954	3,937	42	3	41	135	41
New York	38,216	696,405	-	762,793	-	698,057	-	737,358	-	828,374	-	*not reported*	*not reported*	*not reported*	*not reported*	*not reported*	*not reported*

Source: Federal Highway Administration, Office of Highway Policy Information, Highway Statistics Series:
Column 2.Table HM-81, State Highway Agency-owned Public Roads, Rural and Urban Miles, Estimated Lane Miles and Daily Travel.
Columns 3-12. Table SF-4C, Disbursements by States for State-Administered, Classified by Function.

Table 2.6. Annual State Cost (USD) of Snow and Ice Removal (*continued)*.

STATE	TOTAL ON SYSTEM LANE MILES	2007 PHYSICAL MAIN-TENANCE x $1000	2007 SNOW AND ICE REMOVAL x $1000	2008 PHYSICAL MAIN-TENANCE x $1000	2008 SNOW AND ICE REMOVAL x $1000	2009 PHYSICAL MAIN-TENANCE x $1000	2009 SNOW AND ICE REMOVAL x $1000	2010 PHYSICAL MAIN-TENANCE x $1000	2010 SNOW AND ICE REMOVAL x $1000	2011 PHYSICAL MAIN-TENANCE x $1000	2011 SNOW AND ICE REMOVAL x $1000	AVERAGE SNOW AND ICE REMOVAL x $1000	RANK	AVERAGE SNOW AND ICE REMOVAL AS PERCENT OF PHYSICAL MAINTENANCE	RANK	AVERAGE SNOW AND ICE REMOVAL COST PER ON-SYSTEM LANE MILE x $1	RANK
North Carolina	170,221	775,086	22,000	623,815	24,705	609,270	29,484	600,619	44,211	700,778	26,989	29,478	18	5	37	173	40
North Dakota	16,996	12,318	10,323	18,201	8,432	17,355	17,171	13,693	9,826	13,225	18,123	12,775	35	88	5	752	30
Ohio	49,349	168,467	89,723	163,051	120,850	341,647	104,605	141,014	104,605	141,140	129,694	109,895	3	65	7	2,227	15
Oklahoma	30,252	158,025	11,995	172,313	7,743	129,856	7,696	122,324	11,630	159,060	14,653	10,743	37	7	33	355	36
Oregon	18,606	228,730	12,361	184,954	18,857	152,773	29,317	138,095	21,363	184,386	32,575	22,895	24	14	30	1,231	23
Pennsylvania	88,450	1,235,501	203,572	1,055,208	280,795	1,026,411	235,717	453,158	268,728	540,537	275,302	252,823	1	35	15	2,858	7
Rhode Island	2,916	60,966	6,224	65,720	9,353	80,049	16,202	110,506	11,704	61,989	17,877	12,272	36	17	26	4,209	3
South Carolina	90,233	337,178	1,059	322,811	1,190	342,292	1,963	355,028	5,370	332,848	9,288	3,774	43	1	44	42	43
South Dakota	18,210	32,502	16,293	51,090	17,414	49,593	15,088	35,231	16,279	38,145	17,606	16,536	31	41	11	908	27
Tennessee	36,858	236,346	8,681	251,537	8,686	305,894	12,674	239,184	23,668	262,432	33,409	17,424	29	7	35	473	34
Texas	194,763	1,311,537	23,374	1,300,886	7,924	1,133,383	9,633	1,228,654	22,601	1,537,642	23,271	17,361	30	1	42	89	42
Utah	15,812	90,588	15,571	97,937	25,830	202,917	22,167	208,522	21,234	184,320	21,234	21,207	28	15	27	1,341	20
Vermont	6,037	50,392	17,402	66,057	14,411	71,851	11,886	65,363	10,368	81,551	11,691	13,152	34	21	21	2,179	16
Virginia	126,124	819,790	61,008	1,038,727	57,303	1,052,926	88,624	803,996	263,680	1,146,983	192,490	132,621	2	14	28	1,052	24
Washington	18,397	265,422	36,518	562,706	47,652	508,418	47,185	550,789	35,001	607,234	71,124	47,496	12	10	32	2,582	10
West Virginia	71,588	171,223	31,846	196,360	33,052	216,260	43,063	208,533	66,230	232,099	47,063	44,251	13	21	19	618	31
Wisconsin	29,593	62,531	55,053	66,713	86,716	64,735	87,002	59,343	67,286	58,552	81,063	75,424	6	121	2	2,549	11
Wyoming	15,794	87,551	20,099	81,824	26,499	39,446	31,416	33,441	33,931	32,287	27,412	27,871	19	64	8	1,765	18
Total	1,866,268	11,934,983	1,257,937	12,499,324	1,675,824	12,697,405	1,736,573	11,954,829	1,966,480	13,368,332	1,958,928	**1,719,148**		**14**		**1,480**	

Source: Federal Highway Administration, Office of Highway Policy Information, Highway Statistics Series:
Column 2.Table HM-81, State Highway Agency-owned Public Roads, Rural and Urban Miles, Estimated Lane Miles and Daily Travel
Columns 3-12. Table SF-4C, Disbursements by States for State-Administered, Classified by Function.

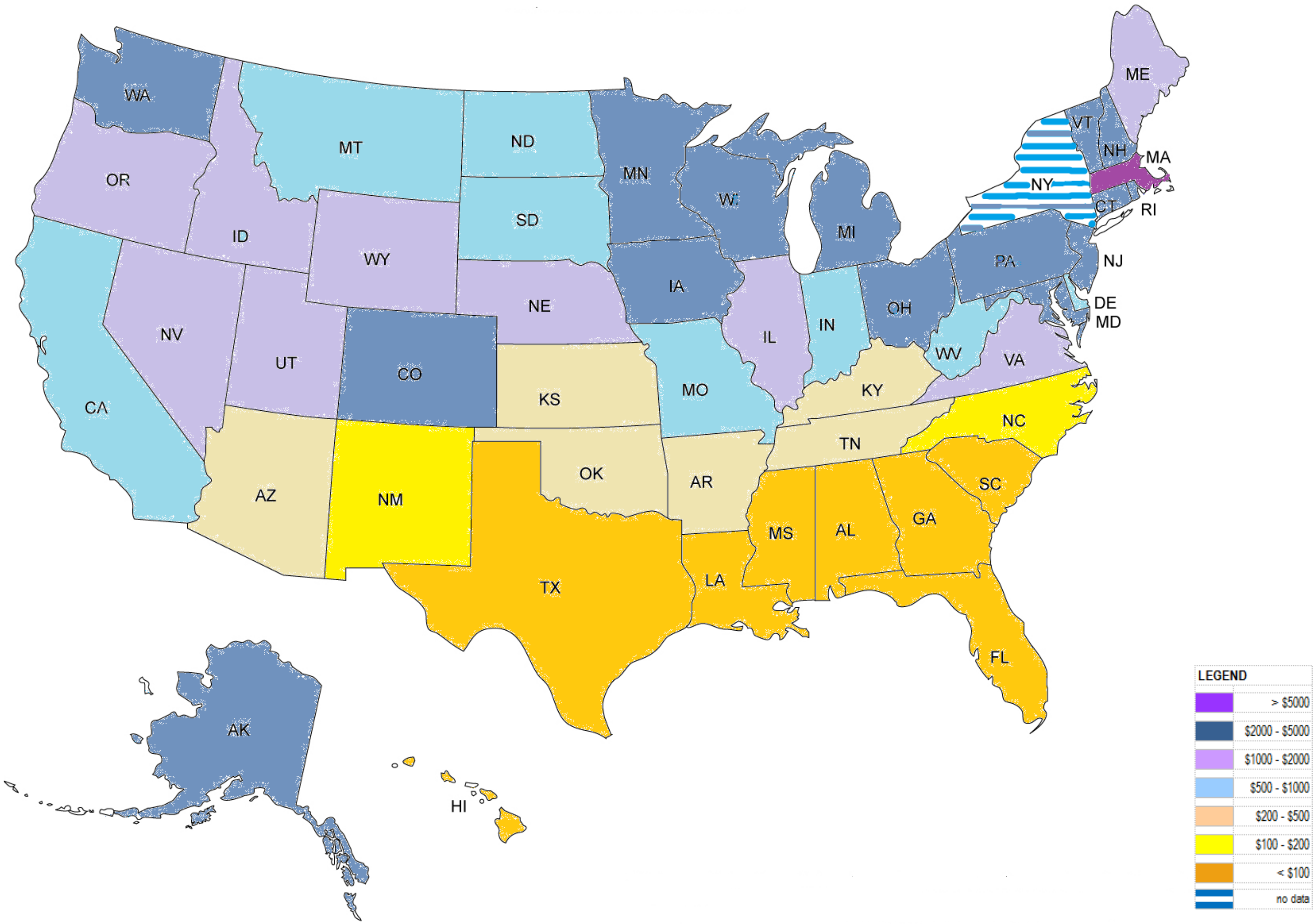


Figure 2.2. United States removal of snow and ice, annual average maintenance cost per lane mile.

Source: Washington State DOT

Figure 2-3. Salt Price Comparison and Usage Based on 2012-2013 State Survey.

(Hawaii and Florida) to $8,615/lane mile (Massachusetts). Texas ranks 42nd with an average annual cost for snow removal of $89/lane mile. In terms of the percentage of cost for snow and ice removal as a function of physical maintenance effort, the range is 0% (Hawaii and Florida) to 424% (New Hampshire). Texas ranks 42nd in the U.S. with the average annual cost for snow and ice removal representing only 1 percent of the physical maintenance expenditures.

2.3.4.2 Other Considerations in Selection of Snow and Ice Control Materials The increase in manufactured blended products has added to the complexity of material selection for snow and ice control. Blended products come at increased costs but with claims of lower corrosion potential and better performance. Many states use the effectiveness of corrosion inhibitors as a weight factor in the bidding process. The more expensive alternatives are commonly used in specific situations, such as automated bridge de-icing systems.

Many states use a combination of chloride salts for snow and ice removal. There are two primary reasons for this. First, the natural occurring rock salt deposits which are mined are a combination of chloride salts, with sodium chloride as the dominant salt type. Second, the chloride salts are often combined to increase the performance of the material (Levelton Consultants Ltd., 2006).

In the NCHRP 577 agency survey, respondents were asked to rank their present purchasing criteria for snow and ice control materials by assigning percentages to various criteria. They were also asked to do the same for future purchases. Weighted averages were used because not all of the respondents completed this section. The results can be seen in Table 2.7.

Table 2.7. Snow and Ice Control Material Product Selection Process (*source: NCHRP 577)*

Criterion	Present Priority Average	Future Priority Average
Environmental	7.3%	9.6%
Corrosion	8.5%	9.8%
Human Exposure	3.5%	3.8%
Purchase Price	38.7%	35.2%
Cost of Use (*i.e*. capital and operational)	6.7%	6.8%
Storage and Handling	7.7%	7.8%
General Performance and Ease of Use	14.6%	14.0%
Climatic Requirements	10.5%	11.1%
Tradition	2.1%	1.5%
Others (*e.g*. friction, odor, wildlife attraction)	0.4%	0.4%

This table indicates that selection of snow and ice control materials is mostly heavily influenced by cost considerations (42 to 45% of all considerations). General performance and ease of use comes in second (14% to 15%). These two criteria, however, are not independent. The availability of the source is a large factor in the cost of the material. From the NCHRP study, it can be seen that purchase price is both the highest present and future priority in selection.

2.4 Snow and Ice Control Materials in Texas

2.4.1 History of Snow and Ice Control Material Usage in Texas

2.4.1.1 Early Usage of Snow and Ice Control Materials Sanding has long been the winter weather roadway maintenance strategy of choice in Texas, both because of Texas' generally mild winters (in most geographic areas of the state) and because sanding is a very visible low-cost approach to managing pavement friction. Chemically-inert, granular materials are applied to ice and snow on the roadway surface with the intention of improving traction on the pavement surface. While research has shown that the traction improvement from abrasives can be very short-lived, abrasives continue to be commonly used in many parts of Texas.

2.4.1.2 More Recent Usage of Snow and Ice Control Chemicals Texas is known for its geographic diversity and its changeable weather. These factors suggest the need for different winter weather roadway maintenance strategies which are tailored to Texas' different geographic regions. In the past 5 to 10 years, snow and ice control chemicals – primarily granular road salt, granular MeltDown 20®, and liquid MeltDown Apex™ – have gained more widespread usage throughout the state. This is especially true for Texas' heavy snow areas –Amarillo, Childress, and north part of the Lubbock districts.

A study of best practices for winter weather operations by Prairie View A&M/ Texas Transportation Institute identified the primary and secondary chemicals used by each TxDOT District for snow and ice control, as reported by the Districts in 2011. Table 2.8 presents this information (Perkins, et al. 2012). A total of 18 out of 25 districts participated in the survey. In the case where chemicals are used interchangeably, both are listed as primary.

Table 2.8 indicates that only 6 of the 18 reporting districts used anti-icing as part of their winter weather maintenance operations strategy. Most districts address snow and ice using a de-icing strategy. Of these, 17 of 18 districts use abrasives (*i.e.*, sanding), with abrasives being a primary snow and ice control material in 16 districts.

Table 2.8. Snow and Ice Control Materials Used by TxDOT (*source*: Perkins, et al. 2012)

District	Anti-Icing Treatment	Deicing Material Used*				
		Chloride Salts$^{\beta}$			Organic Products	Abrasives
		$NaCl_2$	$MgCl_2$	$CaCl_2$	CMA/KA	
Abilene		1	1			1
Amarillo	YES	2	1		1	1
Atlanta			1			1
Austin		2	1		2	2
Beaumont			1			1
Brownwood			1			1
Bryan			1			1
Childress	YES		1			1
Corpus Christi		1				1
Dallas						
El Paso	YES					
Fort Worth						
Houston						
Laredo						1
Lubbock	YES	1	1		1	1
Lufkin			1			1
Odessa						
Paris			1			1
Pharr						1
San Angelo						
San Antonio	YES		1			1
Tyler						
Waco						
Wichita Falls	YES	1	1			1
Yoakum			1			1

1–Primary chemical; 2–Secondary chemical
β–Liquid and/or granular forms

When it comes to deicing chemicals, the dominant material is identified as "$MgCl_2$" – *i.e.*, magnesium chloride – which is used in 14 of 18 reporting districts, all of these identifying $MgCl_2$ as primary. This material is actually *not* $MgCl_2$ but rather is the granular "MeltDown 20®" product which often is mistakenly referred to as magnesium chloride. Just 6 of 18 reporting districts indicate that they use road salt (NaCl) for deicing, with road salt being primary in only 4 of these. Overall, Table 2.8 indicates that TxDOT districts do not use anti-icing to a great degree, they use abrasives extensively, and when they use deicing chemical, the material is most likely granular MeltDown 20® although a few districts use road salt.

2.4.1.3 TxDOT's Localized Winter Weather Roadway Maintenance Strategy Interviews with TxDOT roadway maintenance personnel indicate that, with the exception of the heavy snow areas in the Texas Panhandle, roadway maintenance professionals in most areas of the state have relied on a localized approach to winter weather maintenance that leverages the benefits of Texas' typically mild winters which are characterized by infrequent and short-duration storms. The mild weather has allowed most areas of the state to manage and "get by" in this manner.

However, maintenance personnel in the heavy snow regions of the state, of necessity, have been more proactive. Snow and ice control chemicals, often blended with abrasives, have been used for many years to help keep roads open and safe during the more severe snow and ice storms these areas experience every winter. Maintenance personnel in these northern districts, led by Amarillo, initiated a regional cooperative effort in the early 2000s to share knowledge and expertise associated with both management and operational response to winter storms. Topics have included winter weather maintenance operations strategies, lessons learned, results from limited field trials on various types of snow and ice control chemicals, and recommended practices.

2.4.1.4 The 2011 Groundhog Day Blizzard TxDOT initiated its OneDOT concept in 2010, the objective being to establish a culture of shared vision, goals, and information to promote cohesiveness across the agency. OneDOT was an intentional shift away from localized practices and procedures, and winter weather roadway maintenance was one of the expressions of the OneDOT concept. In February 2011, this was put to the test when Texas received national visibility through Superbowl XLV at Cowboys Stadium in Arlington. More significantly for TxDOT, the DFW Metroplex experienced extreme winter weather associated with the *2011 Groundhog Day Blizzard* (Figure 2.4), identified by the National Weather Service as one of the "…biggest snowstorms in the United States from 1888 to present" (NOAA 2011).

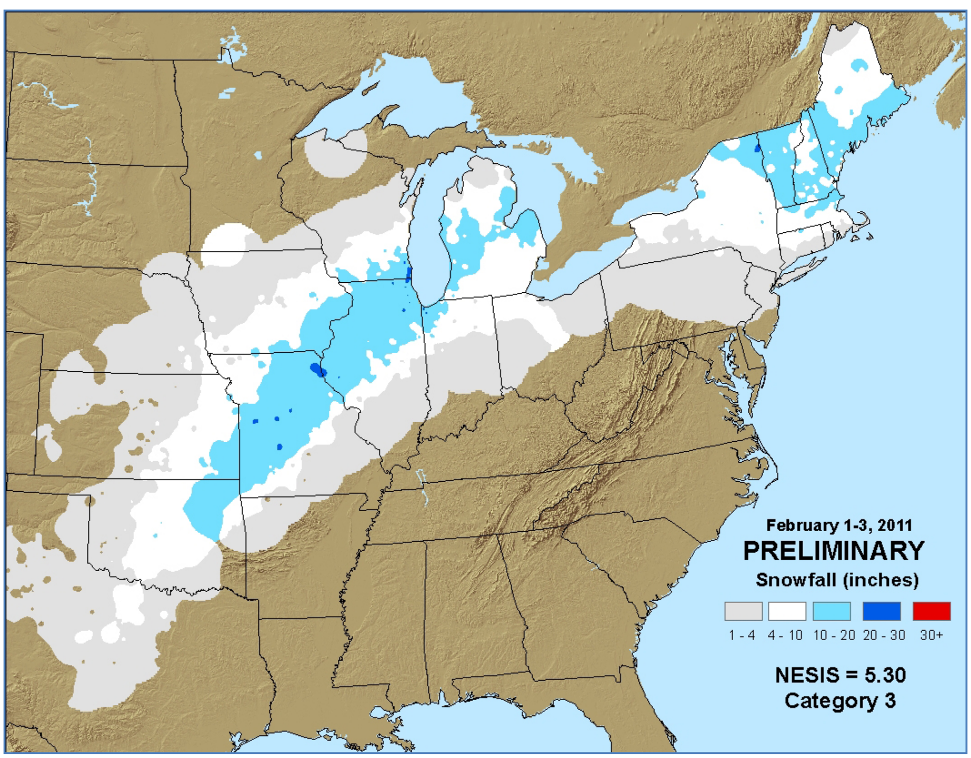


Figure 2.4. Snowfall Map, 2011 Groundhog Day Blizzard (*source*: NOAA)

Through careful planning, advance preparation, and snow-fighting assistance involving maintenance personnel and equipment from across the state, TxDOT was, for the most part, able to keep DFW-area highways open during Superbowl XLV. However, this record-breaking, extreme winter weather event and subsequent freezing temperatures produced snow and ice across the state as far south as Houston, with accumulations and mobility impacts on major US highways and interstate highways lasting up to five days.

As an extreme winter weather event, the 2011 Groundhog Day Blizzard overwhelmed roadway maintenance forces in its path across much of the United States, including parts of Texas. This storm revealed Texas' need for an improved, coordinated roadway maintenance response to both typical and extreme winter weather events, statewide.

2.4.1.5 TxDOT Policy and Sponsored Research on Winter Weather Maintenance
TxDOT's primary source document for policy on winter weather roadway maintenance is the TxDOT *Maintenance Management Manual* (TxDOT 2014), which identifies snow and ice control as routine maintenance and part of emergency operations. The TxDOT *Maintenance Operations Manual* (TxDOT 2010) devotes Chapter 5 to snow and ice operations and addresses topics including the priority of work, district plans, snow and ice control methods, road closures, highway condition reporting, and railroad grade crossings. TxDOT published the *Snow and Ice Control Operations Manual* (TxDOT 2012) which presents more detailed agency guidance for winter weather management and operations.

In 2011, TxDOT sponsored research project 0-6669, performed by Prairie View A&M University and the Texas Transportation Institute, to research best practices for winter weather operations. That study yielded a 210 page research report identifying "actionable practices" relative to winter weather operations (Perkins, et al. 2012). About this same time, following the 2011Groundhog Day Blizzard, TxDOT sponsored implementation project 5-9044-01 for the purpose of creating instructional materials and delivering training on the topic of winter weather roadway maintenance, statewide, to TxDOT management and operations personnel. In January 2012, TxDOT authorized this present research study, focusing on the identification and classification of the types of snow and ice control materials suitable for use on Texas roads under Texas winter weather conditions.

2.4.2 Types of Snow and Ice Control Materials Commonly Used in Texas

TxDOT uses only a few types of snow and ice control materials for their winter weather roadway maintenance operations. Granular chemicals include MeltDown 20® and road salt. Liquid chemicals include MeltDown Apex™ and more recently, an interest in both manufactured salt brine and natural brine. TxDOT also uses a variety of abrasives for temporary friction improvement. A brief description of each material follows.

MeltDown 20® is a granular product distributed to TxDOT by Envirotx. This manufactured blend is a type of sea salt, mined in Redmond, Utah (Speer 2012). The mined salt is crushed and processed in Redmond and a performance enhancer – similar to a concentrated form of Envirotx' liquid chemical, MeltDown Apex™ – with corrosion inhibitor is spray-applied to the granular salt. The final granular MeltDown 20® product is then shipped from Redmond, Utah, under the guidance of Envirotx, to Texas. MeltDown 20® contains 90 to 98 percent sodium chloride (NaCl). The details on the chemical composition for MeltDown 20® and other chemicals discussed in this section appear on their respective Material Safety Data Sheet (MSDS), shown in Appendix F.

Road Salt (NaCl) is the granular form of sodium chloride (NaCl). TxDOT has extensively used road salt from a site near Carlsbad, New Mexico. Currently road salt is distributed by United Salt Corporation and by Envirotx.

MeltDown Apex™ is a magnesium chloride brine solution obtained by solarizing natural salt brine from the Great Salt Lake in Utah (Speer 2012). This liquid product is shipped from Utah to EnviroTech in Greeley, Colorado, where the proprietary blend is added. The final product is then distributed to TxDOT through Envirotx. MeltDown Apex™ contains 25-35 percent magnesium chloride, 65-75 percent water, and proprietary additives.

Salt Brine (NaCl) is the liquid form of sodium chloride (NaCl). Although TxDOT has used various types of salt brine over the years, in 2011, the TxDOT Childress District invested in a salt brine manufacturing tank system where they now make their own salt brine, at proper concentration for anti-icing applications (23 percent salt), in a dedicated mixing tank. The raw materials for salt brine are water and brine-quality road salt.

TxDOT uses several types of abrasives for snow and ice control. Among the most common is Item 302, Grade 5 aggregate for surface treatments. The material is of various types (crushed stone, crushed gravel, etc.) and has a maximum nominal particle size of 3/8 inch. Similar products include Item 421 fine aggregate (concrete sand), crushed limestone screenings, and blotter sand. Where available, TxDOT personnel also use bottom ash, this being a by-product from coal-burning power plants. Aggregate-salt or bottom ash-salt blends are also common.

Table 2.9 is from the Prairie View A&M report (Perkins, et al. 2012). This table lists the winter weather chemicals and materials used by the TxDOT Districts in 2011. Note that these material descriptions are TxDOT descriptions and are not necessarily representative of the true active chemical ingredients of the product (Perkins, 2012).

Table 2.9. Fiscal Year 2011 Inventory of Winter Weather Chemicals and Materials (*source*: Perkins, et al. 2012).

	Districts																								
Chemicals & Materials	ABL	AMA	ATL	AUS	BMT	BWD	BRY	CHS	CRP	DAL	ELP	FTW	HOU	LRD	LBB	LFK	ODA	PAR	PHR	SJT	SAT	TYL	WAC	WFS	YKM
Aggregate: Bottom Ash; Pit Run (Fine)	X	X																							
Aggregate; Bottom Ash; Pit Run, (Coarse), ASTM C 136-92		X						X																	
Aggregate; Concrete; I#421, Fine, Grade 1				X							X				X		X		X	X	X	X	X		
Aggregate; Concrete; I#421, Fine, Grade 1 (2004 Spec)	X			X			X				X		X				X		X	X			X		
Aggregate; Ice Control; Coarse Btm Ash and Salt Mixed F		X																							
Aggregate; Ice Control; Fine BTM Ash and Salt Mixed F/I		X													X										
Aggregate; Ice Control; Remixed Sand/Chloride Mix												X													
Aggregate; Ice Control; Remixed Sand/Grade 5 Aggregate																							X		
Aggregate; Ice Control; Remixed Sand/Salt								X			X	X	X												
Aggregate; Sinter Material; By Product from Crushed Stone						X																			
Aggregate; Surface; Crushed Limestone Screening Material		X													X					X					
Aggregate; Surface; I#302, Blotter Sand, Grade-Spec									X																
Aggregate; Surface; I#302, Type A, Grade 5 S, (2004 Spec)																						X			
Aggregate; Surface; I#302, Type B, Grade 5-Mod	X		X																		X	X			
Aggregate; Surface; I#302, Type B, Grade 5 (2004 Spec)	X	X	X	X				X	X					X	X	X		X	X		X	X	X		X
Aggregate; Surface; I#302, Type B, Grade Special	X									X		X												X	
Aggregate; Surface; I#302, Type B, Grade Special (2004 Spec)	X								X	X	X	X		X			X						X	X	X
Aggregate; Surface; I#302, Type E, Grade 5-Mod			X	X	X				X				X								X	X			
Aggregate; Surface; I#302, Type E, Grade 5 (2004 Spec)	X			X			X		X				X	X	X	X				X	X				X
Aggregate; Surface; I#302, Type L, Grade 5 (2004 Spec)					X	X	X	X		X				X		X		X				X		X	
De-Icer; Liquid Solution, 50% Potassium Acetate																		X							
De-Icer; Roadway; 100% Calcium Mag Acetate, 2205 LB/Bag		X		X						X										X		X	X		
De-Icer; Roadway; 100% Calcium Mag Acetate, 55 LB/Bag	X					X	X			X								X		X		X	X		
De-Icer; Roadway; 40% Calcium Mag Acetate-60% Salt, 2250 LB																					X		X		
De-Icer; Roadway; 89% Mag Chloride, 11% Corrosion & Dus	X	X		X		X	X	X		X	X	X	X		X		X			X	X	X		X	
De-Icer; Roadway; 89% Mag Chlorine, 11%, 50LB/Bag, Corr	X	X		X				X		X	X	X			X		X	X		X				X	
De-Icer; Roadway; Complex Chloride with Corrosion and D	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X		X		X	X	X	
De-Icer; Roadway; Crystals, 20lb Moisture Proof Bag								X																	
De-Icer; Roadway; Liquid Magnesium Chlorine w/Corrosion	X	X	X					X		X	X	X	X		X					X	X			X	
De-Icer; Roadway; Liquid Solution, 50% Potassium Acetat																					X				
De-Icer; Roadway; Liquid Solution, Magnesium Chloride									X			X													
Salt; Sodium; Chloride, 50 LB. Bag, Road Maintenance	X			X		X		X		X	X	X			X		X							X	
Salt; Sodium; Chloride, for Highway Maintenance		X	X					X		X		X			X		X	X						X	

2.4.3 Application Rates for Snow and Ice Control Materials in Texas

In 2010, TxDOT performed an internal analysis of cost effectiveness and usage of various snow and ice control materials (Markwardt 2010). This study looked at not only the initial purchase price, but also the typical application rates and the normalized cost per lane mile for treatment. Table 2.10 summarizes the findings from this internal analysis. Among other things, this chart shows nominal application rates for typical snow and ice control materials used in Texas, as well as the statewide average unit cost for 2010. More importantly, by normalizing the costs per lane mile, it is possible to obtain a more clear understanding of the range of costs for the different materials.

Table 2.10. Unit Costs for Typical Snow and Ice Chemicals Used by TxDOT, statewide averages (*source*: Markwardt 2010)

Product	Material	Rate	$/Unit	$/Lane Mile	Comments
MeltDown Apex™	$MgCl_2$	20 gal/Lmi	$1.68/gal	$33.60	Anti-icing/ brine
MeltDown Apex™	$MgCl_2$	40 gal/Lmi	$1.68/gal	$67.20	De-icing/ brine
MeltDown 20®	NaCl/ Proprietary	150 lb/Lmi	$0.23/ lb	$34.50	De-icing/ granular
Freezeguard	$MgCl_2$	20 gal/Lmi	$1.26/gal	$25.20	Anti-icing/ brine
Freezeguard	$MgCl_2$	40 gal/Lmi	$1.26/gal	$50.40	De-icing/ brine
Road Salt	NaCl	60 gal/Lmi	$0.066/gal	$3.96	Anti-icing/ brine
Road Salt	NaCl	300 lb/Lmi	$0.033/lb	$9.90	De-icing/ granular

Published national guidance on snow and ice control material application rates appears in Section 2.3 of this report, and TxDOT practice is consistent with this and other recommendations.

2.4.4 Cost of Snow and Ice Control Materials in Texas

2.4.4.1 Statewide Average Annual Cost of Snow and Ice Control Materials Figure 2.5 summarizes TxDOT's statewide average annual cost of snow and ice control materials including abrasives, liquid chemical (MeltDown Apex™), and granular chemical (road salt, MeltDown 20®), for fiscal years 2008-2012. This figure shows that abrasives comprise about 43 percent of TxDOT's expenditures for snow and ice control materials and thus continue to play a significant role in TxDOT's winter weather operations. However, more than half (57 percent) of TxDOT's current expenditures for snow and ice control materials are for granular chemicals (51 percent) and liquid chemicals (6 percent), not abrasives, indicating that chemicals are featuring more prominently in TxDOT's snow and ice operations.

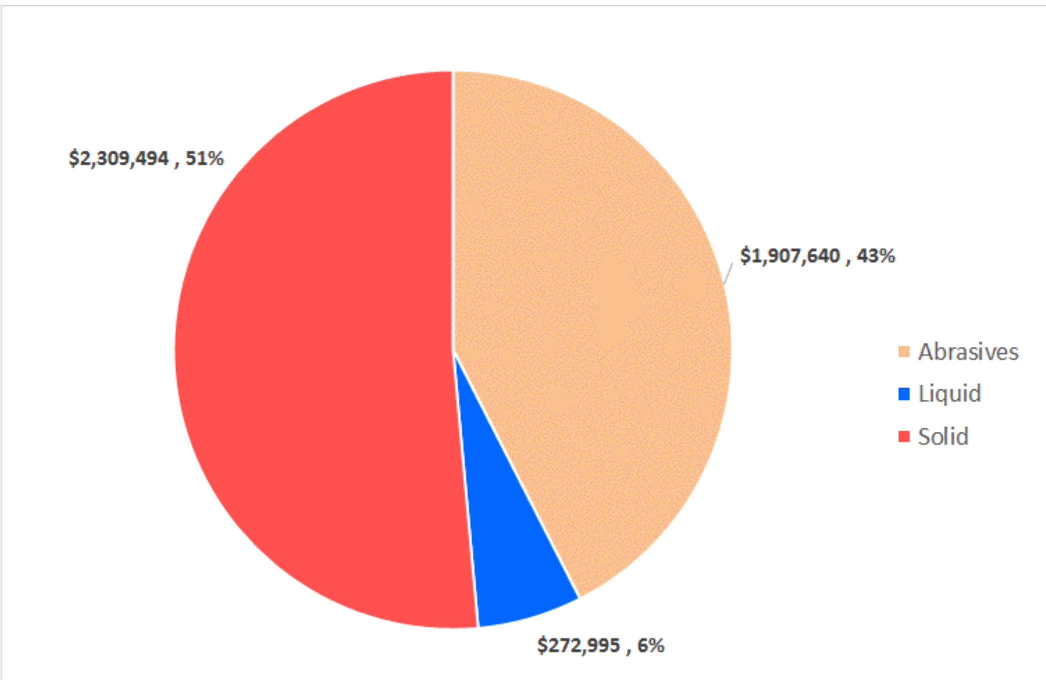


Figure 2.5. TxDOT Average Annual Cost for Snow and Ice Control Materials, FY2008-12

Figure 2.6 and Figure 2.7 provide a more detailed breakdown of costs for TxDOT's granular and liquid snow and ice chemicals. Based on TxDOT maintenance procurement data, the percentages represent the annual average (mean) of the quantity of material purchased in the fiscal years 2008 through 2012. For the liquid products (Figure 2.6), the percentages are based on the quantity, in gallons, of the products at time of purchase. The quantity of chemical in each of the brines varies depending on the product and manufacturer. The charts do not include salt brine that is made in-house by TxDOT, which began in fiscal year 2012. For the granular products (Figure 2.7), the percentages are based on the quantity, in pounds, of the products at time of purchase. Bulk purchases were often in units of cubic yards, so using typical unit weights, cubic yards was converted to pounds.

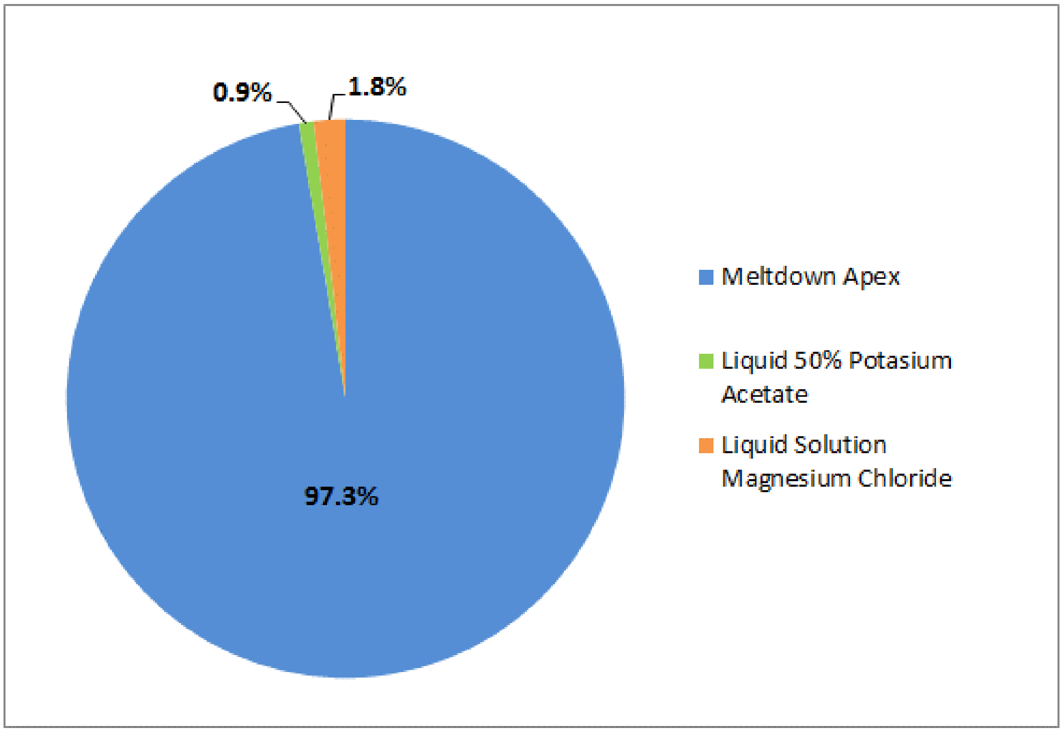


Figure 2.6. Liquid Snow and Ice Control Chemical, % by volume, 5-year average (FY2008-12).

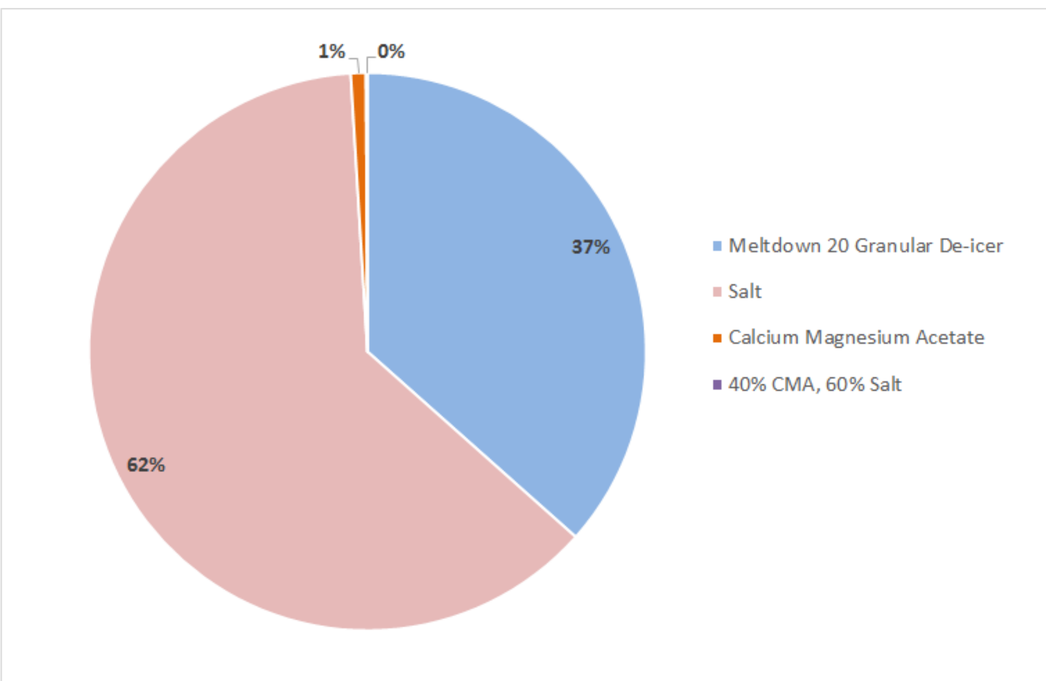


Figure 2.7. Granular Snow and Ice Chemical, % by Weight, 5-year average (FY2008-12)

2.4.4.2 Details on Materials used in Texas As has been noted, TxDOT historically has used four materials for most of their snow and ice operations: MeltDown 20® (granular, deicing), MeltDown Apex™ (liquid, anti-icing), Road Salt (granular, deicing), and abrasives (granular, friction improvement). Manufactured salt brine is a relative newcomer and historic cost data are not available for salt brine.

Table 2.11 identifies the quantity (yearly mean) of these materials purchased statewide in TxDOT for fiscal years 2008 to 2012, the five year unit cost average, and FY2012 unit cost. The unit cost for abrasives is an overall average, realizing that TxDOT uses several different types of abrasives.

Table 2.11. Statewide Unit Cost Data for TxDOT's Primary Snow and Ice Control Materials

Material	Unit	5 Year Average (FY2008-12)		FY 2012
		Quantity	Unit Cost ($/Unit)	Unit Cost ($/Unit)
MeltDown 20® granular, deicing	LB	6,307,276	0.281	0.298
Road Salt granular, deicing	LB	11,736,040	0.035	0.032
MeltDown Apex™ liquid, anti-icing	GAL	160,007	1.65	1.84
Abrasives Granular, friction improvement	LB	206,256,000*	0.009	0.013
	TON	103,128*	18.17	25.73
*Average quantity is 68,752CY, with weight estimated at 1.5 tons/CY				

The unit costs in Table 2.11 provide a way to contextualize the 2010 cost data from the TxDOT internal analysis, as presented in Table 2.10. These data show that unit costs for MeltDown 20® and MeltDown Apex™ have risen 30 percent and 10 percent, respectively, compared to FY2012, whereas unit costs for road salt have remained relatively constant.

2.5 Winter Weather and Roadway Maintenance

2.5.1 National Perspective on Winter Weather Impacts

The quantity of snow and ice chemicals a State DOT uses is fundamentally based on the weather. For example, snow and ice control materials are usually purchased and stored before the winter season, and climatology is used to predict the amount of material needed as well as the frequency of storms.

The National Oceanic and Atmosphere Administration (NOAA) has developed climate plots for the United States for several of the key metrics associated with winter weather roadway maintenance. These include the length of the winter season, temperature, and winter precipitation in the form of snow, ice and freezing rain.

For example, the length of the winter season is often determined as the numbers of days from first freeze to last freeze. Figure 2.8 shows the mean freeze-free period for the United States, the inverse of which would indicate the length of the winter season.

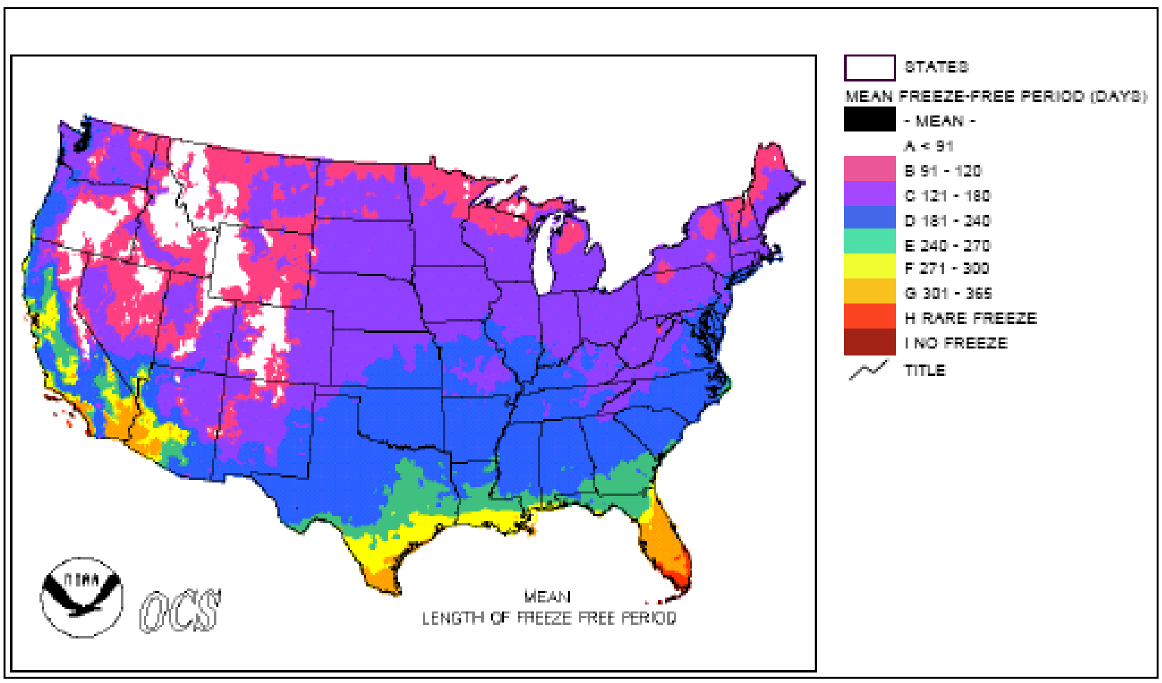


Figure 2.8 . Mean Freeze-Free Period for the United States (*source*: NOAA)

It is not only important to know the duration of the winter season but the temperatures as well. Ambient temperatures relate to pavement temperature, and pavement temperature is a key variable relative to the application and effectiveness of snow and ice control chemicals. Temperatures are often not at the minimum during the duration of the storm. Clouds often form an insulating effect, and minimum temperatures usually occur the night (or more specifically, early morning, before sunrise) after precipitation has ceased. This produces a major problem of re-freeze on the pavement. Climate data can be used to characterize the severity of low temperatures expected in a particular region as shown in Figure 2.9, which depicts the mean daily minimum temperature for January (National Climatic Data Center, 2012).

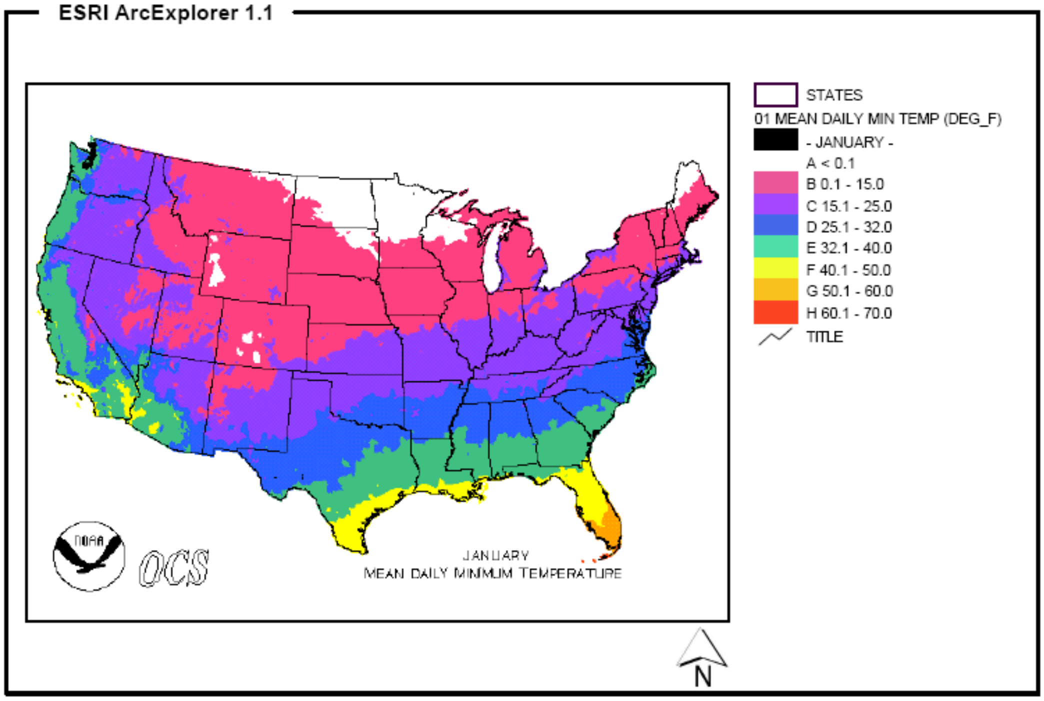


Figure 2.9. Mean Daily Minimum Temperature for January. *(source: NOAA)*

Another key winter weather roadway maintenance metric is the annual mean total snowfall, as shown in Figure 2.10 (National Climatic Data Center, 2012). Snow is the type of precipitation in which anti-icing with chemicals is most effective. From the figure it can be seen the Texas Panhandle receives 6 to 24 inches of snow annually, but most of the state receives 3 inches of snow or less and the coastal areas receive none. This map bears striking resemblance to Figure 2.2 which shows the annual cost of snow and ice removal, per lane mile, in each of the states. Winter weather roadway maintenance costs in populous northern states that receive 24 inches of snow per year are higher by an order of magnitude, compared to Texas.

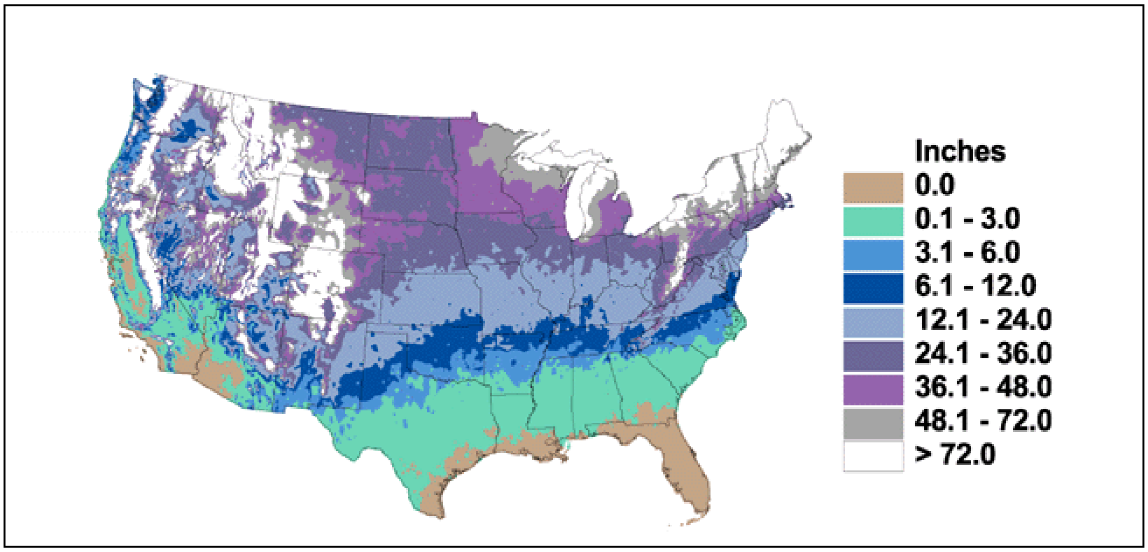


Figure 2.10. Annual Mean Total Snowfall *(source: NOAA)*

Ice events are also a concern for winter weather operations. Ice is formed both through precipitation such as freezing rain, or the melting and subsequent refreezing of snow. Ice also can present as frost and black ice. Frost, on roadway surfaces, occurs when both the dew point and pavement temperature are below freezing, with the pavement temperature being below the dewpoint. Black ice occurs when the pavement temperature is below both the dewpoint and freezing point, and the dew point is above freezing. This leads to dangerous conditions, as thin, clear ice forms on the roadway. Freezing rain occurs when the atmospheric temperature is not sufficiently cold enough for snow to form. However, depending on pavement temperatures, freezing rain may turn into ice. Freezing rain is a special circumstance in which the reactive de-icing strategy is primarily used.

Figure 2.11 shows the average number of freezing rain days based on 52 years of data (Changnon, 2003). This chart indicates that in Texas, an average of one to two days of freezing rain occurs annually. The frequency of annual days with freezing rain decreases from north to south.

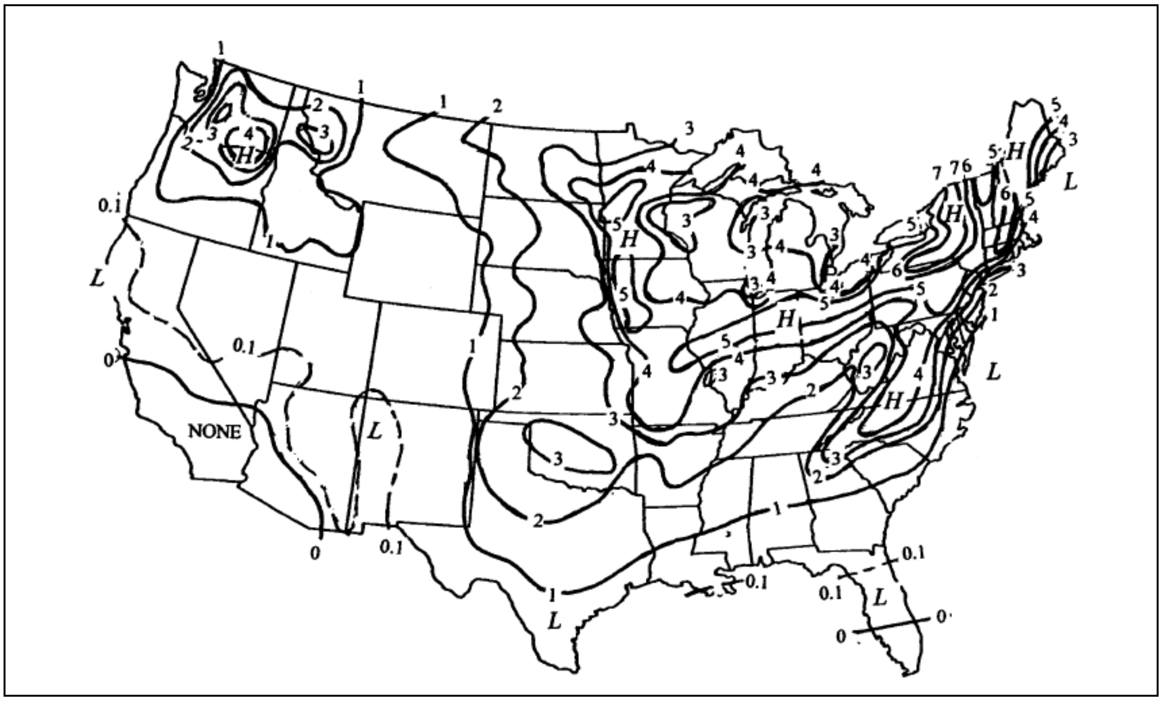


Figure 2.11. The average annual number of days with freezing rain. (source: *Changnon 2003)*

2.5.2 The Texas Perspective on Winter Weather

Statewide data are available for the same winter weather metrics illustrated at the national level. Table 2.12 shows the length of the winter season, determined as the numbers of days from first freeze to last freeze. This table derives from climate data for the principal cities in all TxDOT districts. Figure 2.12 provides this same information graphically. This illustrates that climate data are available such that it is possible to obtain a relatively fine-grained characterization of particular winter weather metrics for all of TxDOT's districts.

Relative to temperature, Figure 2.13 shows the mean number of days in January where the temperature is at or below freezing. As with the national data, correlations exist between length of season and temperature.

Table 2.12. Average Winter Season Length, Start Date, and End Date by District (1971-2000 data) (*source: NOAA)*.

TxDOT District	Length of Winter Season (Average)	First Fall Freeze Average	Last Spring Freeze Average
Abilene	133	Nov 12	Mar 24
Amarillo	181	Oct 20	Apr 18
Atlanta	127	Nov 14	Mar 20
Austin	73	Dec 6	Feb 17
Beaumont	85	Dec 2	Feb 25
Brownwood	135	Nov 11	Mar 25
Bryan	94	Nov 29	Mar 2
Childress	147	Nov 6	Apr 1
Corpus Christi	42	Dec 23	Feb 3
Dallas	99	Nov 25	Mar 3
El Paso	135	Nov 8	Mar 22
Fort Worth	128	Nov 14	Mar 21
Houston	92	Nov 30	Mar 1
Laredo	66	Dec 5	Feb 9
Lubbock	154	Nov 1	Apr 3
Lufkin	119	Nov 15	Mar 13
Odessa	139	Nov 12	Mar 30
Paris	125	Nov 14	Mar 18
Pharr	30	Dec 25	Jan 24
San Angelo	136	Nov 13	Mar 28
San Antonio	95	Nov 25	Feb 28
Tyler	146	Nov 7	Apr 1
Waco	115	Nov 19	Mar 13
Wichita Falls	140	Nov 9	Mar 28
Yoakum	87	Dec 2	Feb 27

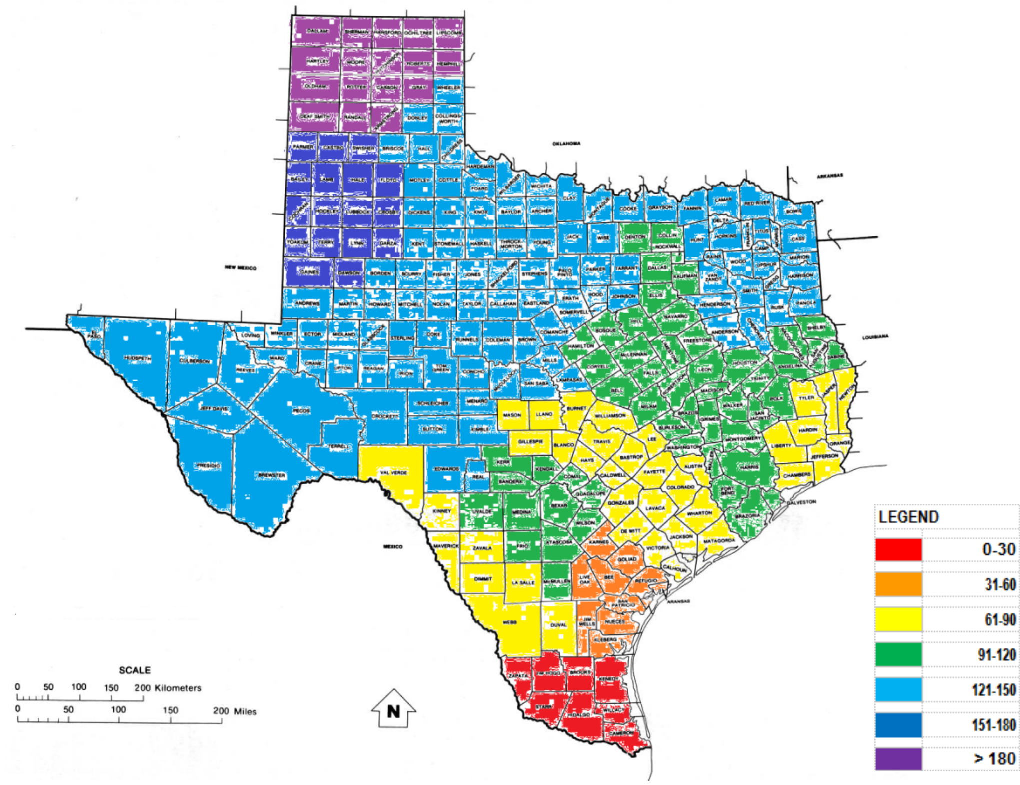


Figure 2.12. Length of Winter Season by TxDOT District.

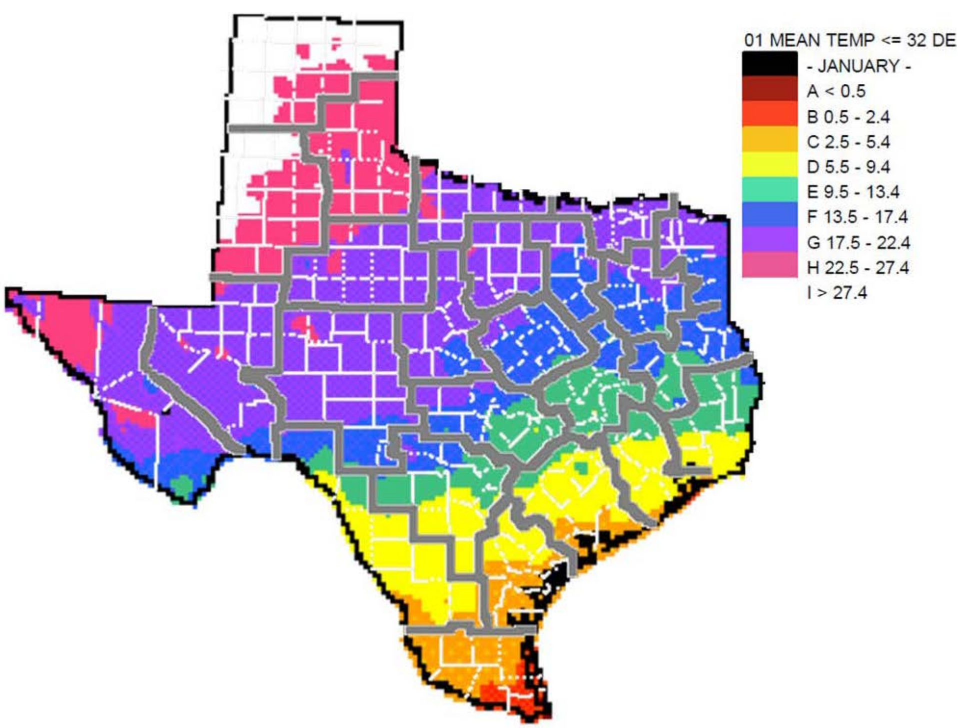


Figure 2.13. Number of Days in January with Temperatures at/below Freezing (*source*: NOAA).

Snowfall data are available for Texas for the principal cities in each district. Table 2.13 shows the average annual snowfall by district (National Oceanic and Atmospheric Administration. , 2001). Figure 2.14 presents a climate map illustrating this same information.

Table 2.13. Average Annual Snowfall by District (*source: NOAA)*

TxDOT District	Average Annual Snowfall (Inches)
Abilene	5.6
Amarillo	17.9
Atlanta	1.1
Austin	0.6
Beaumont	0.1
Brownwood	1.4
Bryan	0.6
Childress	7.8
Corpus Christi	T
Dallas	1.7
El Paso	6.1
Fort Worth	2.6
Houston	0.5
Laredo	0.1
Lubbock	10.4
Lufkin	0.5
Odessa	5.0
Paris	4.2
Pharr	T
San Angelo	3.1
San Antonio	0.8
Tyler	1.9
Waco	1.1
Wichita Falls	5.5
Yoakum	T

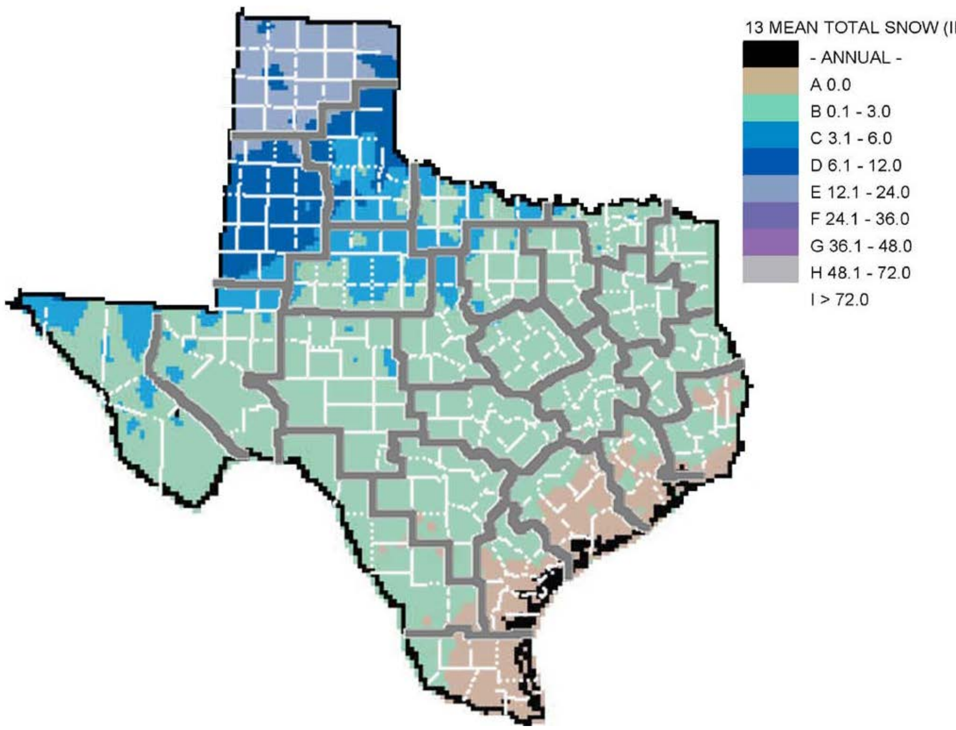


Figure 2.14. Annual Mean Total Snowfall, in inches (*source*: NOAA).

As has been noted, the Texas Panhandle receives the state's greatest snowfall. Figure 2.15 is a detailed map showing the cumulative average annual snowfall in the Panhandle region of the state (National Climatic Data Center, 2012).

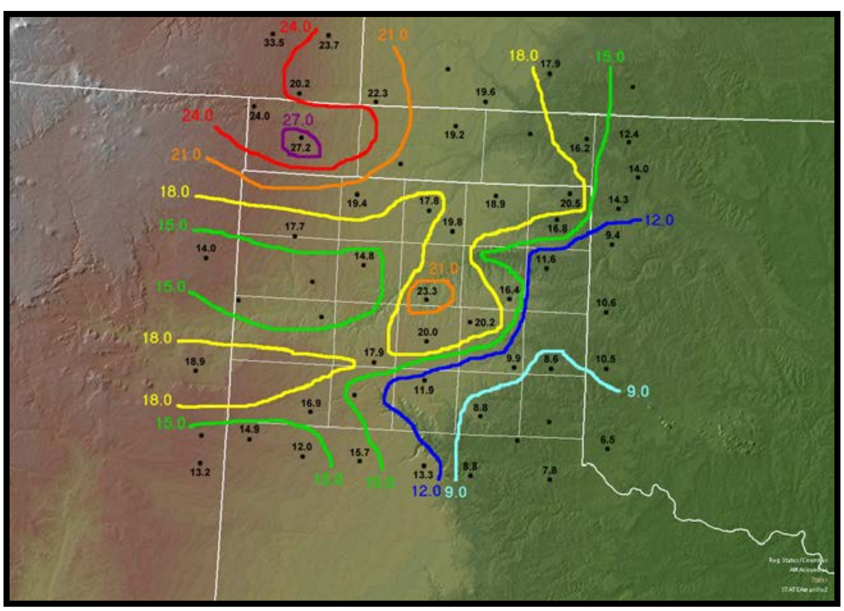


Figure 2.15. Average annual snowfall in the Texas Panhandle *source: NOAA*

2.5.3 Observations about Winter Weather Relative to Snow and Ice Control Materials

2.5.3.1 Perspective from Weather Severity The climate data presented herein demonstrate that Texas winters are relatively mild compared to the northern parts of the United States. More significantly, from the perspective of temperature considerations in selection of snow and ice control chemicals, none of the chemicals should be precluded based on their ineffectiveness at lower temperatures. One example is road salt, which some northern agencies choose not to use in very cold conditions, say, when pavement temperatures are below 15 degrees F. Texas climate data do not support this approach, since pavement temperatures in Texas very rarely drop low enough for any of the typical chemicals to become ineffective. Further, maintenance practices in colder and snowier states than Texas, such as Iowa and Minnesota, effectively use both granular road salt and liquid salt brine in their winter roadway maintenance operations.

2.5.3.2 Perspective from Snow and Ice Control Material Usage Corrosion and environmental impacts are a significant consideration in the selection and use of snow and ice control chemicals, and this is addressed in detail in the corrosion section of the report (Chapter 4). When one considers that corrosion and environmental impacts directly relate to the quantity of chemical used, and the quantity of chemical is driven by climate severity, it can be observed that because Texas winters are relatively mild, most portions of the state see only a few winter storms per year, and some see no storms at all. Further, even the coldest and snowiest portions of Texas have less severe winters than northern states with active, chemical-based winter roadway maintenance programs. Figure 2.2 indicates that Texas' winter maintenance activities are an order of magnitude lower – one-tenth to one-fiftieth – than states such as Iowa, Ohio, and Massachusetts. Quantitatively, it is reasonable to infer that TxDOT winter maintenance operations apply an order of magnitude (or lower) of chemical to Texas bridges and roads. While this does not eliminate corrosion and environmental concerns associated with winter roadway maintenance in Texas, it does put these issues in perspective.

2.5.3.3 Perspective from Weather Variability Not only does Texas weather change quickly, but it is also true that Texas receives different kinds of winter weather. Table 2.14 summarizes specific Texas winter weather events and a combination or mix of these events over a ten year period (Perkins, et al, 2012).

This table illustrates three key points about winter storms in Texas. First, the number of Texas winter storms in any given year varies to a *remarkable* degree. Five of the eleven years reported 20 or fewer storms. Three years experienced 21 to 100 storms, and three years experienced between 100 and 150 storms. Variability in the number of storms is one of the key planning challenges associated with winter weather roadway maintenance in Texas.

Table 2.14. Frequencies of Reported Winter Weather Events in Texas (2000–2010) (*source: NOAA*)

Storm Type	Year											Total
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	
Blizzard	0	0	0	0	0	0	1	0	0	7	0	8
Freezing Rain	0	1	0	0	0	0	0	0	0	0	0	1
Heavy Snow	5	7	4	2	20	7	28	24	2	9	53	161
Ice Storm	8	1	1	0	1	4	3	41	1	8	2	70
Ice/Snow	0	0	1	0	0	0	0	0	0	0	0	1
Winter Storm	7	6	6	3	6	6	11	35	8	24	4	116
Winter Weather	0	0	0	0	0	0	30	46	44	56	39	215
Winter Weather/Mix	0	0	0	1	10	2	2	0	0	0	0	15
Freezing Fog	0	0	0	0	0	0	0	1	0	0	0	1
Frost/Freeze	0	0	0	0	0	0	0	0	4	9	38	51
Sleet	0	0	0	0	0	0	0	1	0	0	1	2
Sleet Storm	0	0	0	0	1	0	0	0	0	0	0	1
Total	20	15	12	6	38	19	75	148	59	113	137	642

Second, the types of winter storms are diverse and include snow, ice, and various forms of freezing rain. The most common storm type is "winter weather" which is defined as "a winter precipitation event that causes a death, injury, or a significant impact to commerce or transportation but does not meet locally/regionally defined warning criteria." This is followed by "heavy snow" which is "snow accumulation meeting or exceeding locally/regionally defined 12 and/or 24 hour warning criteria, on a widespread or localized basis." The third most common is "winter storm" which is defined as "a winter weather event which has more than one significant hazard (i.e., heavy snow and blowing snow; snow and ice; snow and sleet; sleet and ice; or snow, sleet and ice) and meets or exceeds locally/regionally defined 12 and/or 24 hour warning criteria for at least one of the precipitation elements, on a widespread or localized basis." The fourth most common is "ice storm" which is defined as "ice accretion meeting or exceeding locally/regionally defined warning criteria (typical value is 1/4 or 1/2 inch or more), on a widespread or localized basis." Rounding out the top five, "frost/freeze" refers to "a surface air temperature of 32 degrees Fahrenheit (F) or lower, or the formation of ice crystals on the ground or other surfaces, over a widespread or localized area for a period of time long enough to cause human or economic impact, during the locally defined growing season."

Complete definitions for these and the rest of the storm types in Table 2.14 appear in Winter Weather Definitions from the National Weather Service (NWS) Directive 10-1605 "The Collection and Dissemination of Storm Data", and are presented in Appendix G. The point for this discussion is that Texas does not just receive snow, or ice, but it receives the entire range of winter storm types. This variability correlates strongly with Texas geography and is another significant challenge for winter weather roadway maintenance.

The third key point about winter storms in Texas is their variability in *intensity*. As has been noted, the most common storm type is "winter weather" which is a winter precipitation event that does not meet locally/regionally defined warning criteria. In contrast, blizzard, heavy snow, ice storm, sleet, and others are more severe winter storm events which do meet defined warning criteria. Variability in intensity is another significant challenge for winter weather roadway maintenance in Texas.

2.5.3.4 Perspective from TxDOT Maintenance Professionals The TTI report, *Research on Best Practices for Winter Weather Operations*, developed Table 2.15 and Figure 2.16 based on interviews with TxDOT maintenance supervisors and personnel. This table and figure illustrate that winter weather typically falls into one of three storm categories: mostly snow, snow and ice, and ice and freezing rain (Perkins, et al. 2012).

Table 2.15. Type of Winter Weather in Texas in Texas Districts and Counties (*source*: Perkins, et al. 2012)

Mostly Snow	**Snow and Ice**	**Ice and Freezing Rain**
Atlanta (*Bowie*)	Abilene	Austin
Amarillo	Atlanta	Beaumont
Childress	Brownwood	Bryan
El Paso (*Brewster, Presidio*)	Bryan (*Freestone, Leon, Madison, Milam, Robertson*)	Corpus Christi
Lubbock (*Parmer, Castro, Swisher*)	Dallas	Houston
Paris (*Grayson, Fannin, Lamar, Red River*)	El Paso	Laredo
Wichita Falls	Fort Worth	Lufkin
	Lubbock	Odessa
	Paris	Pharr
	San Angelo	San Antonio
	Waco	Tyler
		Yoakum

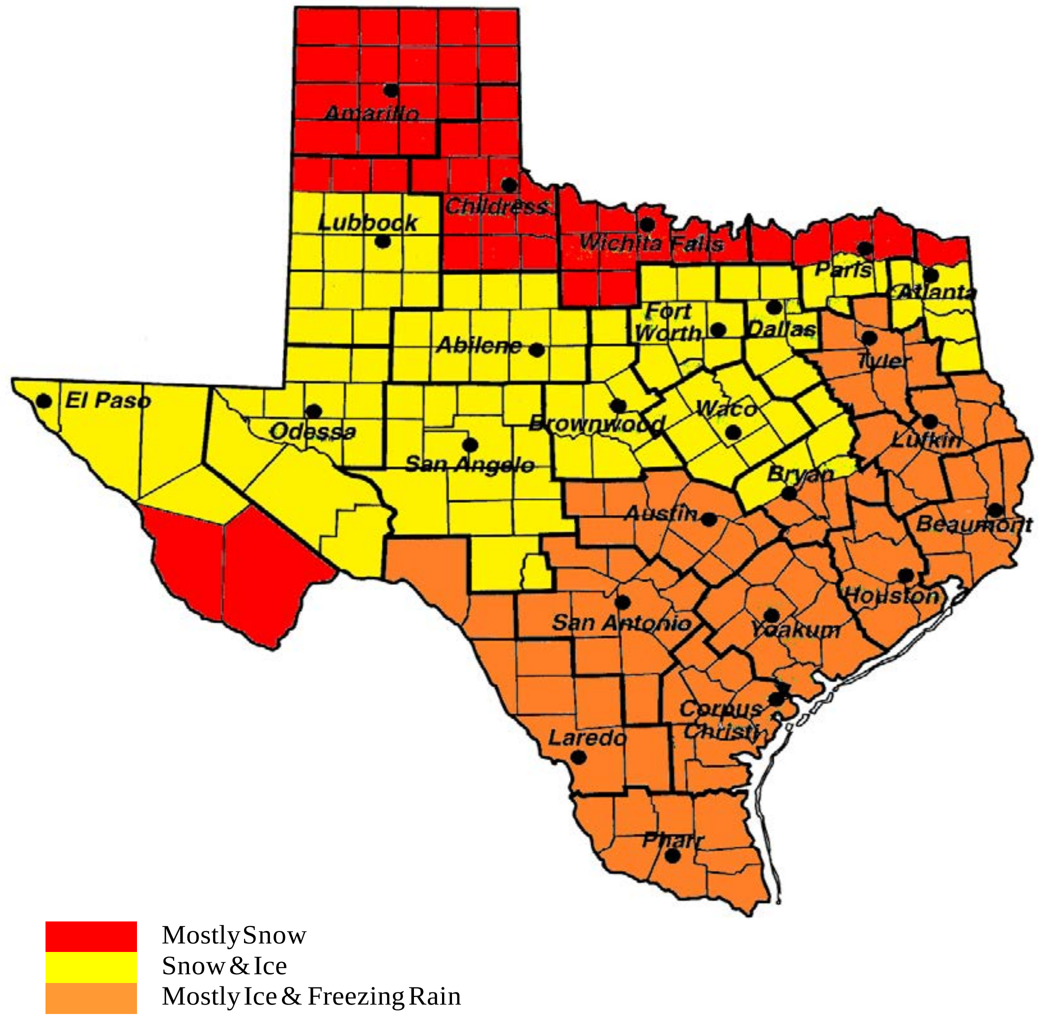


Figure 2.16. Winter Weather in Texas as Perceived by TxDOT Maintenance Personnel (*source*: Perkins, et al. 2012)

Collectively, the winter weather categories in Figure 2.16 serve to "ground-truth" the discussion in this report relative to the relationship between climate and winter weather roadway maintenance activities in Texas. In sum, winter weather roadway maintenance is driven by climate, the typical maintenance challenges vary across the state, and conditions can be associated with Texas geography.

2.6 A Suggested Winter Weather Maintenance Strategy for Texas

2.6.1 Overview

The effectiveness of TxDOT's maintenance response to winter weather storms will be a direct function of TxDOT having a clearly-articulated maintenance strategy for responding to winter weather. Based on information provided in this report, key aspects of a TxDOT winter weather maintenance strategy should address winter weather variability, level of service expectations, and winter maintenance materials, equipment and training. Relative to this present research study, it can be seen that the selection, application, and effectiveness of snow and ice control materials represent only one of many maintenance challenges associated with TxDOT achieving an effective response to winter storms. The following sections briefly outline a recommended winter weather maintenance strategy for Texas.

2.6.2 Texas Winter Weather Zones

It has been noted that winter weather varies across Texas, and because of this, TxDOT's maintenance strategy should not be "one size fits all." Figure 2.17 presents a map from the National Climatic Data Center showing the mean annual number of days below freezing in Texas, this based on 30 years of data (1961-1990). This map is overlaid with hypothetical "zones" that seem to capture the nature of winter weather across Texas, as follows:

- Zone 1. 23 or more freezing days, frequent snow and occasional ice
- Zone 2. 15 to 22 freezing days, occasional ice and rare snow
- Zone 3. 6 to 14 freezing days, rare ice and very rare snow
- Zone 4. 5 or fewer freezing days, very rare ice and snow

Zone 1 is the Panhandle region characterized by frequent snow events with occasional ice events. In Zone 2, winter storms result in rare snow and occasional ice. Zone 3 experiences very rare snow and rare ice. Zone 4, a region in which temperatures rarely drop below zero, experiences very rare snow and ice events.

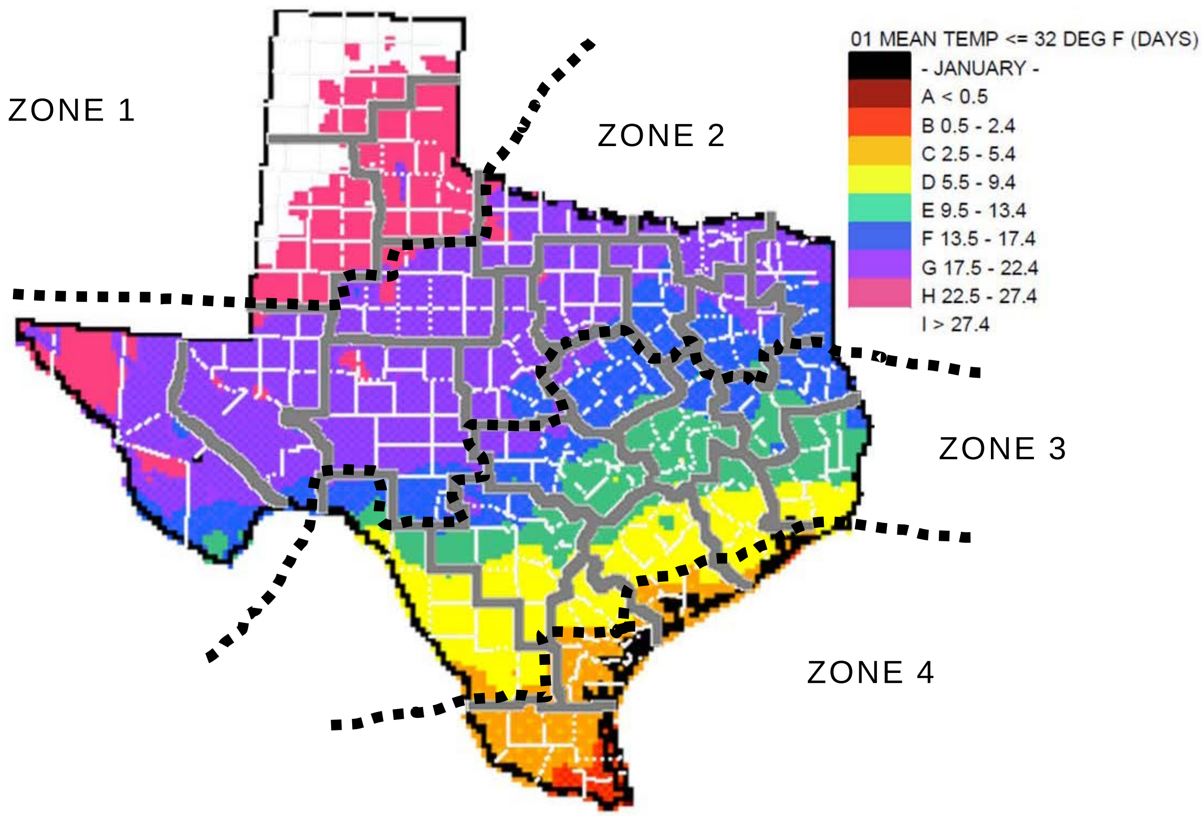


Figure 2.17 . Texas classification of winter storm events by zones

The zone boundaries could be drawn or described differently. The key reason for identifying these zones is that the geographic areas correspond to climatic conditions where different maintenance approaches make sense, in a manner relatively consistent with Figure 2.16. On this basis, TxDOT's winter weather strategy should recognize that the maintenance response in each Zone will be different.

2.6.3 Level of Service

2.6.3.1 Alternative Approaches to Winter Maintenance Level of Service NCHRP Report 526 defines Level of service (LOS) in the context of roadway snow and ice control operations as "…a set of operational guidelines and procedures that establish the timing, type, and frequency of treatments. The maintenance actions are directed toward achieving specific pavement condition goals for various highway sections" (Blackburn, et al. 2004).

Interviews with TxDOT maintenance personnel indicate that for the most part, TxDOT uses a combination of input LOS and output LOS approaches for winter maintenance. The input-type LOS approach focuses on providing resources for winter maintenance including personnel, equipment, and materials. The output-type LOS approach describes the methods for performing the work and addresses topics such as the sequence of calling out crews, the proper order of plowing the road, the speed at which plows should travel, the rate chemicals should be applied, the requirement that spreaders be calibrated, etc. The focus of these LOS approaches is on prioritizing resource allocation with the objective being to provide added confidence that a given output will be achieved (Bourdon 2001).

Alternatively, *outcome-based* LOS approaches exist which reflect winter roadway maintenance results *as perceived by the motorist*. Outcome-based approaches, also termed performance-based, include measures such as bareness of pavement, reaction time, friction improvement, reduction in accidents, duration and frequency of closures, advance warning time to customers, etc. (Bourdon 2001). *NCHRP Report 526* identifies performance-based LOS as the preferred LOS approach to winter maintenance, and this is viewed as a best practice. The discussions that follow presume a performance-based LOS approach for winter maintenance, consistent with *NCHRP Report 526*.

2.6.3.2 Performance-Based LOS Thresholds for TxDOT Winter Maintenance Because winter weather is intermittent in Texas, it makes sense to think in terms of two LOS thresholds: "typical" and "extreme." "Typical" winter weather would be defined by climate season normals in a particular zone or District. This should be the LOS threshold that maintenance forces typically prepare for and respond to each and every year. "Extreme" winter weather should also be defined for a particular zone or District, and it will vary. For example, in Zone 1 or Zone 2, "extreme" might refer to a 20-year event or greater. In Zone 3 and Zone 4, any ice or snow storm would probably be considered extreme.

Further, the level of service for each winter weather zone should be expressed for both the typical and the extreme events. As a benchmark, consider a typical Zone 2 winter ice storm, say, two days duration. Here, a performance-based LOS might be expressed something like "for priority routes, keep all intersections and at least two lanes passable with at least one bare wheel path, to be accomplished within 4 hours following the storm and maintained throughout." In contrast, consider an extreme event in Zone 2. Here, the LOS might be expressed something like "for priority routes, keep all intersections and one lane passable with at least one bare wheel path, to be accomplished within 8 hours following the storm and maintained throughout."

The goal in expressing the LOS in this manner is not to specifically define what the level of service ultimately ought to be for Zone 2, although that type of definition needs to be established. Rather, it is helpful to point out that a clearly-articulated performance-based level of service directly relates to safety and mobility outcomes that directly impact the traveling public. From these outcomes, a performance-based LOS provides an operationally-sound guide for allocation of resources necessary to respond to such a storm. That is, a maintenance section supervisor will either have the resources on hand to provide this level of service, or s/he will not. If the maintenance supervisor does not have the resources, sound maintenance strategy would be require that s/he have a contingency plan to obtain these resources. In this way, the level of preparedness needed for the benchmark storm becomes clear.

2.6.4 Weather Information, Materials, Equipment, and Training

With the winter weather zones identified and performance-based LOS outcomes for both typical and extreme weather events defined, it should be possible to describe and plan out the various factors necessary to achieve a satisfactory roadway maintenance response in each zone or District. Success factors include, among other things, the type of weather information needed for an effective response, the type of equipment that is or should be available, the materials used for treating roads, the level of training needed for supervisors and operators, and others. Maintenance strategies will vary by zone and by storm type, and it should be apparent that such a strategy will influence maintenance practices, procedures, equipment, materials, and other resources. Ultimately, these variables will establish the cost of the maintenance program and also provide a measure of its effectiveness.

2.6.5 Snow and Ice Control Materials by Zone

The winter weather maintenance strategy recommended herein recognizes the variability of Texas weather and therefore supports variability in the selection of snow and ice control materials for winter weather maintenance. Because most of Texas does not typically experience severe winter weather, the use of abrasives makes sense for Zone 2, Zone 3, and Zone 4. For Zone 4, abrasives will be the primary if not the only snow and ice control material used.

However, for Zone 1, Zone 2, and Zone 3, given the benefits of a chemical-based approach to winter weather roadway maintenance, using chemicals is both appropriate and is recommended. In Zone 1, chemicals would be the primary snow and ice control material. In Zone 2 and Zone 3, chemicals would be used to leverage maintenance efforts and improve the level of service that can be achieved for a given maintenance dollar. In answer to the question of which snow and ice control chemicals should be used, the previous discussions about cost, effectiveness, application, corrosion, environmental impacts, and related factors come into play. Some observations are:

- All snow and ice control chemicals currently used by TxDOT are effective for Texas climate conditions. Texas climate does not experience temperatures that drop below the effectiveness-limits of these chemicals.

- A national trend exists relative to moving from "traditional" strategies involving dry abrasives, dry salt, and abrasive/salt mixes to techniques that involve using various combinations of chemicals and application methods such as anti-icing and pre-wetting of salt and/or abrasives to address specific storm events (Levelton Consultants Ltd., 2006).

- The proactive approach of pre-treatment in advance of the storm (anti-icing), whenever possible, is the recommend strategy. This is consistent with the evolving strategies of other State DOTs. The pre-treatment approach requires the heavy use of specifically anti-icing chemicals, or brines.

- The low cost option of in-house brine manufacturing is recommended.

- Several potential vendors for natural brines are available in Texas. This is covered in the brine section of the report.

- Over half of the current chemical placed by TxDOT does not include any type of corrosion inhibitor, so in very low quantity applications it may be acceptable practice to use chemicals without corrosion inhibitor additives.

- It is an option to purchase and introduce corrosion inhibiting additives for natural brines and in-house manufactured brines. More information on additives can be obtained from Appendix A, the PNS Qualified Products List.

- Relative to granular road salt, the use of salt deposits within the borders of Texas is currently underutilized by TxDOT.

- TxDOT nomenclature in reference to snow and ice chemicals needs to be updated in order to accurately compare application and effectiveness of chemicals. For example, in the DHT descriptions of chemicals, chemicals should be described by the active chemical with the highest percentage by weight. In the case of mixed chemicals, the chemical description still must have the active chemical with the highest percentage by weight (i.e. instead of the description complex chlorides, use the description sodium chloride with other complex chlorides and corrosion inhibitor).

2.7 Summary

This chapter provides a literature review on the application and effectiveness of snow and ice control materials for winter roadway maintenance operations. Primary knowledge sources include the substantial body of published literature sponsored by and developed for northern states that experience frequent and heavy winter weather events, as well as interviews with subject matter both nationally and in Texas.

Snow and ice control materials in the United are generally categorized as chloride salts, organic products, nitrogen products, and abrasives, with chloride salts being the most commonly-used. Application strategies include (1) anti-icing where snow and ice control chemicals are placed onto the roadway surface *prior to* the storm event, (2) de-icing where snow and ice control chemicals are applied during or after the storm when ice and snow have bonded on the roadway surface, and (3) friction improvement where chemically-inert abrasives are used to increase the friction between vehicle tires and driving surface after ice and/or snow have already bonded to the roadway.

Snow and ice removal represents a considerable roadway maintenance cost in the United States with an average annual cost for snow and ice removal of $1.7 billion for the years 2007 through 2011. Average cost for snow and ice removal per state ranges from $0/year (Hawaii and Florida) to $253 million/year (Pennsylvania). Texas ranks 30th nationally with an average cost for snow and ice removal of $17.4 million/year. On a cost per lane mile basis, Texas ranks 42nd with an average annual cost for snow removal of $89/lane mile. In terms of the percentage of cost for snow and ice removal as a function of physical maintenance effort, Texas ranks 42nd in the U.S. with the average annual cost for snow and ice removal representing only one (1.0) percent of TxDOT's physical maintenance expenditures.

In Texas, sanding has long been TxDOT's winter weather roadway maintenance strategy of choice, both because of Texas' generally mild winters and because sanding is a very visible low-cost approach to managing pavement friction. In the past 5 to 10 years however, snow and ice control *chemicals* – mostly chloride salts – have gained more widespread usage throughout the state, especially in Texas' heavy snow areas –Amarillo, Childress, and north part of the Lubbock districts. Granular chemicals used for winter roadway maintenance include MeltDown 20® and road salt. Liquid chemicals include MeltDown Apex™ and more recently, an interest in both manufactured salt brine and natural brine.

Weather directly influences winter roadway maintenance strategy as well as operational issues including the type, quantity and effectiveness of snow and ice materials. Key metrics for winter roadway maintenance include the length of the winter season, temperature, and winter precipitation in the form of snow, ice and freezing rain. In Texas, climate varies significantly across the state and can be associated with Texas geography. For this reason, TxDOT's maintenance strategy should not be "one size fits all" but should be zoned to capture the type, frequency and intensity of Texas' winter weather.

The effectiveness of TxDOT's maintenance response to winter weather will be a direct function of TxDOT having a clearly-articulated strategy for responding to winter weather, both for typical climate and extreme winter storm events. In addition to weather variability, TxDOT's winter weather maintenance strategy should address level of service expectations, winter maintenance materials, equipment and training. The selection, application, and effectiveness of snow and ice control chemicals represents one of many operational issues associated with TxDOT achieving an effective response to winter storms.

CHAPTER 3
AVAILABILITY AND WATER QUALITY OF BRINES ACROSS TEXAS

3.0 Introduction

This chapter addresses Task 2 of the research study, namely, to "determine the availability, storage requirements, and transport issues related to natural brines." The objective has been to characterize natural brines as a potential snow and ice control chemical for Texas roads including the availability and water quality of the brines. Further, we considered transport issues including mode of transport, time of transport, and cost. Durability concerns associated with corrosion are discussed in Chapter 4, and environmental concerns and regulatory issues of the use of brines are addressed in Chapter 5.

3.1 Availability and Water Quality of Texas Brines

3.1.1 Overview

Brine is defined as any snow and ice control chemical mixed with water to form a liquid solution. This solution is then sprayed onto the roadway. Brines can be made from several snow and ice control chemicals, and can be further classified as to the major chemical in the brine, such as a sodium chloride brine, magnesium chloride brine, etc. Natural brines and manufactured brines can possibly have a combination of chlorides.

Three types of "geologic" brines exist for consideration in snow and ice control, so-called because they source to underground geologic salt formations. The first type is natural brine that naturally exists either as surface water or in water-bearing formations unrelated to oil or gas plays. The second type is brine manufactured by circulating fresher water in naturally occurring below-ground NaCl deposits. The third type is produced water related to oilfield operations for oil and gas production.

These geologic brines are in addition to TxDOT's pre-approved, vendor-supplied, pre-blended brine products such as Meltdown Apex™ or FreezGard®, or other products identified on the Pacific Northwest Snowfighters (PNS) qualified product list (Appendix A). Similarly, the three geologic brine types do not include homemade brine such as brine manufactured at the Memphis Maintenance Section (Childress District). The raw materials for homemade brine are water and brining-quality road salt blended in a salt brine manufacturing system with a dedicated mixing tank. Because the parent chemical – in this case, brining salt – is an approved product, the brine resulting from this salt is also approved by TxDOT.

3.1.2 Natural Brine (Kent County, Texas)

Brine is simply salt dissolved in water. Natural brine can be found in surface water (e.g., Dead Sea or the Great Salt Lake) or groundwater (e.g., Kent County Brine). The use of natural brines is a relatively unexplored option for snow and ice control in Texas. Of the State DOTs contacted as part of this study, none of these DOTs directly use natural brines. In fact, only one type of natural brine, Kent County brine, has been identified as a potential candidate for snow and ice control in Texas.

Table 3.1 shows the relationship between the pounds of salt per gallon, concentrations of sodium and chloride, and total percent NaCl. The nominal brine product is a "10-lb brine" with the weight corresponding to the percentage of dissolved solids. A 23 percent salt level – which is the ideal concentration of solids for salt brines – corresponds to 10.25-lb brine. The Kent County brine is approximately an 11-lb brine, as a 31.7 percent solution, so that water could be diluted to reach the 23 percent level. A complete water quality description for the brine from the Kent County site as shown in Table 3.2.

Table 3.1. Man-made Brine Quality Descriptions Assuming NaCl as Only Solute

Brine (lb/gal)	Sodium (mg/L)	Chloride (mg/L)	Total (mg/L)	% NaCl
10.00	78,700	121,500	200,200	20.0
10.25	90,400	140,000	230,400	23.0
10.50	102,000	158,000	260,000	26.0
10.75	114,000	176,000	290,000	29.0
11.00	126,000	194,000	320,000	32.0

Table 3.2. Kent County Natural Brine Quality (*source*: Ana-Lab Report)

Analyte	Value	Units	Reporting Limit
Calcium	659	mg/L	12.5
Magnesium	1140	mg/L	12.5
Potassium	1180	mg/L	12.5
Sodium	104000	mg/L	500
Bromide	<1000	mg/L	1000
Chloride	212000	mg/L	3000
Fluoride	<1000	mg/L	1000
Nitrate	<1000	mg/L	1000
Ortho-phosphate as P	<300	mg/L	300
Sulfate	7200	mg/L	3000

Table 3.2. Kent County Natural Brine Quality (*source*: Ana-Lab Report), continued

Analyte	Value	Units	Reporting Limit
Iodide	<300	mg/L	300
Alkalinity as $CaCO_3$	38.3	mg/L	1
Boron	<100	mg/L	100
Phosphorus	<200	mg/L	200
Aluminum	0.198	mg/L	0.1
Barium	<0.010	mg/L	0.01
Copper	0.91	mg/L	0.01
Total Iron	<0.209	mg/L	0.209
Strontium	23.4	mg/L	20
Zinc	<0.050	mg/L	0.05
Total Dissolved Solids	316000	mg/L	1000
Laboratory pH	6.8	s.u.	2
Specific Gravity	1.207		

3.1.3 Manufactured Brines

Manufactured brines are made by mixing fresher water with deep salt formations to obtain a mixture that is free from hydrocarbon contamination and useful for multiple applications. Inquiry with the Texas Railroad Commission (RRC) office in Austin obtained available data listed in their database system concerning brine pit operators and brine pit locations in Texas that are permitted to sell their brines.

For the entire state, 190 pits were listed, and 34 are located in convenient areas in northern Texas. The RRC database includes addresses and phone numbers for the permit holders, some of which are out of the state, but did not provide physical addresses or latitude/longitude coordinates of the brine sources, only general area information such as distance from the nearest town. Many of the company names, contact personnel, and phone numbers were incorrect as companies and assets have been bought and sold over the years.

Based on phone contacts, pit operators with produced water from oil and gas wells will not sell their brine for TxDOT's intended use, but rather use their produced water for secondary recovery or eventual disposal in deep wells. The only brines available for sale to TxDOT for snow and ice control purposes are *non-produced* waters. These are 10-lb brines that are made by mixing fresher water with deep salt formations to obtain a mixture that weighs 10 lb per gal and that is free from hydrocarbon contamination and useful for multiple applications.

A total of 20 manmade brine sites were identified from the Texas Railroad Commission permit list (2011). The locations of these 20 manufactured brine sources plus the Kent County source are mapped in Figure 3.1. The sites are located in the Permian Basin or Southern High Plains of West Texas. Table 3.3 provides owner information about each site as well as their estimated unit cost per barrel (bbl or 42 gal) of brine. It should be noted that other similar brine sources may exist beyond this list, as based on experience the brine vendors do not typically advertise their products through normal business media such as telephone listings or internet websites.

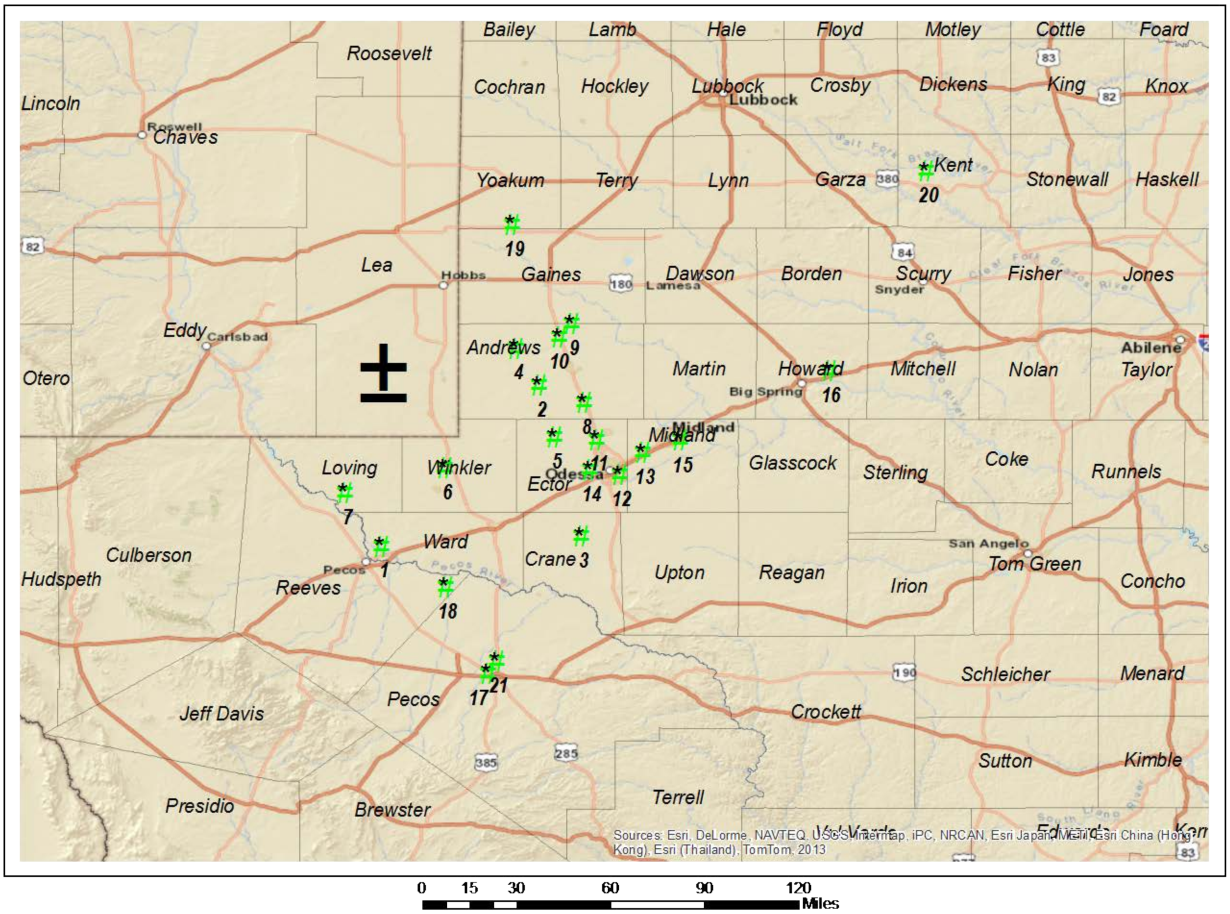


Figure 3.1. Selected Locations of Available Manufactured Brines in West Texas

The nominal product from the manufactured brine sources is 10-lb brine, with the dissolved solids made up primarily of sodium and chloride from the targeted salt beds. The vendors can also make denser brines up to 14-lb if requested by the customer. None of the brine vendors would provide tabulated laboratory water quality analyses.

Table 3.3 Identification and Locations for Manufactured Brine Sources in West Texas

No.	Owner	County	Latitude	Longitude	Contact	Price ($/bbl)
1	Basic Energy Services	Reeves	31.480209	-103.408728	Barry Byrd	1.35
2	Basic Energy Services	Andrews	32.221942	-102.678469	Barry Byrd	1.35
3	Basic Energy Services	Crane	31.525979	-102.485082	Barry Byrd	1.35
4	Basic Energy Services	Andrews	32.393769	-102.784277	Barry Byrd	1.35
5	Basic Energy Services	Ector	31.982053	-102.610009	Barry Byrd	1.35
6	Basic Energy Services	Winkler	31.840287	-103.112848	Barry Byrd	1.35
7	Basic Energy Services	Loving	31.726853	-103.577321	Barry Byrd	1.35
8	Basic Energy Services	Andrews	32.141701	-102.469009	Barry Byrd	1.35
9	Basic Energy Services	Andrews	32.505455	-102.526731	Barry Byrd	1.35
10	Basic Energy Services	Andrews	32.443663	-102.587274	Barry Byrd	1.35
11	Basic Energy Services	Ector	31.972269	-102.413682	Barry Byrd	1.35
12	Basic Energy Services	Ector	31.808656	-102.306983	Barry Byrd	1.35
13	Basic Energy Services	Midland	31.912445	-102.197936	Barry Byrd	1.35
14	Basin Brine Sales	Ector	31.831250	-102.443804	Jason Hickerson	1.00-1.50
15	Chaparral Water Systems	Midland	31.967961	-102.024919	Darrel Franklin	1.10
16	Newpark Environmental Services	Howard	32.287024	-101.338792	Phillip Meyer	1.00
17	Newpark Environmental Services	Pecos	30.894289	-102.915341	Phillip Meyer	1.00
18	Enstor Waha Storage & Transport	Reeves	31.293007	-103.110195	Peter Sterzing	1.25
19	Salty Brine 1 LTD	Yoakum	32.964405	-102.802033	Josh Parker	1.10
20	Salt Fork Water Quality District	Kent	33.209608	-100.888428	Judge Jim White	0.50
21	Wilson Systems, Inc.	Pecos	30.948258	-102.876617	Sylvia Delgado	1.00

3.1.4 Oilfield Brines

Oilfield brines are a type of produced water related to oilfield operations for oil and gas production. The only readily available database for oilfield produced brines identified for this study was published by the USGS (U.S. Geological Survey 2002) and discussed by Welch and Rychel (Welch, R. and Rychel, D., 2004). Figure 3.2 shows the distribution of produced oilfield brine qualities across the State using that database. The produced water total dissolved solids (TDS) concentrations ranged from a few thousand to almost 400,000 mg/L, with many samples reported from the northern half of the State.

Per the Texas Railroad Commission (RRC), oilfield brines can only be purchased from brine pit owners that hold specific permits from the RRC that allow them to sell the brine, whether the brine was produced from an oil or gas well or manufactured by mixing fresher water with a subsurface salt formation. Historically, the pit operators with actual produced water from oil and gas wells will not sell their brine for TxDOT's intended use, but rather use their produced water for secondary recovery or eventual disposal in deep wells.

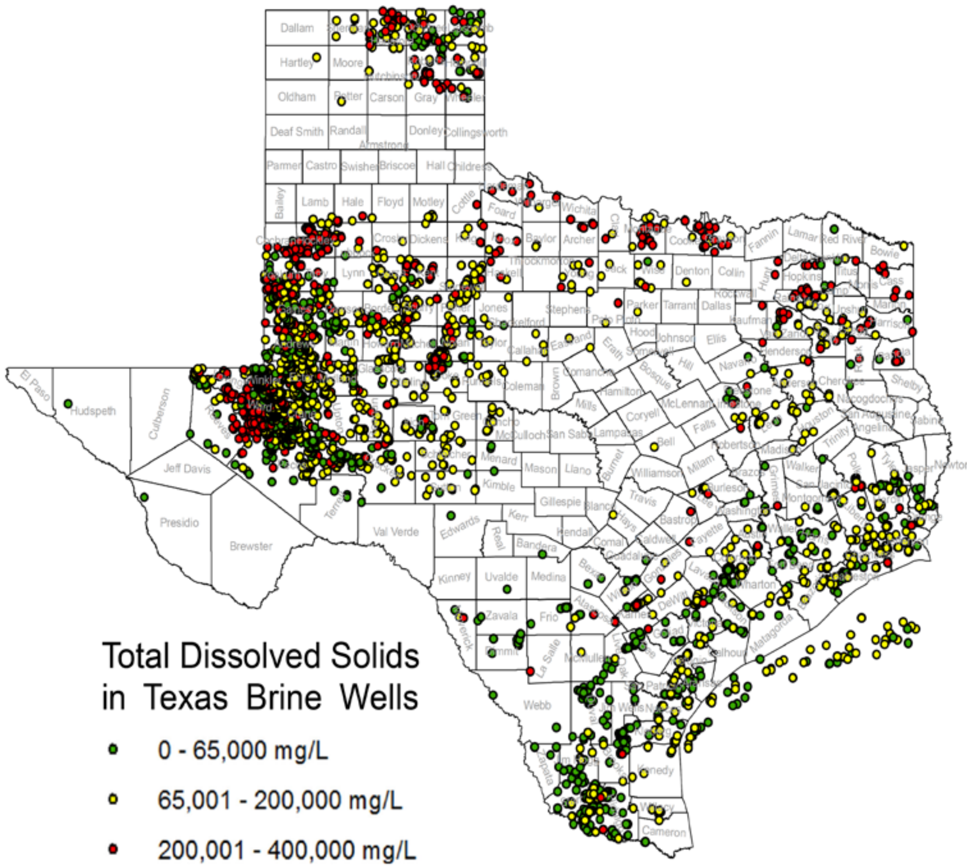


Figure 3.2 Distribution of total dissolved solids concentrations in Texas oilfield brine samples included in the USGS (2002) database

Notwithstanding the fact that oilfield brines are normally not permitted for sale for non-oilfield applications, in 2014, the RRC voiced a more open perspective about TxDOT's desired usage of oilfield brine for snow and ice control. The RRC's willingness to consider oilfield brine came during a period of statewide drought exacerbated by a shortage of salt supply – conditions that were not considered "normal" at the time. The RRC's consideration of oilfield brine included requirements for analytical chemical testing for multiple parameters intended to "characterize the produced water so that TxDOT's risks would be known and minimized as the water is applied to the pavement." The discussion also recognized that produced water should not be required to meet drinking water standards.

The Pacific Northwest Snowfighters (PNS) group has established detailed procedures for testing de-icing and anti-icing chemicals and maintains specifications that these products must meet to be considered for widespread use. The PNS "Snow and Ice Control Chemicals Products Specifications and Test Protocols" document (Appendix H) provides guidance on preparing and submitting products for the testing and evaluation process required to be placed on the Qualified Products List. Table 3.4 summarizes the PNS required tests and methods.

Table 3.4. Test Methods for PNS Snow and Ice Chemical Product Evaluation (revised 12/2010)

No.	Test Description	Test Method (abridged)
1	Percent Concentration of Active Ingredient In The Liquid	Atomic Absorption or Inductively Coupled Plasma Spectrophotometry as described in "Standard Methods for the Examination of Water and Waste Water", APHA-AWWA-WPCF
2	Weight Per Gallon	Specific Gravity by ASTM D 1429 Test Method A
3	Corrosion Control Inhibitor Presence and Concentration	Test procedures provided by the manufacturer
4	pH	ASTM D 1293 as modified by PNS
5	Corrosion Rate	NACE Standard TM0169-95 (1995 Revision) as modified by PNS
6	Percent Total Settleable Solids and Percent Solids Passing a 10 Sieve	Test Method "C" in Appendix A of PNS Specifications
7	Total Phosphorus	Standard Methods for the examination of Water and Waste Water, APHA-AWWA-WPCF
8	Total Cyanide	Standard Methods for the examination of Water and Waste Water, APHA-AWWA-WPCF
9	Total Arsenic, Barium, Cadmium, Chromium, Copper, Lead, Selenium and Zinc	Atomic Absorption Spectrophotometry or Plasma Emission Spectroscopy as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
10	Total Mercury	Cold Vapor Atomic Absorption Spectrophotometry as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
11	Milliequivalents	Milligrams of acetic acid to neutralize 1 gram of unreacted base
12	Moisture Content Of Solid Chemical Products	ASTM E 534
13	Gradation	ASTM D 632
14	Visual Inspection and Field Observations	As specified
15	Toxicity Test	"Short-Term Methods for Estimating the Chronic Toxicity of Effluent and Receiving Waters to Freshwater Organisms", Third Edition, EPA-600/4-91/002
16	Ammonia - Nitrogen	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
17	Total Kjeldalh Nitrogen	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
18	Nitrate and Nitrite as Nitrogen	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
19	Biological Oxygen Demand	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
20	Chemical Oxygen Demand	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF
21	Frictional Analysis	As specified
22	Insoluble Material	ASTM E534 "Standard Test Methods for Chemical Analysis of Sodium Chloride"
23	Chloride	"Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF

3.2 Analyses of Trace Elements of Concern in Natural and Homemade Brines

3.2.1 Analytical Approach

The research team employed several procedures to analyze the concentrations of trace metals in Kent County brine and Memphis brine. The list of trace metals analyzed is tabulated in Table 3.5. A prior lab analysis performed by Ana-Lab in July 2011 on Kent County brine measured approximately 104,000 mg/L of sodium and 212,000 mg/L of chloride (Table 3.2). Due to a high salt content in the brine, there are concerns about significant matrix interference and potential damage to the detection instruments. Methods to selectively extract the trace elements from the salt matrix are needed to achieve detection limits below the regulatory limits.

Table 3.5. Regulatory Standards and Extraction and Analytical Methods Used in this Study

Trace element	Extraction/ preconcentration method	Detection method	MCL/MCLG^ (µg/L)
Copper (Cu)	Solid-phase extraction	ICP-MS	1300
Zinc (Zn)	Solid-phase extraction	ICP-MS	5000*
Cadmium (Cd)	Solid-phase extraction	ICP-MS	5
Lead (Pb)	Solid-phase extraction	ICP-MS	15
Uranium (U)	Solid-phase extraction	ICP-MS	30
Arsenic (As)	APDC solvent extraction	GFAA	10
Chromium (Cr)	ASTM D6800-12	ICP-MS	100

^ EPA National primary drinking water Regulations (U.S. Environmental Protection Agency, 2009)

* EPA National Secondary drinking water regulations (U.S. Environmental Protection Agency, 2009)

Based on literature survey the team shortlisted a list of extraction techniques that have been previously used for brine or seawater analysis. We then conducted preliminary analysis using the brines and synthetic samples to determine the extraction efficiency of each elements of concern. Three extraction methods were selected (Table 3.5). Inductively-coupled-plasma-mass spectrometry (ICP-MS) was used to detect all elements except for arsenic. Arsenic was analyzed by graphite-furnace atomic absorption (GFAA) due to the presence of organic solvent in the extraction solutions.

3.2.2 Analysis of Copper, Zinc, Cadmium, Lead and Uranium

A commercial solid-phase extraction reagent SPR-IDA was purchased from CETAC Technologies (CETAC Technologies, 2012). The reagent is made of polystyrene resin cast into spherical beads of approximately 10 µm in diameter. The surface of the beads was derivatized with iminodiacetate (IDA). The imine and carboxylic groups in the IDA moiety is known to form stable chelates with many transition metals. The manufacturer recommends the use of SPR-IDA for the following metal elements: Mn, Co, Ni, Cu, Zn, Cd, Pb, U (CETAC Technologies, 2012). Each brine was treated with 600 µL of 10% SPR-IDA suspension which was added to 15 mL of a pre-acidified brine solution. pH of the solution was then adjusted with ammonium hydroxide (NH_4OH, 29%) to around 8. The suspension was briefly mixed and allowed to settle. The resin beads were collected, rinsed with DI water, and re-suspended in 18 mL of a dilute nitric acid solution (1.1% v/v). The supernatant was collected and analyzed by ICP-MS.

All samples were spiked with rhodium (Rh) and bismuth (Bi) as internal standards. Sample quantitation was performed using an addition calibration method as recommended by CETAC (CETAC Technologies). In brief terms, each sample was spiked with calibration standards of known concentrations. Analysis was performed on an ICP-MS system (Perkin Elmer ELAN DRC-e) following EPA Method 200.8 (U.S. Environmental Protection Agency, 1994). Three readings were measured for each sample and the average value was used. The results (*i.e.*, intensity of each analyte) were plotted against the concentrations of standards spiked into the sample. The slopes and intercepts of the calibration lines were used to back calculate the sample concentrations.

3.2.3 Analysis of Chromium

The ASTM D6800-12 method (ASTM International, 2013) was adapted for preconcentrating chromium from the bine matrix. It is essentially a reductive precipitation method for preconcentrating metals in brine water or seawater. It uses ammonium 1-pyrrolidinedithiocarbamate (APDC) as a complexing agent for selective extraction of metal species from the background matrix. The metals bound with APDC were reduced by sodium borohydride solutions and precipitate out as solids. The solids were harvested and digested in dilute nitric acid in the presence of hydrogen peroxide. The final solution was analyzed with ICP-MS. All reagents were of ACS reagent grade. They were used as purchased without further purification. Table 3.6 lists the key chemicals and their manufacturers.

Table 3.6. List of Key Chemicals Used in Trace Element Analysis

Chemicals	Manufacturer	CAS #
SPR-IDA, 10% w/v suspension	CETAC Technologies	
Ammonium hydroxide (NH_4OH, 29%)	Fisher	1336-21-6
Nitric acid (HNO_3, 70%)	Fisher	7697-37-2
Ammonium pyrrolidinedithiocarbamate (APDC)	Sigma-Aldrich	5108-96-3
Sodium borohydride ($NaBH_4$)	Fisher	16940-66-2
Methyl isobutyl ketone (MIBK)	Fisher	108-10-1
Ethylenediaminetetraacetate disodium salt (EDTA)	Sigma-Aldrich	6381-92-6
Potassium iodide (KI)	Fisher	7681-11-0
Sodium thiosulfate ($Na_2S_2O_3$)	Fisher	10102-17-7
Hydrochloric acid (HCl, 37.2%)	Fisher	7647-01-0
Sodium acetate ($NaCH_3COO$)	Fisher	127-09-3
Acetic acid (CH_3COOH)	Fisher	64-19-7

Pre-acidified brine sample (16 mL) was diluted to 100 mL with a dilute nitric acid solution. 1 mL of Fe and Pd chloride solution (at 500 μg/L for each metal) was spiked into the sample. The pH of the solution was adjusted with ammonium hydroxide (NH_4OH, 29%) to around 8.5. We then added 1 mL of 5% sodium borohydride ($NaBH_4$) solution and mixed for several minutes. Following that, 0.25 mL of 2% APDC solution was added and allowed to mix for a few minutes. The solution was set aside for 1 hr. Solids precipitated out during this time period. We filtered the samples using a vacuum filter and 47 mm polycarbonate filter paper (pore size 0.2 μm). The filter paper, together with metal precipitates on it, was folded into a compact packet. It was placed into a centrifugal tube. Concentrated nitric acid (0.25 mL) was added and the mixture was heated to 70^{o}C for 30 to 60 min, followed by an addition of 0.5 mL of 30% hydrogen peroxide (H_2O_2) and heating for another 30 to 60 min. The digestion liquid was diluted to 10 ml, spiked with internal Bi and Rh standards and analyzed by ICP-MS immediately. The same procedures were applied to calibration standards. Analysis was performed on an ICP-MS system (Perkin Elmer ELAN ERC-e) following EPA method 200.8 (U.S. Environmental Protection Agency, 1994). Quantitation was done using 4-point calibration. Three readings were measured for each sample and the average value was used. The regression coefficient (R^2) for Cr calibration was > 0.999. In addition, we verified the method by spiking the blank and brine samples with 50 μg/L of Cr. The measured value agreed with the expected value within 6% accuracy.

3.2.4 Analysis of Arsenic

We analyzed arsenic (As) by selective extraction of As(III) with APDC into an organic solvent (methyl isobutyl ketone, MIBK) followed by GFAA analysis (Kamada, T., 2976, Brooks,1976). Detection of total arsenic involves an additional pre-reduction step using potassium iodide (KI) and sodium thiosulfate ($Na_2S_2O_3$) to convert As(V) to As(III). pH was controlled by an acetate buffer. Ethylenediaminetetraacetate (EDTA) was added during extraction to suppress interference caused by other metal species. All reagents were of ACS reagent grade. They were used as purchased without further purification.

Extraction of As(III) was carried out by adding 10 mL of a brine sample into a separatory funnel. The sample was amended with 5 mL of 1 M acetate buffer, 5 mL of 5% EDTA solution and 2 mL of 1% APDC solutions, respectively. The volume was brought up to 25 mL with DDI water. After gentle mixing, 10 mL of pure MIBK was added and the funnel was swirled for 5 min. After a standing period of 30 min, the aqueous phase was discarded. The solvent was sent for GFAA analysis immediately. To measure total arsenic, we performed a pre-treatment step prior to the solvent extraction procedure. Briefly, HCl solution was added to a 10 mL sample to bring the acidity to 0.5 N. 2 mL of 20% KI solution, and 1 mL of 1% $Na_2S_2O_3$ were introduced. The solution was then neutralized with NH_4OH. The sample was then subject to the extraction procedure described above. All extractions were done in duplicate for each sample.

The presence of organic solvent precluded analysis using the more sensitive ICP-MS method. The analysis was performed instead on a GFAA system (Perkin Elmer Analyte 800) following EPA Method 200.9 (U.S. Environmental Protection Agency, 1994). Quantitation was done using 4-point calibration. One reading was measured for each sample and measurement repeatability was check periodically using QC standards. The recovery of total arsenic spiked into brine was 90%. It was found that the arsenic measurement was moderately sensitive to the background salt concentration.

3.2.5 Analytical Results

The analytical results are shown in Table 3.7. Detection limits were estimated based on the instrument detection limits (IDLs), dilution factor introduced during extraction, and analyte recovery efficiency.

Table 3.7. Concentrations of Trace Elements in Kent County and Memphis Brines

Element	Detection Limit (μg/L)	Kent County (μg/L)	Memphis (μg/L)
Copper	0.04	146.6	4.0
Zinc	0.4	13.2	49.4
Cadmium	0.06	1.6	1.0
Lead	0.1	49.9	21.9
Uranium	0.02	0.34	0.84
Arsenic	10	BDL*	Not measured ^
Chromium	0.16	12.2	6.3

* Below detection limit
^ Brine unavailable

The analytical results suggest that concentrations of trace metals could be highly variable among different brine sources. Total trace metal concentration measured in Kent County brine was 224 μg/L, which was about three times that in Memphis brine. Much higher levels of copper (Cu) and lead (Pb) were also identified in the Kent County brine. Since only one sampling event was performed at each brine source, we were unable to determine whether the high variability was due to well location or other factors. Analyses of a more statistically-significant number of samples from different sources are recommended if large-scale application of brine is pursued by the TxDOT in the future. It should also be noted that when the brines are applied to the actual pavement surfaces for anti-icing purposes, the trace elements and all other solutes in the brines would be subject to subsequent dilution by the melting ice and snow, which could typically reduce the concentrations of all solutes by 500-fold within a short distance of the roadway (U.S. Geological Survey, 2002) and thus limiting eventual environmental impacts.

Another comment it that it is necessary to perform method validation and optimization using actual brine samples to ensure quality of analysis. Although the ASTM D6800-12 method is considered to be applicable to a host of metals such as copper, cadmium, and lead, our data indicated poor recovery for these elements. The measurement procedures for arsenic are amenable to further improvement to enhance the detection limit.

3.3 Required Processing, Storage, and Transport Requirements of Brines for Use as Anti-icing or De-icing Chemicals

Review of the literature pertinent to application of chemicals for anti-icing and de-icing purposes provided no direct detailed reports on the applications of natural or oilfield brines for these purposes. Levelton Consultants Limited (2007) mentioned concerns about naturally-occurring radioactive materials in natural brines, but provided no information about actual applications in NCHRP Report 577. Guerra et al. (Guerra, K., Dahm, K, and Dundorf, S., 2011) provided a significant summary of beneficial uses of produced waters in the western United States, but did not include any discussion of applications for transportation safety. We have heard of anecdotal mentions of oilfield brine on icy roads in northern Texas, but as yet we have not found any documentation.

The locations of the manmade and natural brine vendors and their pricing details are shown in Figure 3.1 and Table 3.3, respectively. If the manmade brines are purchased from the vendors at the target 23 percent or 10.25-lb concentration, those brines would need no further processing prior to storage and roadway application. The Kent County brine would require some dilution to lower its 32 percent or 11-lb concentration to the target concentration, and the amount of dilution water would depend on the total dissolved solids content of the fresher water.

Transportation costs are based on hourly rates for tanker trucks with nominal capacities of 60, 80, 100, and 120 bbl. Typical hourly rates, contact information, and locations served are shown for two regional water trucking companies in Table 3.8. Both example haulers mentioned the possibility for negotiation of the hourly rates. For example, the total cost of a 100-bbl tanker truck delivery of $1.00/bbl brine with a 4-hr travel time at $90/hr would be $460. The combination of brine purchase and delivery would yield a total unit cost of $0.11/gal.

Table 3.8. Examples of Brine Hauling Companies

Company	Phone	Location	Contact	Cost ($/hr)	Locations Served
Globe Energy Services	(432) 263- 2801	312 N. Hwy 87 Big Spring	Gary Torres	90	Andrews, Big Spring, Hobbs, Midland, Monahans, Odessa, Perryton, San Angelo, Snyder, Westbrook
Nabors Completion & Production Service	(432) 683- 5000	5000 N. FM 1053 Fort Stockton	Eddie Gonzalez	85	Crane, Fort Stockton, Iraan, Midland, Monahans, Odessa, Pecos, San Angelo, Sheffield, and further east

The equipment available at the TxDOT maintenance sites, including storage tanks and tank trucks to handle the brine, would have to be evaluated to determine whether transportation and storage needs can be met with existing equipment or if new facilities would be required. The amount of brine storage for each site would be related to the number of lane miles in the priority categories that require anti-icing treatments under appropriate weather conditions and the target application rate in gal/lane mile. Delivery of the brines should be planned during warm weather and clear road conditions, as the hauling companies will not send their trucks out in bad weather. It should also be noted that natural brines do not have any corrosion inhibitors such as those included in other commercial products. Addition of such chemicals would add to the unit costs of this approach.

3.4 Summary

Brine is defined as any snow and ice control chemical mixed with water to form a liquid solution. This chapter characterizes natural brines as a potential snow and ice control chemical for Texas roads including the availability, water quality, storage requirements, and transport issues related to natural brines.

Three types of geologic brines exist for consideration in snow and ice control. The first type is natural brine that naturally exists either as surface water or in water-bearing formations unrelated to oil or gas plays. The second type is brine manufactured by circulating fresher water in naturally occurring below-ground NaCl deposits. The third type is produced water related to oilfield operations for oil and gas production. These three are in addition to pre-approved brines such as homemade salt brine manufactured at the Memphis Maintenance Section (Childress District) or vendor-supplied, pre-blended brine products such as Meltdown Apex™ which are not considered in this chapter.

The use of natural brines for snow and ice control is rare. Only one type of natural brine, Kent County brine, has been identified as a potential candidate for snow and ice control in Texas.

A total of 20 manufactured brine sites were identified from the Texas Railroad Commission permit list. These are 10-lb brines that are made by mixing fresher water with deep salt formations to obtain a mixture that weighs 10 lb per gal and that is free from hydrocarbon contamination and useful for multiple applications. These sites are located in the Permian Basin or Southern High Plains of West Texas.

Oilfield brines are a type of produced water related to oilfield operations for oil and gas production. Per the Texas Railroad Commission (RRC), oilfield brines can only be purchased from brine pit owners that hold specific permits from the RRC that allow them to sell the brine. Historically, the pit operators with produced water from oil and gas wells will not sell their brine for TxDOT's intended use, but rather use their produced water for secondary recovery or eventual disposal in deep wells.

The research employed several procedures to analyze the concentrations of trace metals in Kent County (natural) brine and Memphis (homemade) brine. The analytical results suggest that concentrations of trace metals could be highly variable among different brine sources. For this reason any geologic brine – natural, manufactured, or oilfield – should be tested and approved prior to widespread use. The PNS product specification and test protocols identified herein are appropriate for such evaluation.

It should be noted that when brines are applied to actual pavement surfaces for anti-icing purposes, the trace elements and all other solutes in the brines are subject to subsequent dilution by the melting ice and snow, which could typically reduce the concentrations of all solutes by 500-fold within a short distance of the roadway.

Transportation costs are based on hourly rates for tanker trucks, and the combination of brine purchase plus delivery would yield a total (nominal) unit cost of $0.11/gal. Storage tanks, tank trucks and other equipment to handle the brine will be subject to district transportation and storage needs.

CHAPTER 4
IMPACT OF SNOW AND ICE CONTROL CHEMICALS ON INFRASTRUCTURE DURABILITY

4.1 The Research Problem

This chapter addresses Task 3 of TxDOT research project 0-6793, which is to summarize technical literature about infrastructure durability impacts directly related to snow and ice control chemicals used on Texas roads under Texas winter weather conditions. This includes snow and ice control chemicals which are currently used by TxDOT as well as locally available brines. Durability concerns apply to the corrosion of steel reinforcement and scaling of surfaces of concrete structures, and also to corrosion of other structures, e.g., steel bridge girders, steel equipment, etc.

4.2 Method

4.2.1 Literature Review

The research team accomplished Task 3 through literature review and project-specific testing. Available literature was collected and synthesized regarding corrosion due to snow and ice chemicals. With this, gaps in literature were addressed.

4.2.2 Laboratory Evaluation

Testing was completed to evaluate the unknown corrosion rates of local brines, using a local representative sample. Test methods were identified and the Tex-624-J Atmospheric Corrosion Test and the AASHTO T 259-02 Resistance of Concrete Chloride Ion Penetration Test were chosen for laboratory evaluation of snow and ice control materials.

Laboratory evaluation was completed to compare the effectiveness of corrosion-inhibited chemicals to that of non-inhibited chemicals and to assess the impacts on infrastructure facilities. The laboratory evaluation originally planned for two widely used concrete mixes along with the chemicals sodium chloride and magnesium chloride. After discussion with the TxDOT Bridge Division and local Lubbock District personnel, it was determined that one concrete mix design, representative of the "worst case scenario", that is, a concrete mix design least resistant to snow and ice chemicals, was to be used. A test matrix including benchmark chemicals, chemicals currently used by TxDOT, and one representative natural brine, was developed and approved by the Project Monitoring Committee.

4.3 Corrosion

4.3.1 Overview of Corrosion

Corrosion is a significant durability issue relative to the application and use of snow and ice control chemicals. Corrosion is inevitable regardless of the snow and ice control chemical used. Corrosion is a complex process that includes many factors making it site specific and hard to predict in the field environment. Studies that have tried to compare specific snow and ice control chemicals show a wide range of conclusions, and sometimes contradict one another (Levelton Consultants Limited, 2006). Corrosion due to snow and ice materials varies between concentration of chemical, metal type, and metal alloy. Overall, chloride-based snow and ice control materials are the most corrosive. Studies attempting to rank the corrosiveness of chloride salts have not come up with definitive conclusions. The hygroscopic magnesium and calcium chlorides are generally considered the most aggressive due to the longer time of wetness, but for practical purposes all chloride salts can be considered *highly corrosive* (Levelton Consultants Limited, 2006). The main corrosion concern to infrastructure is the corrosion of ferrous metals, specifically iron (Fe) in wrought carbon steels.

4.3.2 Background on Redox Reaction

Corrosion is a natural redox process that oxidizes metals. Corrosion of iron (Fe) occurs due to the presence of water and oxygen. Iron does not rust in dry air because moisture must be present, nor does iron rust in oxygen-free water because oxygen must be present. A winter storm event, regardless of whether snow and ice chemicals are used, satisfies the criteria for both water and oxygen, and therefore, corrosion will occur. Snow and ice chemicals are electrolytic, so the rate at which corrosion occurs is increased. The corrosion process may be modeled as an electrolytic cell. There is an anode, a cathode, an electrical connection between the two, and an electrolyte in contact with both the anode and cathode. The anode is the area where metal is oxidized causing material loss. This corrosion usually occurs at surface irregularities (Silberberg, 2006). The half-reaction is:

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^{-} \text{ [anodic region, oxidation]}$$

The free electrons move through the electrical connection, which is the metal itself, to the cathode. The cathodic process is almost exclusively the reduction of oxygen. Therefore, the cathode is a region of relatively high O_2 concentrations, such as the surface of a surrounding water droplet. The rate of corrosion is controlled by the rate of the cathodic process (Kotz, 2009).

$$O_2(g) + 2H_2O(l) + 4e^{-} \rightarrow 4OH^{-}(aq) \text{[cathodic region, reduction]}$$

$$2Fe^{2+}(aq) + 4OH^{-}(aq) \rightarrow 2Fe(OH)_2(s) \text{ [precipitation]}$$

Water is the electrolyte in contact with both anode and the cathode, ferrying ions back and forth. In a completely dry atmosphere, corrosion would be negligible. However, metal does not need to be saturated; only a thin film of water will cause corrosion. The process is complete without rust (iron(III) oxide) forming.

Rust is a secondary redox reaction in which iron(II) hydroxide ($Fe(OH)_2$) reacts with oxygen (O_2) forming a red-brown iron(III) oxide. The rust deposits occur at a different place than the anodic region, or region of iron loss (Silberberg, 2006). The formation of iron (III) oxide is:

$$4Fe(OH)_2(s) + O_2(g) \rightarrow 2Fe_2O_3 \cdot H_2O(s) + 2H_2O(l)$$

The volume of the resultant iron(III) oxide is greater than the volume of metal from which the iron(III) oxide forms. This can allow the iron(III) oxide to form a protective barrier to oxygen diffusion. The effectiveness of the barrier depends on several things: thickness of the oxide film, whether there are cracks or pores (reducing protection), whether it was formed in tension (favoring fracture and reducing protection) or compression, etc. (Revie, 2008).

Depending on the acidity and amount of oxygen present, slightly different cathodic reactions and oxidation of the iron (II) hydroxide can occur. Snow and ice chloride salts (sodium chloride, magnesium chloride, calcium chloride) form an ionic solution and improve the electric conductivity of the solution near the anodic and cathodic regions, accelerating corrosion. Corrosion is also accelerated at low pH (high $[H^+]$).

4.3.3 Corrosion of Infrastructure Due to Snow and Ice Chemicals

When snow and ice control chemicals, which are soluble ionic compounds, are added to water, the water separates the ions and replaces the attraction with one between the water molecule and ion. The substance then forms an electrolyte, which conducts current. It is the ability of these aqueous solutions to conduct current which accelerates the rate of corrosion (Silberberg, 2006). Conductivity also has a secondary corrosion effect by disturbing the formation of passive rust. For example, in a sodium chloride solution, conductivity is greater which allows additional anodes and cathodes to operate much farther from one another. At these cathodes, sodium hydroxide (NaOH) does not react immediately with iron(II) chloride ($FeCl_2$) formed at anodes. Instead, these substances diffuse into the solution and react to form iron (II) hydroxide ($Fe(OH)_2$) away from the metal surface. The iron (II) hydroxide formed in this way does not provide as adequate of a protective barrier on the metal surface. Hence, iron corrodes more rapidly in dilute sodium chloride solution because more dissolved oxygen can reach cathodic areas (Revie, 2008).

Chloride anions specifically, in chloride salts, have additional negative effects. Chlorides break down the protective layer formed on steel in the atmospheric environment and the passive layer on steel rebar formed due to the high alkaline environment of concrete. Also, chlorides are oxidizers which are good depolarizers (oxidizing salts can either be depolarizers, more corrosion, or passivators, corrosion inhibitor). The chloride ions (Cl^-) are attracted to the anode where chloride forms ferrous chloride complexes. The soluble ferrous chloride complexes are oxidized to ferric hydroxide on contact with air. The chloride ions are released which then supply the anode front again (Revie, 2008).

The table below shows the percent chloride in each of the three main salts used for snow and ice operations (Levelton Consultants Limited, 2006).

Table 4.1. Molecular weight calculations of chloride based materials (*source: NCHRP 577)*

Cation	Atomic Weight	Compound	Molecular Weight	% Chloride	% Cation
Sodium	22.98977	Road Salt (NaCl)	58.442	60.66%	39.34% (Na)
Magnesium	24.3050	Magnesium Chloride ($MgCl_2$)	95.210	74.47%	25.53% (Mg)
Calcium	40.078	Calcium Chloride ($CaCl_2$)	110.983	63.89%	36.11% (Ca)

4.3.3.1 Atmospheric Corrosion Atmospheric corrosion includes the corrosion of vehicles, roadside infrastructure, and steel bridges. Types of atmospheric corrosion include uniform (or general) corrosion, crevice, poultice, pitting, and galvanic corrosion, and filiform corrosion of aluminum and magnesium alloys (Levelton Consultants Limited, 2006). Alloying, coating such as hot-dip galvanized or aluminum-zinc painting, and sacrificial anodes are methods used to prevent or control atmospheric corrosion.

4.3.3.2 Corrosion of Concrete Reinforcing Steel and Deterioration of Concrete Good quality concrete has high alkalinity, with a pH in the range of 12 to 13. This environment produces a thin passive oxide film which protects steel rebar from corrosion. The passive layer can deteriorate by neutralization of the alkalinity of the concrete or by chloride ions. The chloride ions diffuse through the concrete cover to the depth of the rebar and destroy the passive oxide layer (American Society for Metals, 2005).

Chloride ions breakdown the passive layer locally, so consequently, large cathodic areas of passive metal surround small anodes. If sufficient water and oxygen are available, corrosion will occur. When the steel corrodes the rust occupies a greater volume, creating expansion. The expansion causes tensile stresses in the concrete which lead to cracking, delamination, and spalling. This, in turn, allows more moisture to infiltrate and corrode the steel.

A typical threshold value for chloride in concrete to initiate corrosion is 0.4 percent by weight of cement, but values as low as 0.15 percent may be considered dangerous (Levelton Consultants Limited, 2006).

Sulfates are a concern for the deterioration of concrete. Sulfates can be introduced in snow and ice operations when natural brines are used. The sulfates react with hydrated compounds in the hardened cement. This results in pressure that disrupts the cement paste, causing a loss of cohesion and strength (American Society for Metals, 2005). Resistance to sulfates can be achieved by using low water-to-cement ratio and cement with a small amount of tricalcium aluminates. Some pozzolans, such as fly ash meeting the requirements of ASTM C 618 Class F, can increase the resistance to sulfates while other pozzolans, such as ASTM C 618 Class C fly ash can decrease sulfate resistance (American Society for Metals, 2005). Acids also cause deterioration of concrete.

Concrete scaling, flaking, peeling, or pitting of the concrete surface has been caused by snow and ice control chemicals in concrete lacking sufficient strength or air entrainment. However, scaling has not been an issue on roads built and maintained by State DOTs where strict standards for design and construction are followed. This is also true for roads maintained by DOTs in northern states, even though the amount of snow and ice control chemical on their roads is greater than that placed on Texas roads (Concrete Scaling Committee, 2002). The full memorandum from the concrete scaling committee can be seen in Appendix I. For comparison on the quantity of snow and ice control material placed by TxDOT and other states, refer to Chapter 2.

4.3.4 Corrosion Inhibitors

Multiple strategies exist to mitigate corrosion. Measures can be introduced directly to the infrastructure to protect against corrosion. Alternatively, corrosion inhibitors can be added to the snow and ice chemicals themselves. These different methods vary in effectiveness and depend on several factors. Of particular interest are corrosion inhibitors added to snow and ice chemicals.

Corrosion inhibitors are added to many of the manufactured and blended snow and ice products. These corrosion inhibitors are almost always proprietary, so little is known about the chemical makeup. In the past, agricultural by-products have been popular additives. Though the corrosion inhibitors could have some corrosion-inhibiting effect on vehicles, these agricultural products biodegrade and are thought to offer little long-term effect for inhibiting corrosion for infrastructure. There are three basic types of corrosion inhibitors: anodic inhibitors, cathodic inhibitors and mixed inhibitors (Levelton Consultants Limited, 2006).

4.3.4.1 Anodic Inhibitors Anodic corrosion inhibitors work by forming a passivizing film that inhibits the anodic reaction, which is the dissolution of metal. The passive oxide film is cathodic to steel. In theory, this is the best type of inhibitor as it can completely prevent corrosion. However, if the concentration of anodic inhibitor is lower than optimal, it can accelerate corrosion. If the passive layer is penetrated, the exposed metal becomes a small anodic area surrounded by a large cathodic (corrosion inhibitor) passivating film. Anodic snow and ice control corrosion inhibitors can show very low corrosion results in the laboratory environment, but in the field environment, when the chemical becomes diluted, corrosion results can be much different. Forms of anodic inhibators include chromates, nitrites, molybdates, phosphates, carbonates, and silicates. In snow and ice control practice, only phosphates, carbonates, and silicates tend to be suitable to prevent corrosion of iron-based alloys (Levelton Consultants Limited, 2006).

4.3.4.2 Cathodic Inhibitors Cathodic inhibitors work by preventing the reduction of oxygen at the cathode. These are precipitating corrosion inhibitors which form an insoluble film on the cathode under localized conditions of high pH. Cathodic inhibitors are generally considered less effective than anodic corrosion inhibitors but are considered good, *i.e*. safe, corrosion inhibitors for snow and ice applications due to the variability of dilution rates. Cathodic inhibitors decrease general corrosion without stimulating pitting corrosion. Forms of cathodic inhibitors include calcium bicarbonate, zinc ions, polyphosphates, and phosphonates (Levelton Consultants Limited, 2006).

4.3.4.3 Mixed Inhibitors Mixed inhibitors are all other inhibitors that are not exclusively considered anodic or cathodic inhibitors. Mixed inhibitors work by physical absorption, chemisorptions, or film formation. Agricultural by-products fall into this category. These organic products come with a wide range of compounds including amines, phosphates, hetrocyclic nitrogen compounds, sulfur compounds and numerous natural compounds such as proteins, plant extracts, phytic acid (inositol hexaphosphoric acid), rice bran, soybean cake, beet juice, and grape seed oil (Levelton Consultants Limited, 2006).

4.4 Atmospheric Corrosion Testing

4.4.1 Overview

This study included a limited program of laboratory testing to evaluate the atmospheric corrosion impacts of selected snow and ice chemicals. The goal of these tests was to compare the durability impacts between chemicals, not to predict the longevity of infrastructure in the field. The atmospheric corrosion test was completed using TxDOT’s Tex-624-J test procedure. The Tex-624-J procedure is based on the Pacific Northwest Snowfighter’s (PNS) Test Method B (Pacific Northwest Snowfighters, 2010). Appendix J provides the method along with notes of extra criteria and procedural annotations used in tests, in an effort to increase repeatability of the test.

4.4.2 Test Procedure and Test Matrix

Three batches of tests were performed using the Tex-624-J method. The test matrix evaluated eight different chemicals including control chemicals, two stock chemicals, and five snow and ice chemicals as per Table 4.2. Details about the sources of these chemicals can be found in Appendix J as well as information for additional materials needed for the test.

Table 4.2 Tex-624-J Test Matrix

Control/Stock Chemicals	Snow and Ice Chemicals
Distilled Water Control	Road Salt
Sodium Chloride Stock	MeltDown 20®
Magnesium Chloride Stock	MeltDown Apex™
	Memphis Brine
	Natural Brine

4.4.3 Test Results

Appendix K presents the raw data from the Tex-624-J atmospheric corrosion tests. Table 4.3 shows the corrosion rate (mils/yr) for each chemical with the corrosion due to the distilled water subtracted from each test. This allows the difference in corrosion rate between the chemicals to be compared without the effect of the corrosion rate due to the distilled water. Subtracting the corrosion due to the distilled water is consistent with the Tex-624-J procedure.

Table 4.3 Tex-624-J Test Results

Chemical	Tex-624-J Test Number	Corrosion (mils/yr)	Mean	Standard Deviation	Coefficient of Variance (%)	*p*-value	Null Hypothesis
Sodium Chloride Control	1	26.392	23.59	2.52	10.7	---	---
	2	22.894					
	3	21.489					
MD 20	1	10.958	8.59	3.92	45.6	0.00254	Reject
	2	10.739					
	3	4.064					
	4	9.408					
MD Apex	1	14.616	13.03	1.67	12.8	0.00189	Reject
	2	13.190					
	3	11.288					
Road Salt	1	27.433	23.45	3.47	14.8	0.47823	Accept
	2	21.141					
	3	21.769					

Table 4.3 Tex-624-J Test Results, continued

Chemical	Tex-624-J Test Number	Corrosion (mils/yr)	Mean	Standard Deviation	Coefficient of Variance (%)	*p*-value	Null Hypothesis
Magnesium Chloride Control	1	32.037	31.50	0.64	2.03	0.00314	Reject
	2	31.658					
	3	30.791					
Memphis Brine	1	24.863	23.71	1.00	4.20	0.47095	Accept
	2	23.146					
	3	23.130					
Natural Brine	1	23.956	23.42	0.489	2.09	0.45693	Accept
	2	23.305					
	3	23.000					

A *p*-value was determined in order to distinguish any differences between corrosion rates of the chemicals. For the *p*-value, a Student's T-test, one-sided tail and equal variance, and a null hypothesis of equal mean with an alpha value of 0.05 were used. The null hypothesis is rejected for Meltdown 20®, Meltdown Apex™, and Magnesium Chloride. Table 4.4 shows a three-test average of the percent corrosion of the chemical as compared to the sodium chloride control.

Table 4.4 Chemical corrosion percent compared to that of the sodium chloride control.

Chemical	Percent Corrosion as compared to the Sodium Chloride Control
MeltDown 20®	37.51
MeltDown Apex™	55.18
Magnesium Chloride Control	134.3

4.4.4 Analysis of Tex-624-J Atmospheric Corrosion Test

The magnesium chloride control shows the highest corrosion rate with a rate 134 percent of the sodium chloride control. Meltdown 20® had a corrosion rate 38 percent of the sodium chloride control, and Meltdown Apex™ had a corrosion rate 55 percent of the sodium chloride control. The road salt (granular sodium chloride), Memphis brine (sodium chloride brine) and the natural brine (sodium chloride brine) showed no difference in corrosion compared to the sodium chloride control.

As noted previously, the Tex-624-J method is not intended to model the corrosion rate (mils/yr) for chemicals applied in a field environment but should be used as a guide to compare the corrosivity between chemicals. Laboratory corrosion rates do not follow those of the field environment, and Test Method Tex-624-J does not try to replicate field conditions. Actual corrosion rates are affected by many factors which are different between the Tex-624-J test and field conditions, most notably: temperature, humidity, and time of wetness.

Test Method Tex-624-J is currently used by TxDOT to evaluate chemicals with proprietary material (corrosion inhibitor) to verify their compliance with Departmental Materials Specification 6400 (DMS-6400). DMS-6400 states that corrosion-inhibited chemicals shall have a corrosion rate less than or equal to 30% of the sodium chloride control. The test results reported in Table 4.3 show that Meltdown 20® and Meltdown Apex™ did not meet this requirement. However, the test program for this study adapted Test Method Tex-624-J with the *sole objective* of comparing chemicals (both generic and proprietary) for corrosion, not to test for compliance.

4.4.5 Conclusions and Observations

Atmospheric corrosion testing per Test Method Tex-624-J indicates that magnesium chloride control has a higher corrosion rate than the sodium chloride control. The road salt (granular sodium chloride), Memphis brine (sodium chloride brine) and the natural brine (sodium chloride brine) all have the same corrosion rate as the sodium chloride control. Both the Meltdown 20® (granular sodium chloride) and Meltdown Apex™ (magnesium chloride brine) have a lower corrosion rate than the sodium chloride control. These are expected results based on review of the literature. The coefficient of variance for the Tex-624-J tests is low enough for this test to be an acceptable test for comparing the corrosion rate between chemicals.

The corrosion percent can vary significantly between chemical samples. Recommendations for future testing would be to test different chemical samples – especially the Meltdown 20® product and natural brines which have the highest variability – to determine a confidence interval for the PNS corrosion percent.

It is recommended that the Tex-624-J procedure be revised to identify an acceptable range of atmospheric temperature during the test. Temperature affects the corrosion rate, and variances in temperature between labs will lead to different corrosion values. The Pacific Northwest Snowfighter's Test Method B sets a temperature range 69.8°F to 73.4°F (Pacific Northwest Snowfighters, 2010).

4.5 Chloride Diffusion Through Concrete

4.5.1 Overview

Chloride diffusion through concrete destroys the steel rebar's passive layer and initiates corrosion of the steel rebar. Testing was done to evaluate the concentration of diffused chlorides of various snow and ice chemicals. The chloride diffusion test was completed using AASHTO T-259-02 Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration (AASHTO, 2002).

4.5.2 Test Procedure and Test Matrix

The concrete mix design was Class S concrete, specifically, a Highland Concrete mix (Appendix L). The materials for the mix including the 1-inch Crockett intermediate aggregate, sand, cement, fly ash (Class C), air entrainment (BASF MBAE-90), and water reducer (BASF Polyhead 1720). All material was donated to the project courtesy of Highland Concrete in Lubbock, Texas. Fiber reinforcement was not included.

Test specimens were cast in 12 in × 12 in × 4 in thick blocks. In accordance with Item 420 Concrete Structures, 420.4 J Curing Concrete, an evaporation retardant and curing compound was applied after the water sheen had disappeared. Test specimens were wet mat cured using cotton batting for 10 days. After the curing time, the test specimens were removed from the forms and were stored on spacers to allow the top, bottom, and sides of the slabs to air dry. The specimens were cured for 28 days, and cylinder specimens were tested to confirm the concrete exceeded the minimum 28-day design strength.

On the 29th day, the slab surfaces of the specimens were sandblasted using 20-30 grit walnut shell media. Acrylic dams were placed one inch inside the top edge of all the specimens. Slabs were then returned to air dry for 13 days.

Samples were then subjected to continuous ponding with three percent by weight of chemical. Eight different chemicals were evaluated for chloride diffusion, the same chemicals as those identified in Table 4.2 for atmospheric corrosion testing. Details about the source of these chemicals can be found in Appendix J.

Acrylic plates were placed over the ponded chemical solutions in such a way that the surface of the slab was sealed from the surrounding atmosphere in order to retard evaporation. Distilled water was added as needed to maintain constant solution depth. Samples were ponded for 180 days.

For sample extraction, the Gilson Model HM-343 Sample Drilling Assembly was used. A pilot hole was drilled using a ⅝ inch bit. The pilot hole was drilled to a depth of 2¼ inches. A 2-inch core bit was used for sample extraction with a vacuum tube assembly collecting the powder from the companion hole. The HM-343 Drilling Assembly had guide stops at a depth of ¼ inch and ½ inch increments thereafter. Concrete samples were taken at four different depths: Level 0 from 0 to ¼ inches, Level 1 from ¼ to ¾ inches, Level 2 from ¾ to 1¼ inches, and Level 3 from 1¼ to 1¾ inches. Only one replicate concrete sample was tested for each specimen at

Level 0 and these data were not included in the analysis due to possible high variability at the surface of the concrete sample. Samples from Level 1, Level 2 and Level 3 were tested with three replicates per concrete specimen at each depth (*i.e.*, 3 cores per specimen). A separate shop vacuum and compressed air system was used to clean the core hole, bit, and sample vacuum assembly between each sample extraction to prevent contamination between samples at different depths.

4.5.3 Corrosion Diffusion Test Results

Table 4.5 shows the results of chloride concentration for concrete samples cored at Levels 1, 2 and 3 in each specimen. Each depth included three replicates (one from each core hole). The chloride concentrations are expressed in mg of chloride per 1 kg of concrete.

Table 4.5. Chloride Concentration at Different Depths from AASHTO T259 Ponding Test

Product Name	Core Number	Depth of Concrete Sample		
		1/4"-3/4" (mg/kg)	3/4"-1 1/4" (mg/kg)	1 1/4"-1 3/4" (mg/kg)
Sodium Chloride	1	146.28	66.79	774.82
	2	214.22	68.67	42.49
	3	548.58	53.98	53.54
	Avg	303.03	63.15	290.28
Distilled Water	1	47.48	55.16	50.48
	2	76.33	34.45	40.94
	3	42.50	33.19	41.52
	Avg	55.44	40.94	44.31
MeltDown 20®	1	98.97	93.00	524.65
	2	32.98	38.15	366.55
	3	47.32	29.74	325.80
	Avg	59.76	53.63	405.67
MeltDown Apex™	1	558.65	143.24	85.39
	2	703.40	164.06	64.47
	3	706.09	107.09	92.23
	Avg	656.05	138.16	80.70
Road Salt	1	1022.65	74.97	3.63
	2	513.41	97.20	61.20
	3	319.71	71.57	63.28
	Avg	618.59	81.25	42.71
Magnesium Chloride	1	691.40	123.61	56.46
	2	1305.20	100.49	94.18
	3	938.05	288.68	73.15
	Avg	978.22	170.93	74.60

Table 4.5. Chloride Concentration at Different Depths from AASHTO T259 Ponding Test, cont.

Product Name	Core Number	Depth of Concrete Sample		
		1/4"-3/4" (mg/kg)	3/4"-1 1/4" (mg/kg)	1 1/4"-1 3/4" (mg/kg)
Memphis Brine	1	183.78	48.31	51.45
	2	283.91	46.45	39.10
	3	366.60	46.40	47.00
	Avg	278.10	47.19	45.85
Natural Brine 1	1	119.27	51.46	45.19
	2	87.44	39.15	25.13
	3	216.47	33.13	28.55
	Avg	141.06	41.25	32.96

4.5.4 Discussion of Chloride Diffusion Results

Figure 4.1 shows chloride concentration values in the form of percent chloride by weight of concrete for each of the chemicals and the control solution (distilled water). The magnesium chloride solution resulted in the highest chloride concentration values at different depths. Previously-published research (West and Hime 1985) identifies threshold chloride concentrations that can damage the protective layer formed around concrete reinforcement to be between 0.031% and 0.039% chloride by weight of concrete.

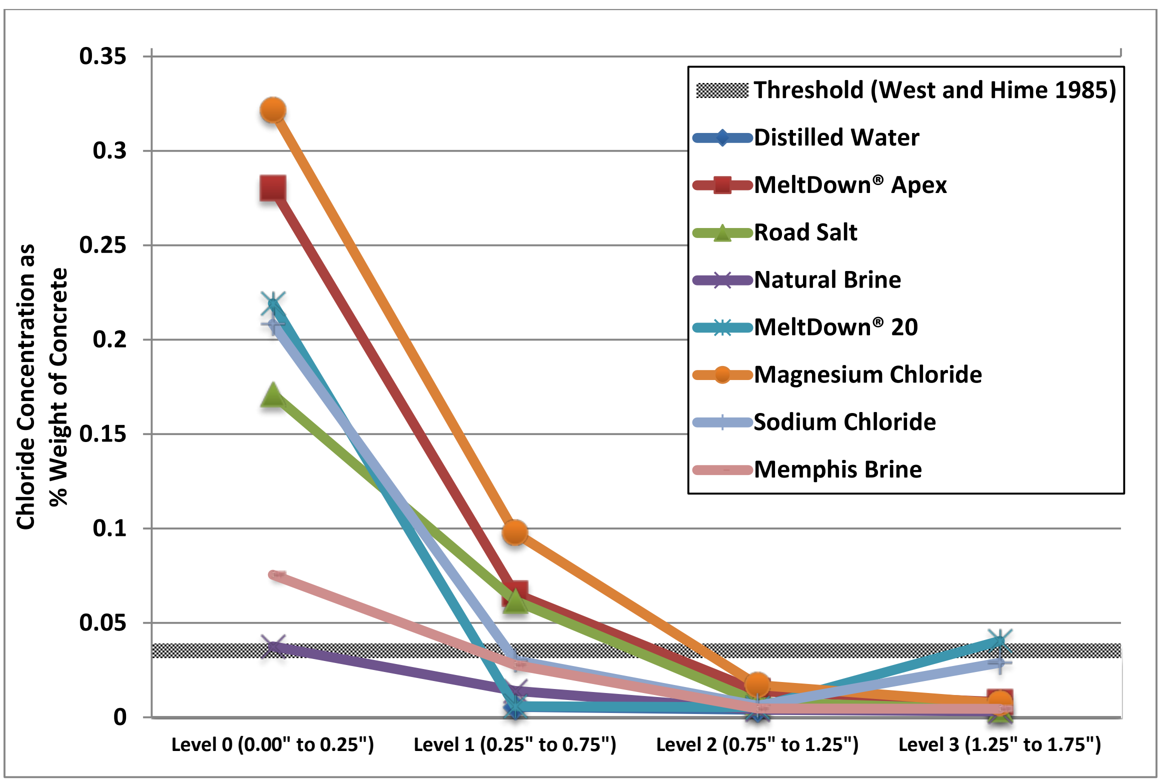


Figure 4.1 Chloride Penetration of Snow and Ice Control Chemicals, AASHTO T259 Ponding Test.

All snow and ice control chemicals tested – except for natural brine which at all depths had values at or below the threshold – were above the threshold range at Level 0. At Level 1, magnesium chloride, road salt, and Meltdown Apex™ were still above the threshold region. Sodium chloride, Memphis brine, natural brine, and Meltdown 20® were below the threshold region. For Level 2 and Level 3, the chloride concentrations were well below the threshold region. There were discrepancies in the Level 3 results for the Meltdown 20® and sodium chloride which are believed to be caused by the non-uniformity of the salt particles sampled from the stockpile. Fabrication variance in the concrete specimens, particularly non-uniformity of concrete compaction, may have also contributed towards this discrepancy. Meltdown 20® showed scatter in the data from the corrosion test. Sodium chloride was still below the threshold region and the Meltdown 20® was just above the threshold region. Overall, the natural brine had the least penetration into the concrete specimen.

Based on these results, it is reasonable to conclude that at a depth of 2 inches, which is typically the shallowest depth where steel reinforcement bars are located in bridge decks, the chloride concentrations were below the threshold levels reported by West and Hime (1985). Sound quality control measures adopted for bridge deck concrete can provide safeguards against high chloride concentrations. However, it is important to verify results in the field environment.

4.5.5 Product-Specific Chloride Diffusion Results

Figures 4.2 through 4.8 show the chloride penetration test results from Table 4.5 for each concrete specimen ponded with one snow and ice control chemical. These charts show the high, low and average chloride concentrations for three replicate concrete samples obtained from each specimen ponded by one chemical, obtained from the AASHTO T259 Ponding Test. Figure 4.9 contains the chloride concentration for distilled water, which was used as the control, and as expected, those results showed very low chloride concentrations.

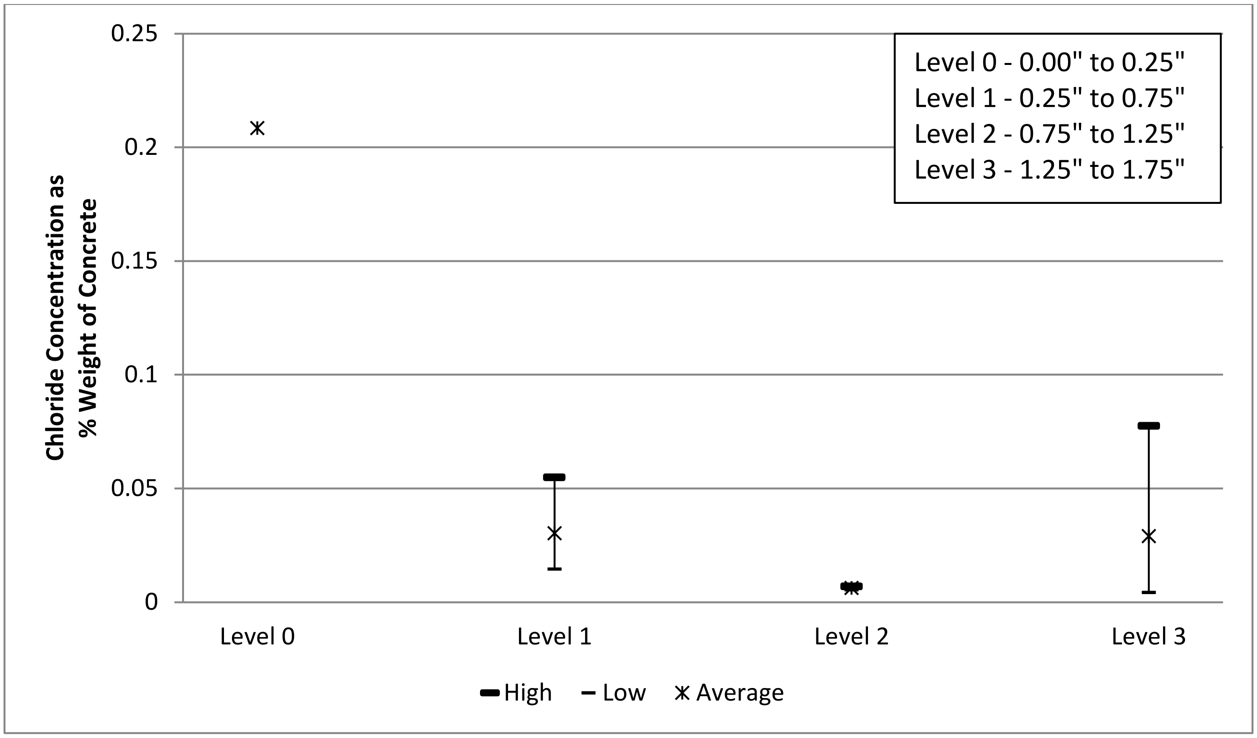


Figure 4.2: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Sodium Chloride.

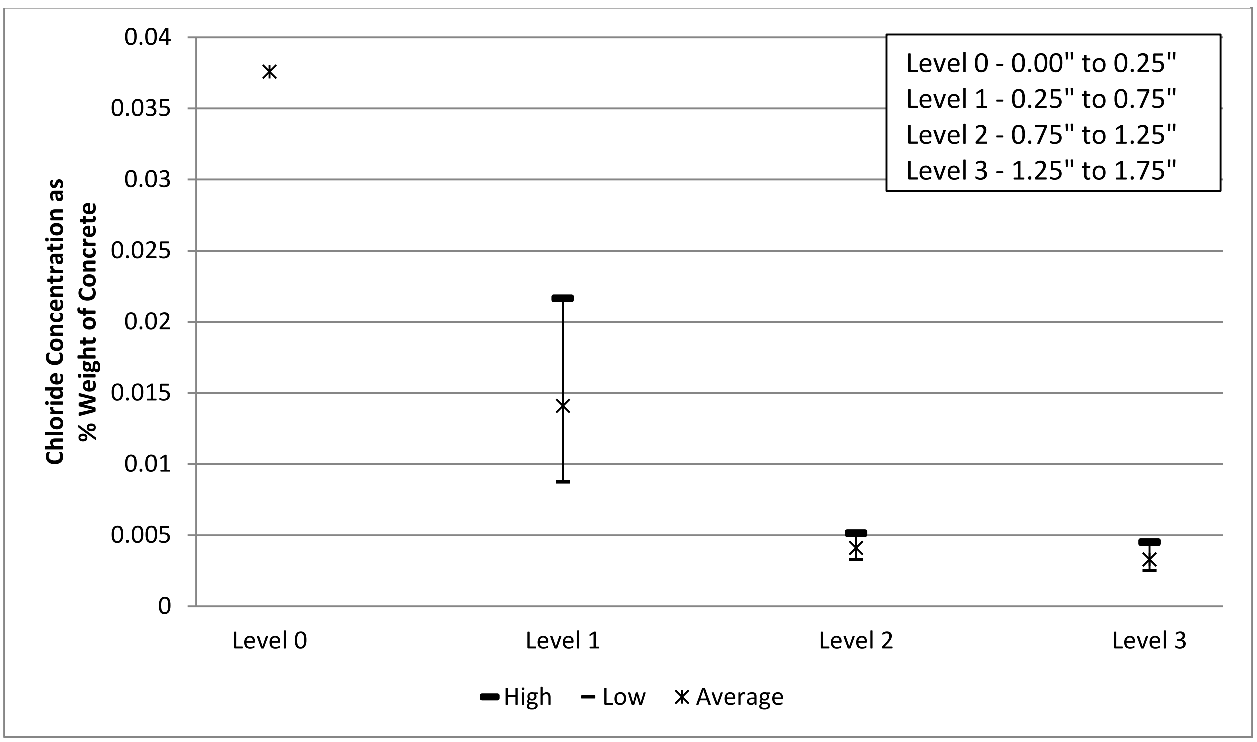


Figure 4.3: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Memphis Brine.

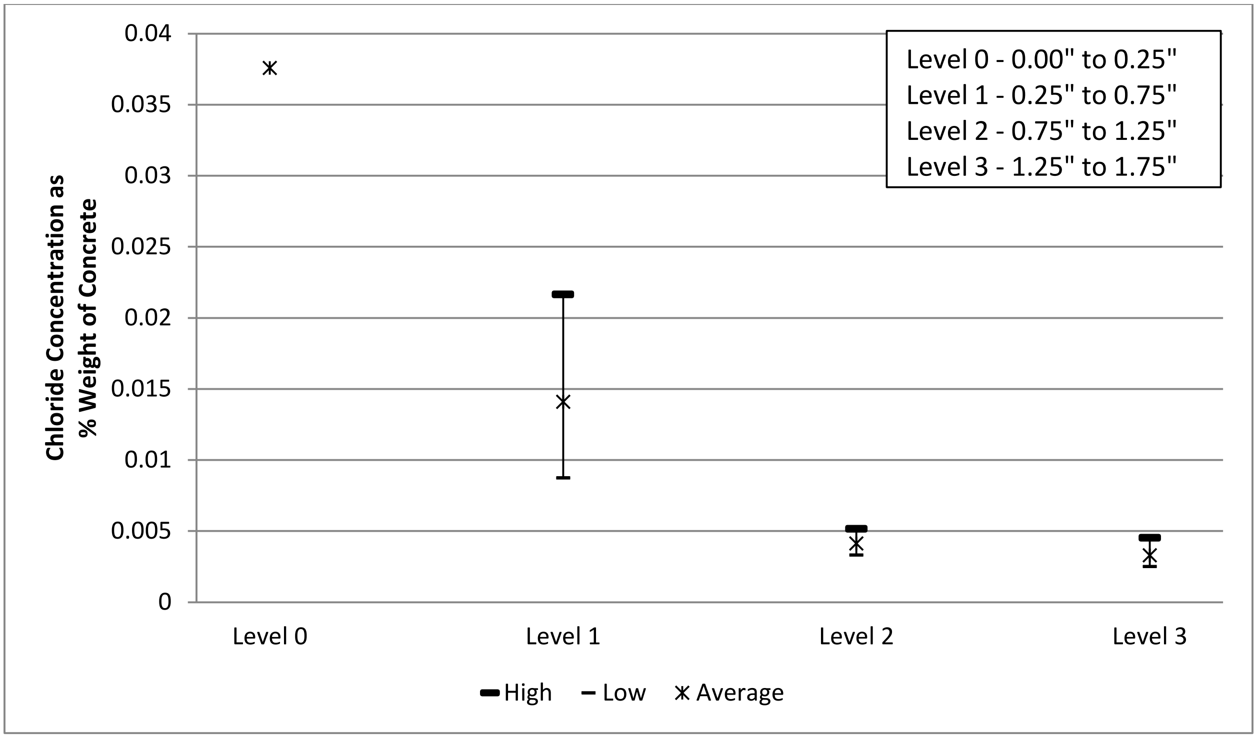


Figure 4.4: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Natural Brine.

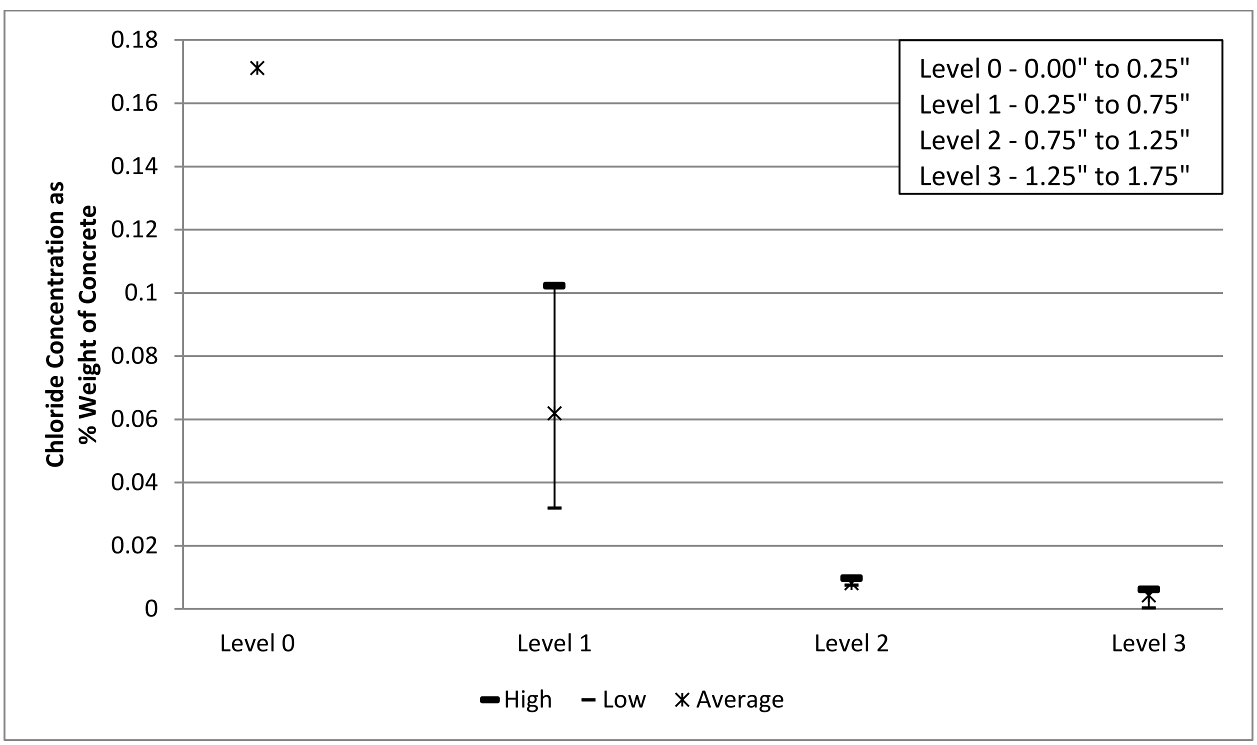


Figure 4.5: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Road Salt.

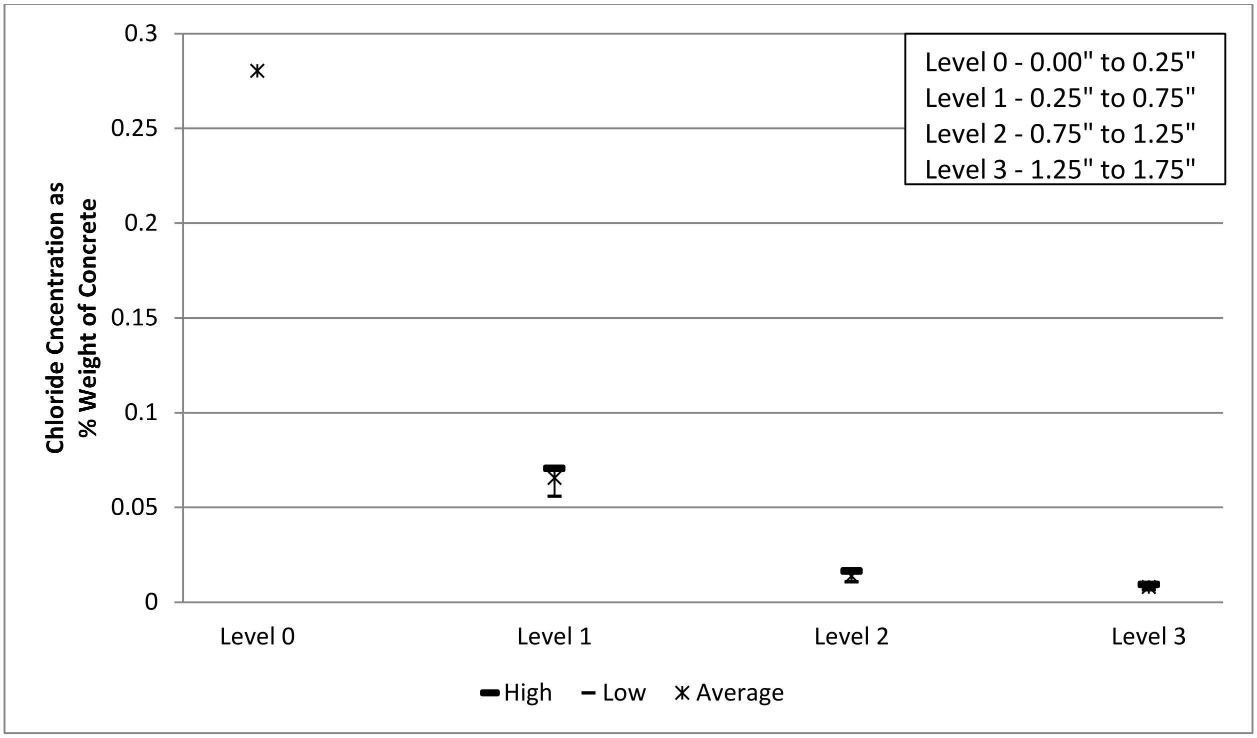


Figure 4.6: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Meltdown Apex™.

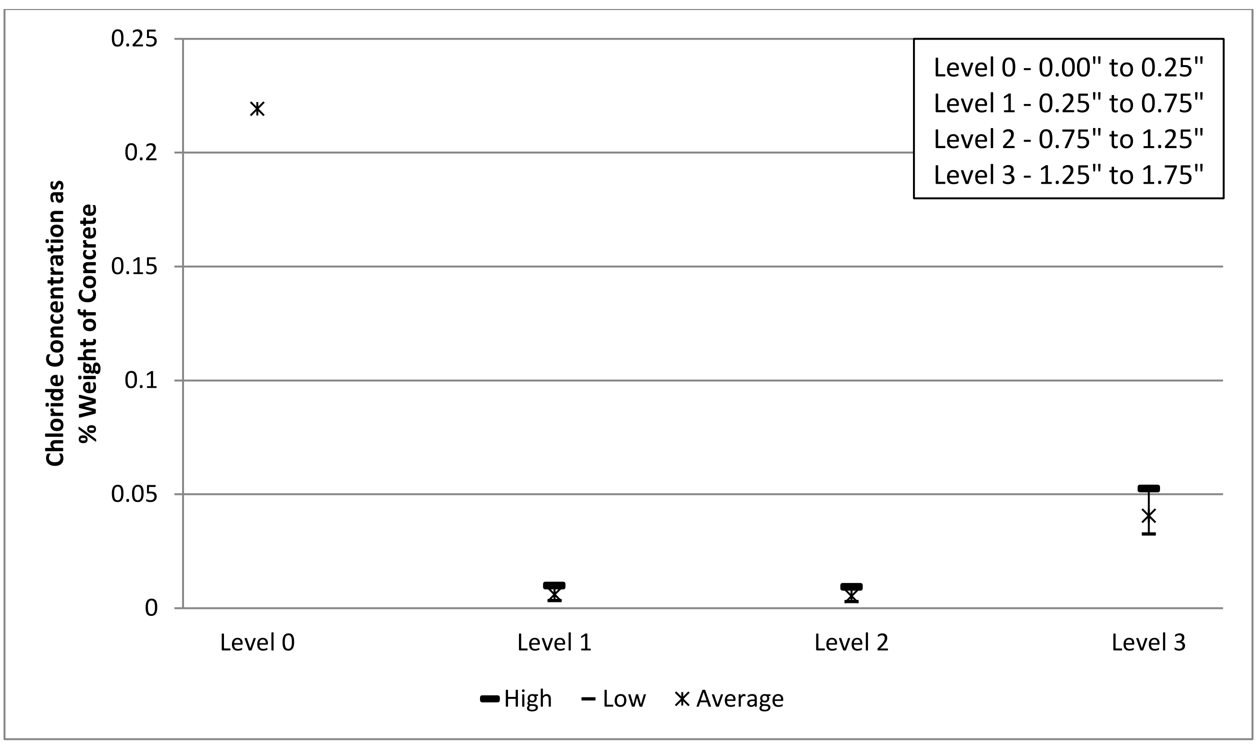


Figure 4.7: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Meltdown 20®.

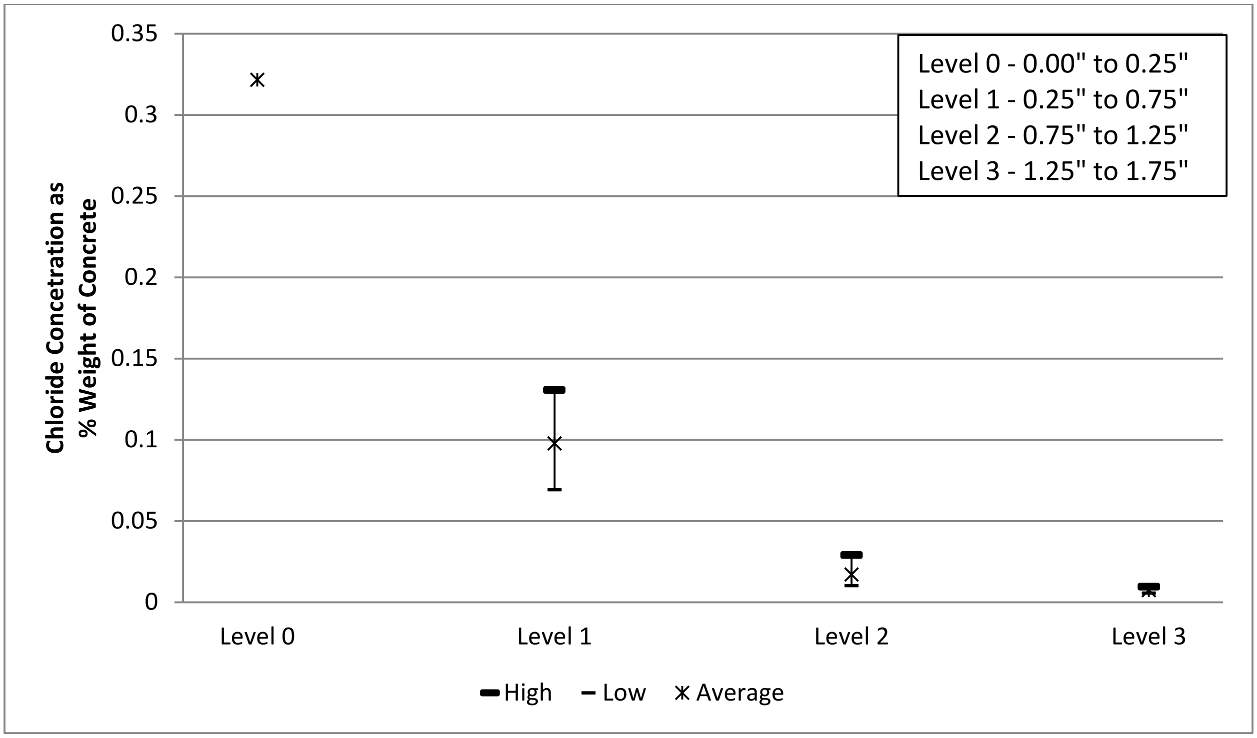


Figure 4.8: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Magnesium Chloride.

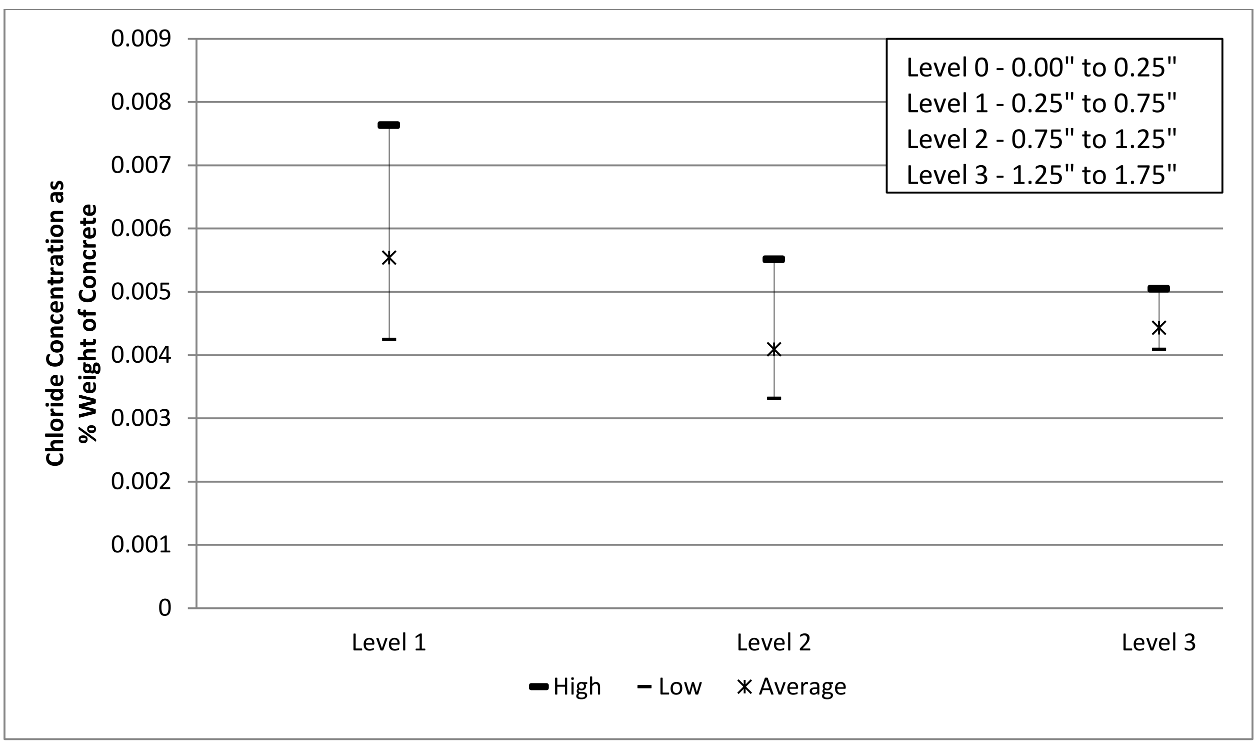


Figure 4.9: Chloride Concentration at different depths of AASHTO T259 Concrete Ponding Specimen – Distilled Water.

4.6 Summary

The primary objective this task has been to evaluate various de-icing chemicals commonly used by TxDOT for snow and ice control, at representative dosages and application frequencies, relative to infrastructure durability impacts. Table 4.7 summarizes the findings and shows that all currently-used de-icing chemicals tested “suitable” relative to infrastructure durability based on TxDOT’s current application rates and application frequency.

Table 4.6 Suitability of Chemicals

Chemical	Suitable relative to infrastructure durability based on TxDOT operations current dosage and application frequency?
Road Salt	Yes
MeltDown 20®	Yes
MeltDown Apex™	Yes
Memphis Brine	Yes
Natural Brine	Yes

Atmospheric corrosion results from laboratory testing showed that the corrosion rates are similar for uninhibited sodium chloride salts. Therefore, infrastructure durability will not see an increase in adverse impacts due to TxDOT operations substituting road salt for the other sodium chloride products, *i.e*. the Memphis Brine or Kent County brine. Historically, over 50 percent of granular chemical placed TxDOT has been road salt without any corrosion inhibitors.

Results from the chloride ponding tests indicate that at a concrete depth of 2 inches below the top of slab, which is the shallowest depth where steel reinforcement bars are typically located in a bridge deck, the chloride concentrations for all chemicals tested were below the threshold impact levels reported by West and Hime (1985). Sound quality control measures adopted for bridge deck concrete will help provide safeguards against chloride concentrations above threshold impact values.

For practical purposes, all chloride salts are considered *highly corrosive* with the main factor being time of wetness. Hygroscopic de-icing materials cause roadway infrastructure to stay wet longer, resulting in higher corrosion (Levelton Consultants Limited, 2006). Corrosion-inhibited snow and ice control chemicals which are tested in the laboratory show reductions in corrosion rates for the metals being tested, but they may show little or no inhibiting effect on other untested metals (Levelton Consultants Limited, 2006). Also, corrosion-inhibited snow and ice control chemicals can show significant reductions in corrosion rates in the laboratory, but under field conditions show much lower inhibiting effects. This was the case in a 2002-2003 field study by Washington State DOT (Baroga, 2003) where results from a test section of magnesium chloride corrosion-inhibited chemical and sodium chloride corrosion-inhibited chemical showed truck-mounted steel coupons with 27 to 30 percent less corrosion than the sodium chloride test section as compared to laboratory results where these same corrosion-inhibited products showed at least 70 percent less corrosion. In this same study, steel coupons placed on guardrails showed that the corrosion-inhibited products yielded no corrosion-inhibiting effects (Baroga, 2003).

When one considers that corrosion impacts directly relate to the quantity of chemical used, and the quantity of chemical is driven by climate severity, it can be observed that because Texas winters are relatively mild, most portions of the State see only a few winter storms per year, and some see no storms at all. Further, even the coldest and snowiest portions of Texas have less severe winters than northern states with active, chemical-based winter roadway maintenance programs. Texas' winter maintenance activities are an order of magnitude lower – one-tenth to one-fiftieth – compared to states such as Iowa, Ohio, and Massachusetts. Quantitatively, it is reasonable to infer that TxDOT winter maintenance operations apply an order of magnitude (or lower) less chemical to Texas bridges and roads than that used in the northern states. While this level does not eliminate corrosion concerns associated with winter roadway maintenance in Texas, it does provide some perspective.

CHAPTER 5
ENVIRONMENTAL IMPACT

5.1 Introduction

This chapter evaluates environmental impacts of common de-icing chemicals used for snow and ice control which was Task 4 of the research study. General conclusions are made about the impacts of de-icers on the environment, with an important caveat that every roadside, stream, and lake is different and may assimilate a de-icer differently because of variables such as precipitation, soil type, wind direction and speed (Salt Institute 2004). The de-icer's chemical composition is the main factor in predicting the environmental impact. Table 5.1 illustrates that a number of de-icing materials have both primary components and secondary attributes (Table 5.1).

Table 5.1 Primary components and secondary attributes of selected snow and ice control materials (NCHRP 2007)

Material Type	Snow and Ice Control Material	Primary Components	Secondary Attributes
Chloride based salts	Sodium Chloride (NaCl)	Na, Cl	Heavy Metals, CN, P
	Calcium Chloride ($CaCl_2$)	Ca, Cl	Heavy Metals, P
	Magnesium Chloride ($MgCl_2$)	Mg, Cl	Heavy Metals, P
Acetates	Calcium Magnesium Acetate (CMA)	Ca, Mg, $C_2H_3O_2$	BOD
	Potassium Acetate (KA)	K, $C_2H_3O_3$	BOD
Organic Products	Agricultural By-Products (Organic Biomass)	Organic Matter (complex sugars)	BOD, Heavy Metals, Phosphorus, Nitrogen
	Manufactured Organic Materials	Organic Matter- varies with product (i.e. glycol, methanol)	BOD
Nitrogen Products	Urea	Urea, Ammonia (i.e. Nitrogen)	Not Available
Abrasive	Abrasives	Air Quality- PM10, PM2.5 Water Quality- Sedimentation	Heavy Metals, P

The information contained in this section was obtained from a combination of a review of the literature as well as interviews conducted with several State DOTs. Primary de-icing salts include sodium, calcium, and magnesium chloride, while the secondary components are typically low levels of heavy metals and phosphorus (NCHRP 2007). Except for small differences, the states contacted generally used the same types of chemicals and tested for similar constituents as per Table 5.2.

Table 5.2 Snow and Ice Chemicals used by other states

State*	Interviewee	Chemicals
Minnesota	Tom Peters	Road Salt
New York	Mike Lashment	Road Salt, Salt treated with $MgCl_2$ + agricultural additives, Salt brine (23%), Liquid $MgCl_2$ or $CaCl_2$
Ohio	Thomas Lyden	Road Salt, $CaCl_2$, a blend of potassium, sodium, magnesium, calcium and organic extracts
Utah	Lynn Bernhard	Liquid $MgCl_2$, liquid NaCl, Solar salt from Great Salt Lake, Road salt, Ice Slicer
Vermont	Wayne Gammell	Road Salt + Sand, liquid chlorides, Salt Brine (23%), Ice-Be-Gone
Washington	Jay Wells	Road Salt, Salt Brine (23%), $CaCl_2$, $MgCl_2$ (Freezegaurd)
*Colorado, Iowa, Michigan, Montana, Massachusetts, New Hampshire and North Dakota were also contacted but provided either no response or no relevant information.		

5.2 Impacts of Sodium Chloride

Sodium chloride (NaCl), or road salt, is one of the most commonly used de-icing chemicals (NCHRP 2007). When used in excess, sodium chloride can be detrimental to the environment; however, a method known as *sensible salting* promotes using the appropriate amount of salt on roads to reduce negative impacts (Salt Institute 2004). All of the State DOTs that were contacted use sodium chloride and none of them expressed environmental concerns involved with using road salt. The state of Washington collects annual soil samples from roadsides to assess if damage is being caused by their de-icing chemicals. The soil samples are tested for their chloride loading and heavy metal contamination. To date, no adverse results have been reported (Jay Wells 2012).

The environmental effects of salt on soil are controlled by factors such as the land topography, the soil type, and the vegetation cover (quantity and type) (Andel et al., 2012). The soil chemistry is affected when cations adsorb to soil particles, changing the relative concentrations of several ionic species in the soil. Adsorption of sodium ions can change the soil's structure by shrinking the soil particle size, compacting the soil, and reducing the permeability (NCHRP 2007). Changing the permeability of the soil affects erosion and surface runoff patterns near the roadway. Sodium ions weaken soil structure, slow water movement through the soil and increase runoff (Fischel 2001). Negative impacts to the soil only occur when excessive levels of sodium accumulate in the soil (NCHRP 2007). The report did not quantify what constitutes an excessive level of sodium. The overall impact will be a combination of application rate, (total material applied and area of application) as well as climatic variables such as precipitation rate.

Texas uses relatively low quantities of NaCl compared to some states. For example, in Washington approximately 50,000 tons of sodium chloride is used each year while Texas uses ~5,900 tons to de-ice roads (Jay Wells 2012).

When an anion like chloride adsorbs to soil particles it too can lead to structural changes in the soil, loss of permeability, soil swelling and increased erosion (Fischel 2001). Chloride ions from de-icers are at their highest concentration 2-3 m from the road and 1 m down into the soil (Fischel 2001). Because the chloride ions do not travel far from the roadway, their effects are negligible beyond 80 feet from the roadway (Salt Institute 2004). Because chloride ions do not generally react with soil, chloride tends to quickly become flushed from the soil preventing accumulation and therefore not posing a risk to the soil (Salt Institute 2004).

Another concern for soil contamination is accumulation and/or mobilization of heavy metals. Some evidence suggests that heavy metals are released from de-icers, especially at higher application rates (like those in Washington State), but the evidence is insufficient (NCHRP 2007). More research is needed to determine how heavy metals in de-icers behave along with their environmental impacts.

Sodium chloride poses a threat for many different types of water bodies. Groundwater is the most at risk for contamination. The Ohio Department of Transportation recorded its application rates over a ten year period and analyzed proximal groundwater quality (Kunze and Sroka 2004). Table 5.3 lists application rates and Figure 5.1 displays a graph of chloride levels in observation wells (Kunze and Sroka 2004). These data suggest that de-icers only impact the environment close to the roadway and it appears that salt only entered the groundwater at relatively low rates. Other studies have suggested concerns with chlorides causing acidification of ground water but no analysis was presented to support this conclusion (Fischel 2001). When evaluating the impacts of de-icers on surface water, NCHRP Report 577 concluded that the magnitude of the impact is proportional to the amount of dilution. The example in Figure 5.2 illustrates how much dilution affects concentration as the de-icer leaves the roadway (NCHRP 2007). A value of 50mm (~2.5 inches) is used for precipitation to reflect conditions found in Texas.

Table 5.3 Countywide sodium chloride and sodium chloride amounts applied by the Ohio Department of Transportation, by year (Kunze and Sroka 2004)

	County								Season total	Season average	State wide total (tons)	Tons per lane-mile, average
	Ashtabula	Portage	Ashland	Richland	Lucas	Clark	Champaign	Pickaway				
Sodium chloride (tons)												
1990-91	e15,000	e7,000	5,754	5,220	4,892	4,087	2,858	998	45,809	5,726	322,698	7.54
1991-92	e17,000	e7,000	6,510	4,712	4,310	2,672	1,723	782	44,709	5,589	338,268	7.90
1992-93	e21,000	e6,000	6,974	4,660	4,503	3,470	1,976	1,071	49,654	6,207	375,264	8.72
1993-94	26,079	6,706	8,065	5,842	5,332	1,733	1,518	2,145	57,420	7,178	514,323	11.97
1994-95	17,494	8,356	4,588	4,252	3,680	2,709	1,289	1,643	44,011	5,501	338,735	7.88
1995-96	43,769	13,514	10,766	8,844	4,592	4,721	2,936	2,540	91,682	11,460	628,616	14.69
1996-97	32,620	9,441	6,605	5,246	3,915	2,902	2,327	698	63,754	7,969	339,834	7.94
1997-98	25,658	9,148	5,278	4,829	2,029	2,082	1,554	924	51,502	6,438	280,820	6.56
1998-99	35,492	16,096	10,259	8,852	5,146	4,971	3,882	2,758	87,456	10,932	599,371	14
Total	234,112	83,261	64,799	52,457	38,399	29,347	20,063	13,559	535,997	67,000		
Average	26,012	9,251	7,200	5,829	4,267	3,261	2,229	1,507	59,555	7,444		9.69
Calcium chloride (gallons)												
1990-91	Data not available										2,854.1	
1991-92											3,101.0	
1992-93											4,023.5	
1993-94	135,844	28,496	10,566	26,022	4,092	0	0	0	205,020	0	4,773.0	
1994-95	44,995	11,680	4,425	1,710	1,780	0	0	0	64,590	316,168	59.5	
1995-96	96,313	24,373	14,549	22,665	4,768	0	0	0	162,668	735,937	71.1	
1996-97	61,481	5,019	7,550	4,863	4,581	0	0	0	83,494	337,502	13.1	
1997-98	61,081	2,881	6,900	0	1,587	0	0	0	72,449	206,160	1.2	
1998-99	81,075	10,198	23,319	6,150	11,695	330	0	0	132,767	681,410	29.4	
Total	480,789	82,647	67,309	61,410	28,503	330	0	0	720,988	2,277,177	4,947.3	
Average	80,132	13,775	11,218	10,235	4,750	55	0	0	120,165	379,530	824.6	

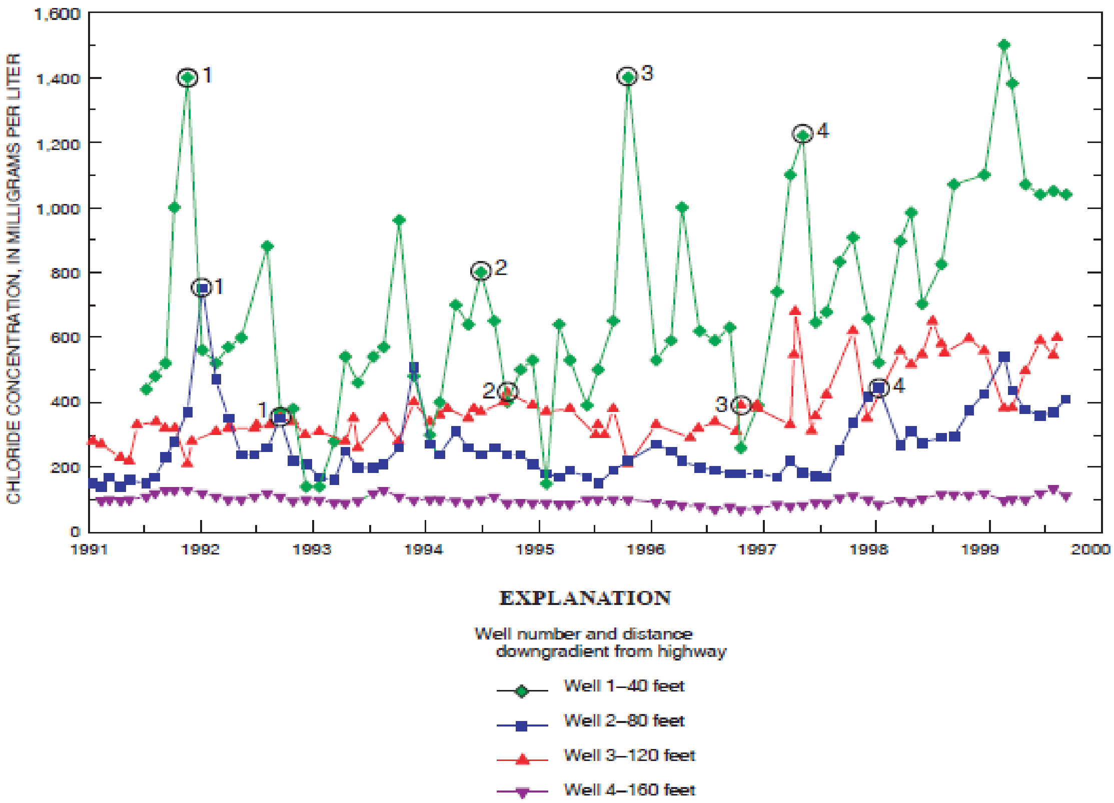


Figure 5.1 Plot of chloride concentration showing peaks as they move down gradient well to well (Kunze and Sroka 2004)

<u>Runoff Value:</u>
Area of Roadway (1 mile): 90,000m^2
Annual Winter Precipitation: 50mm
Runoff = 90000m^2*50mm= 4,500 m^3
<u>Dilution:</u>
NaCl Solution Applied: 8,300 L or 8.3m^3
Dilution: 4,500 m^3/8.3 m^3 = approx. 500 times
Concentration of Cl in undiluted NaCl Solution: 200,000 mg/L
Predicted Concentration of Cl exiting roadway: 200,000mg/L / 500= 400 mg/L

200,000mg/L / 500= 400 mg/L

Figure 5.2 Calculations to predict dilution effects

The concentration of de-icer leaving the road is only 0.2% of the original concentration of de-icer applied. The concentration exiting the roadway is very small and will rapidly dilute further with distance from the road as the dilution volume was only based on the road area while the drainage area will be much larger. Several factors affect dilution and the concentration of de-icers in surface water (Table 5.4). In general runoff that is collected in larger bodies of water will experience less impact from snow and ice control chemicals due to the larger dilution (NCHRP 2007).

Table 5.4 Factors that influence concentrations of snow and ice control materials in receiving waters (streams, lakes, wetlands). (NCHRP 2007)

Factor	Effect on Snow and Ice Control Materials in Receiving Waters
Higher road surface per unit watershed	Increases concentrations
Higher roadway runoff	Decreases concentrations
Higher rate of application	Increases concentrations
Greater distance to receiving water	Decreases concentrations
Greater volume of receiving water	Decreases concentrations
Greater flushing of receiving water	Decreases concentrations

The Salt Institute recognizes that chloride can hinder a plant's ability to take up water (Salt Institute 2004). Section 3.7 of NCHRP Report 577 provides a lengthy assessment of the impacts on vegetation and it states that damage to roadside plants are caused by deposition of snow and ice chemicals on the foliage or infiltration into the soil and root exposure (NCHRP 2007). Foliar deposition can be caused by vehicles or winds that mobilize dried chemicals on the road. Roads with higher speed limits and more traffic increase the transport of snow and ice chemicals into the air (NCHRP 2007). Terrestrial vegetation can be resistant to higher NaCl concentrations but some adverse effects include reduced flowering, reduced root growth, thinning of tree crowns, and even death of the plant (Fischel 2001). High salinity can decrease biodiversity by killing native species and allowing the salt tolerant ones to flourish (Hackley et al. 2009). NCHRP Report 577 also states that the soils 10 to 20 meters closest to the road are the most impacted. It is suggested to minimize the amount of de-icer used in order to minimize detrimental effects to the vegetation (NCHRP 2007). Concentrations of chloride less than 70 ppm will not damage plants while concentrations between 140-350 ppm can cause damage to moderately tolerant plants (Fischel 2001). Sodium is toxic to plants when it reaches a level of 0.3% dry weight in the plant (Fischel 2001).

Sodium chloride may also impact microbial community structure. The roadside environment is a "disturbed" environment and it is unclear what population structure should be present (NCHRP 2007) but at least one study has shown that elevated salinity can shrink and stress microbial populations (Andel et al. 2012).

With regard to the impact on fish, the Salt Institute states that many freshwater fish are able to tolerate peaks in salt concentrations (Salt Institute 2004). An increase in salinity in a lake can create layers in the water by changing the density of the water and reducing temperature. The lower, denser layers have reduced dissolved oxygen concentrations, harming the ecosystem in the lake (Fay and Shi 2012). If the lake turns over and the layers are flipped then the ecosystem in the lake could be harmed.

Many fish and other aquatic organisms are tolerant to chloride. The EPA limit of chloride in water for acute toxicity is 860 ppm, and the limit is 230 ppm for chronic toxicity (Fischel 2001). Additional information about chloride toxicity in freshwater fish and plants can be found in a report by the EPA (Benoit 1988).

In the case of animals, many birds and large mammals are attracted to the sodium in the salt on roads. For example, large mammals need to resalinate their bodies after salt loss. Large mammals such as deer are attracted to the salt on the roads, creating a high risk of a collision. Salt attracting animals to the roadside could be a factor attributing to road kills (Fischel 2001). High chloride levels in animals may be toxic but larger animals may assimilate higher concentrations. NCHRP Report 577 also states that where fresh water is readily available, chlorides will not be a risk for wildlife (NCHRP 2007).

5.3 Impacts of Other Chloride-Based De-icers

Calcium and magnesium are commonly-used components in de-icers. As calcium and magnesium are essential minerals for plants these types of de-icers are considered more environmentally friendly and are very effective when paired with sodium chloride (Lewis 1999). Magnesium and calcium can improve the permeability and structure of soil (NCHRP 2007). These ions alter soil structure by encouraging fine clay particles to aggregate, improving drainage and aeration (Fischel 2001). While improving soil structure, these cations can exchange with heavy metals in the soil, causing the heavy metals to be released into the environment or nearby water sources (Fay and Shi 2012). A positive characteristic of magnesium and calcium salts is that they do not dry, flake, and affect the air in the same way as sodium chloride (NCHRP 2007).

Many of the State DOTs contacted in this project use magnesium and calcium salts as extra tools against snow and ice. These chemicals are typically combined with a corrosion inhibitor, such as a corn syrup, sugar cane molasses, phosphorous, or nitrogen (Bernhard, Lashment and Wells 2012). The sugar in organic corrosion inhibitors could create an oxygen demand, causing problems for the receiving lakes and streams while phosphorous and nitrogen can cause eutrophication – that is, an increased concentration of nutrients, especially phosphates and nitrates, which may be considered a form of pollution.

A report by Colorado Department of Transportation evaluated the environmental impacts of a de-icer called Caliber M1000. Caliber M1000 is mainly a magnesium chloride de-icer. There are also small amounts of sodium (2000 mg/L), calcium (900 mg/L) and potassium (1300 mg/L) but magnesium makes up 95% of the cations (79000 mg/L) (Lewis 2000). This de-icer has high amounts of phosphorous and nitrogen, which raise concerns for eutrophication. These two nutrients are in the form of ammonia (52 mg/L) and soluble phosphorous (130 mg/L) (Lewis 2000).

The State of Texas regulates effluent phosphorous and total nitrogen levels in treated wastewater to be 1 mg/L and 10 mg/L, respectively. Phosphorus is a main constituent of concern because of its high concentration and the sensitivity of inland waters. Dilution effects are not discussed, although, if the 500-fold dilution rate (NCHRP 2007) is used, the concentrations of ammonia and phosphorous would be in regulation with Texas effluent standards. Caliber M1000 also contains a variety of heavy metals such as mercury, arsenic, and cadmium, all at concentrations less than 2 mg/L (Lewis 2000). Caliber M1000 also contains 33mg/L of organic matter. However, typical dilution rates will greatly reduce this impact. A test conducted using Caliber M1000 in which water samples from three different streams were tested by adding 5%, 1%, 0.33% or 0% de-icer found no increase in BOD. According to tests performed in the study the organic matter in the de-icer, surprisingly, did not change the oxygen demand by more than 0.06 mg/L/d (Lewis 2000).

The impact of the phosphorous and nitrogen were evaluated using a model and parameters and impact levels specific to Colorado. Parameters used in the model included an application rate of 12,000 L per lane mile per year, total phosphorus concentration of 190 mg/L, and runoff equal to 300 mm/yr. Equations to execute the model were drawn from studies done in Summit County, Colorado. The model predicted problems with eutrophication in parts of Colorado from the elevated levels of phosphorus. The ammonia concentration also changed ambient water quality above the chronic standard in some places (Lewis 2000). Water quality standards or toxicity values were not cited in the report. The report suggested further testing if Colorado wanted to move forward with using Caliber M1000. The tests conducted were specific to Colorado’s terrain and environment, so if tests were performed in Texas results might differ.

In another study, the Colorado State Department of Transportation evaluated two simple magnesium chloride de-icers. The two magnesium chloride de-icers were FreezeGard Zero and GMCO. Each of these de-icers contained a proprietary rust inhibitor. Neither of the de-icers exhibited an additional oxygen demand when BOD tests were run (Lewis 1999). While being tested for biotoxicity, the researchers also tested pure magnesium chloride to see if the corrosion inhibitors affect organisms. Standard biotoxicity tests were used, which involve introducing different dilutions of the de-icer to the test organisms. Only at higher concentrations of 1-2% were organisms killed, but at smaller concentrations the development of organisms was retarded. The test also showed that the majority of toxicity was from the magnesium and chloride ions, not rust inhibitors. Synoptic sampling – that is, collecting samples from several locations within a short period of time – was conducted in order to show how much dilution occurs when the de-icer leaves the roadway. The study concluded that magnesium chloride de-icers have a relatively low impact on the environment, especially 20 feet from the roadway (Lewis 1999).

5.4 Brines

Brine is simply salt dissolved in water. Three types of geologic brine exist for consideration in snow and ice control: (1) natural brine, (2) manufactured brine, and (3) oilfield brines. Natural brine can be found in surface waters (e.g. Dead Sea or the Great Salt Lake) or groundwaters. Manufactured brines are made by dissolving salt in water. Many companies acquire salt for their manufactured brines from a natural source. The difference between natural and manufactured brine is only due to the processing involved. Oilfield brines are produced from drilling operations where the brine is a waste product of drilling and oil and gas production. There is a possibility that oilfield brines may contain heavy metals, hydrocarbons, or naturally-occurring radioactive materials.

The use of natural brines is an unexplored option for snow and ice control. Of the State DOTs contacted, none directly used natural brines. A few bought brines from companies procuring it from the Great Salt Lake. Those states use a 23% brine solution for pre-wetting the roads in order to increase the effectiveness of the road salt. When discussing the viability of using natural brines in Texas, concerns were raised by some other State DOTs (Table 5.2). For example, oilfield brines cannot be used in Utah because of regulations on the heavy metals and hydrocarbons the brine may contain (Lynn Bernhard 2012). The regulations in Utah require brines to be tested for potentially dangerous constituents.

Many snow and ice supply companies acquire the brine they sell from the Great Salt Lake. The USGS published a survey on the hydrology of the Great Salt Lake. The report only covers the Great Salt Lake from 1847-1986. About 90% of the Lake's ions are chloride and sodium, the other 10% is made up of sulfate, magnesium, and potassium (Arnow and Stephens 1990). Once the brine is extracted from the lake, the brine contains small amounts of calcium, bicarbonate, lithium, boron, fluorine, silica, and bromium dissolved into it (Arnow and Stephens 1990). These trace constituents will not be of concern because of the amount of dilution (NCHRP 2007). Table 5.5 shows the composition of Great Salt Lake brine in percentage by weight. TxDOT currently uses a product, MeltDown Apex™, which derives from brine solarized from the Great Salt Lake.

NCHRP Report 577 also briefly addresses the use of brines from groundwater wells or oilfield brines (NCHRP 2007). According to the EPA, 30 percent of oil and gas operation have

Table 5.5: Composition of Great Salt Lake Brine, percentage by weight, 1850-1986. (Arnow and Stephens 1990)

[Percentages are the ratio of the concentration of the indicated constituent to the sum of the concentrations for all constituents determined Data prior to 1976 from Hahl and Handy (1969, p 14), data for 1976 adapted from Sturm (1980, p 155), data for 1986 from Utah Geological and Mineral Survey, unpublished]

Date	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (as CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Bromium (Br)	Total percentage	Dissolved solids
							Precauseway							
1850	–	–	0 27	38 29	–	–	–	5 57	55 87	–	–	–	100 0	22 3
1869	–	0 17	2 52	33 15	1 60	–	–	6 57	55 99	–	–	–	100 0	15 0
August 1892	–	1 05	1 23	33 22	1 71	–	–	6 57	56 22	–	–	–	100 0	23 8
October 1913	–	16	2 76	33 17	1 66	–	0 09	6 68	55 48	–	–	–	100 0	20 3
March 1930	–	17	2 75	32 90	1 61	–	05	5 47	57 05	–	–	–	100 0	21 0
							South of causeway							
April 1960	0 002	12	2 91	32 71	1 71	–	06	6 60	55 88	–	0 01	–	100 0	24 7
December 1963	001	09	3 29	31 02	1 86	–	07	9 02	54 64	–	01	–	100 0	27 3
May 1966	003	09	3 80	30 56	2 22	0 02	10	7 99	55 21	0 003	01	–	100 0	18 9
June 1976	–	17	3 47	31 29	2 66	02	–	7 22	55 11	–	01	0 04	100 0	9 9
June 1986	–	24	3 66	31 14	2 41	–	–	6 99	55 56	–	–	–	100 0	4 7
							North of causeway							
December 1963	001	09	4 66	29 08	2 75	–	09	7 28	56 04	–	01	–	100 0	27 5
May 1966	–	05	4 38	29 67	2 61	02	09	8 58	54 59	002	01	–	100 0	26 9
June 1976	–	13	3 17	32 04	2 58	02	–	6 62	55 39	–	01	04	100 0	24 7
June 1986	–	16	3 17	32 17	1 82	–	–	6 81	55 87	–	–	–	100 0	15 2

naturally occurring radioactive matter (NORM) in their brine (NCHRP 2007). The report also said that it was lacking information regarding radioactivity in specific regions or how much NORM is actually contained in winter weather chemicals.

5.5 Survey of Regulations

The Texas Commission on Environmental Quality (TCEQ) has no implicit rules about snow and ice control on their website or in the Texas Administrative Code.

Illinois has created policies to keep storm water and highway runoff away from surface water bodies to avoid de-icing chemicals entering the environment (Hackley et al. 2009).

The Iowa Institute of Hydraulic Research released *Technical Report Number 420* as a guide to choosing a de-icer. They took into account the environmental impacts of the de-icer based on the performance results for several tests. The test methods for several parameters are described because the quality of de-icers determines the regulations impacting their use. The parameters are heavy metal concentrations, toxicity, nitrogen levels, the BOD of the liquid and, the chemical oxygen demand (COD) of the liquid (Nixon and Williams 2001). The report instructs users to weight each category for their specific needs in order to differentiate and rank the de-icers. Because this guide takes into account more than just environmental concerns, it can be used to create a standard for which de-icers used specifically in Texas can be judged. Table 5.6 compares the EPA drinking water standards and the Pacific Northwest Snowfighter's (PNS) requirements for de-icers. Table 5.6 shows that the PNS regulations can be more stringent than the drinking water standards for some constituents.

Table 5.6: Allowable Levels of Various Elements. (Nixon and Williams 2001)

Metal	PNS Requirement (ppm)	Drinking Water Standards (ppm)
Phosphorus	25	NA
Cyanide	0.2	0.2
Arsenic	5	0.05
Copper	0.2	1.3
Lead	1	0.015
Mercury	0.05	0.002
Chromium	0.5	0
Cadmium	0.2	0.005
Barium	10	2
Selenium	5	0.05
Zinc	10	5

5.6 Testing and Analysis Methods

NCHRP Report 577 examined water and wastewater industry standard methods for quantifying various parameters. The Iowa Institute of Hydraulic Research *Technical Report Number 420* examines the properties that impact the effectiveness and safety of de-icing chemicals. Table 5.7 lists the parameter, standard method of testing and relevant reference.

Table 5.7 Testing and Analysis Methods

Publication	Parameter	Test Method
Nixon and Williams 2001	Toxicity	EPA Fathead Minnow and Seed Germination Tests
	Nitrogen	Kjeldahl Method
	BOD/COD	BOD Test, COD Test
NCHRP 2007	Metals	AA Spectroscopy, ICP- Atomic Emission Spectroscopy, ICP Mass Spectroscopy
	Phosphorous	American Public Health Association Method
	Nitrogen	APHA Method
	BOD/COD	BOD Test, COD Test
	pH	Electronic pH Meter
	Cyanide	APHA Method, Digestion Process
	Aquatic Toxicity	EPA, Table 5-1

The PNS "Snow and Ice Control Chemicals Products Specifications and Test Protocols" document provides guidance on preparing and submitting products for the testing and evaluation process required to be placed on the Qualified Products List (*see* Appendix H). Per Table 3.4 (Chapter 3), the PNS specification identifies 23 tests which de-icing and anti-icing products must meet to be considered for widespread use.

5.7 Summary

The Federal Highway Administration states that highway runoff is appreciably cleaner than other non point runoff sources such as agricultural and industrial sources (FHWA 1997). The United States Geologic Survey in Ohio reported that de-icing chemicals, including road salt, did not affect the environment in the long term (Kunze and Sroka 2004). The Salt Institute encourages cities and municipalities to plant salt tolerant vegetation along roadways (Salt Institute 2004).

Overall, especially in Texas, the literature suggests that there is minimal added risk to the environment when using snow and ice control chemicals, certainly less risk than that which might typically arise from a significant fuel leak in an accident caused by winter weather (Thompson et al. 2009).

There is a lack of research on natural brines. As has been noted, oilfield brine is a waste product of drilling and oil and gas production, and the possibility exists that oilfield brines may contain heavy metals, hydrocarbons, or naturally occurring radioactive materials. Any geologic brine in question should be tested for constituents and toxicity prior to widespread use. It the brine passes the criteria for an approved de-icer, for example, the Pacific Northwest Snowfighter's requirements, the brine should be safe for use on highways.

De-icing chemicals commonly used in Texas are road salt (both liquid and granular), liquid MeltDown Apex™, and granular MeltDown 20®. MeltDown Apex™ contains 25-35 percent magnesium chloride and MeltDown 20® contains 90 to 98 percent sodium chloride. These are approved products on the PNS Qualified Products List (Appendix A). Excluding the proprietary parts of the de-icers, the literature reviewed and information from the material safety data sheets (Appendix F) suggest these chemicals will not pose a threat to the environment.

Much of the environmental risk involved with putting a de-icer on the roadway is negated by the amount of dilution when the de-icer leaves the roadway. NCHRP Report 577 assumed that the concentrations of the applied materials are diluted 500 times at the point these materials leave the roadway. In a manner similar to the discussion of corrosion impacts, even the coldest and snowiest portions of Texas have less severe winters than northern states with active, chemical-based winter roadway maintenance programs. The inference is that environmental impacts from Texas snow and ice control operations will therefore be less than those from winter maintenance operations in the northern states.

CHAPTER 6
CURRENT USE AND COST OF APPLICATION OF TEXAS SNOW AND ICE CONTROL MATERIALS

6.1. Introduction

This chapter provides a comprehensive cost analysis of the use of snow and ice control materials in Texas, which is Task 6 of the research study. The objective of this work was to analyze the life-cycle cost of various snow and ice control materials including natural brines used in Texas. The analyses considered both short-term cost factors (e.g., purchase, processing, storage, transport, and application) and long-term factors (e.g., potential damage to equipment and roadways) of these materials.

6.2. Expenditure on Snow and Ice Control Materials by TxDOT Districts

Between 2008 and 2012, TxDOT spent an average of $3,429,639 per year on four snow and ice control materials: Meltdown 20®, Meltdown Apex™, Salt, and Abrasive (Figure 6.1). Approximately 51% ($1,765,757) of that amount was used on Meltdown 20®, followed by 29% ($987,839) on Abrasive, 12% ($411,500) on Salt, and 8% ($264,544) on Meltdown Apex™.

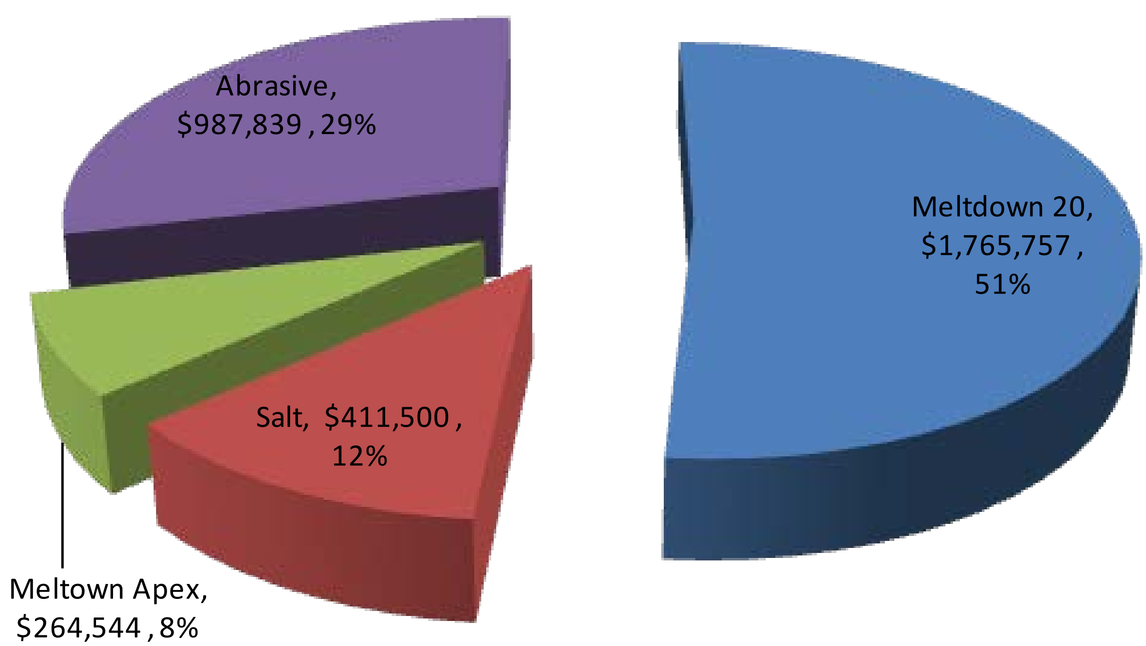


Figure 6.1 Annual expenditures on four snow and ice control materials by TxDOT (2008-2012)

The expenditures on Meltdown 20®, Meltdown Apex™, Salt, and Abrasive varied significantly by year and district. Using the data between 2008 and 2012 period, the lowest, highest and annual average expenditures were calculated to demonstrate the variation in spending patterns of 25 districts (Figure 6.2).

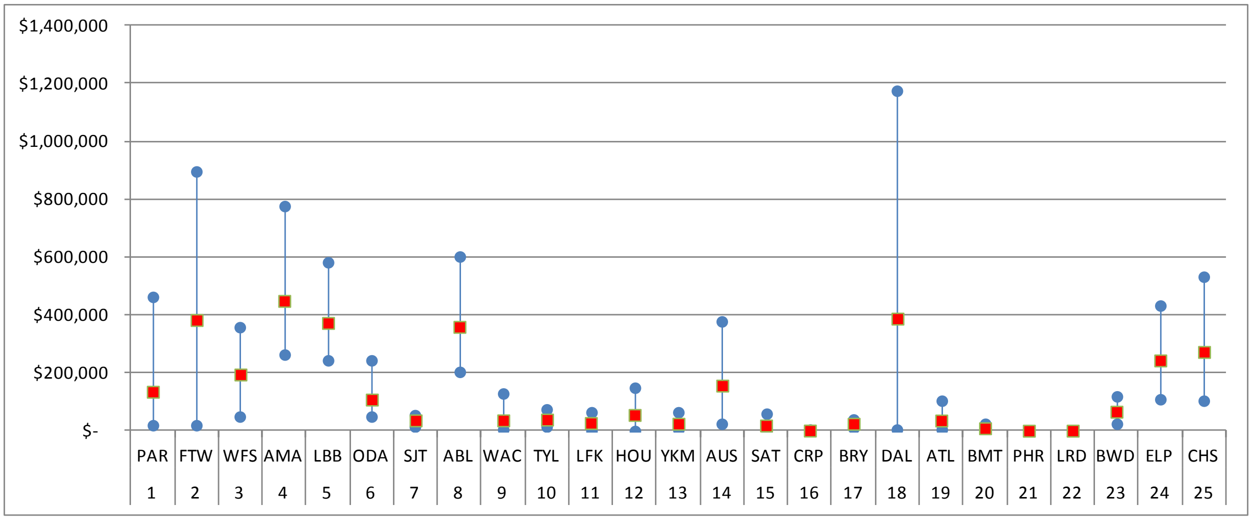


Figure 6.2. Expenditure on snow and ice control materials by district between 2008 and 2012 (Red squares denote mean values while blue circles denote lowest and highest annual expenditures)

As shown in Figure 6.2, the district with the highest expenditure on snow and ice control materials was Amarillo ($448,753 per year), followed by Dallas ($387,527 per year) and Fort Worth ($382,757 per year). In comparison, Corpus Christi, Pharr, and Laredo spent less than $1,000 a year. It is noted that the Top 5 districts (Amarillo, Dallas, Fort Worth, Lubbock and Abilene) accounted for 57% of the total TxDOT material expenditure whereas the Top 10 districts accounted for 86% of that.

Total expenditure by district may not reflect the degree of a district's vulnerability to winter weather as some districts have significantly more lane-miles of roadway than others. The map (Figure 6.3) shows the annual expenditure on snow and ice control material normalized by lane-miles maintained by each district. The values ranged from $0 to $50 per lane-mile. El Paso and Childress led the group by spending $50/lane-mile a year on materials, followed by Amarillo ($48/lane-mile), Abilene ($43/lane-mile), and Fort Worth ($43/lane-mile). Dallas was not in the Top 5 because of its large number of lane miles (10,847), second only to Lubbock among 25 districts (12,132). It terms of geographic area, the Lubbock District covers 15,861 square-miles compared to 5,721 square-miles for Dallas and 6,717 square-miles for Houston.

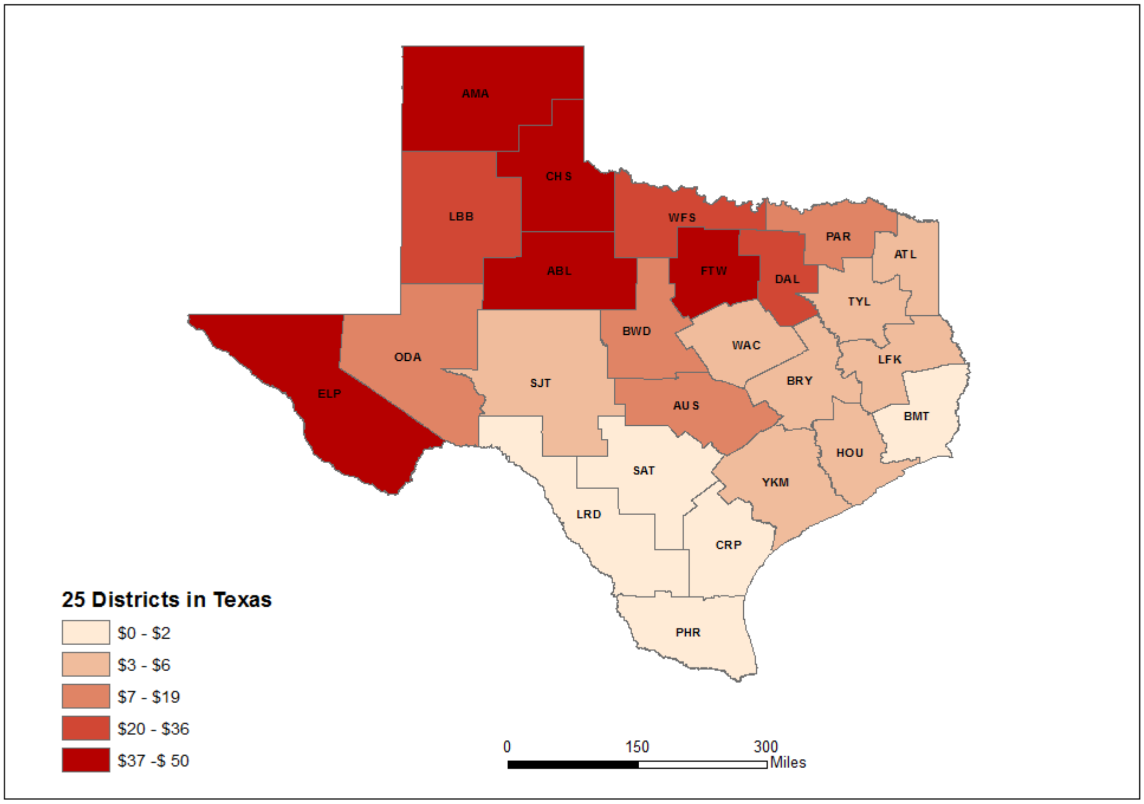


Figure 6.3. Annual expenditure on snow and ice control materials of 25 districts per lane mile

Meanwhile, the expenditures swung wildly from year to year in response to winter conditions. In 2011, Dallas' spending on snow and ice control materials reached a five-year high, at the cost of $1,176,162 while in the following year it spent the least amount - $1,911. Fort Worth had a similar pattern: its highest and lowest years were 2011 and 2012 with the spending of $894,383 and $51,159 respectively while the 5-year average was $382,757. However, the year-to-year expenditures for Amarillo were more consistent.

Dispersion was measured with dimensionless coefficient of variation (CV) by dividing standard deviation with mean. Districts with more mild winter weather such as Dallas, Fort Worth and Austin had much bigger CVs (1.21, 0.89, and 0.95) than those with colder winter including Amarillo, Lubbock, and Childress (0.47, 0.40, and 0.58) as snow falls and storms in former districts were less predictable and less consistent. This pattern would be more conclusive if the study period were longer than the current 5-year analysis time frame.

Expenditures on each of four snow and ice control materials were examined at both Department and district levels and a great deal of variation was revealed. The Department spent an average of $1,765,757 per year on Meltdown 20®, representing 51% of their total expenditure on snow and ice control materials. Per Figure 6.4, the Top 5 districts in term of spending on Meltdown 20® - Abilene, Fort Worth, Lubbock, Dallas and Austin - collectively accounted for

68% of the total department purchase of such material whereas the Top 10 districts accounted for 92%. Among them, Abilene, Fort Worth and Lubbock spent heavily on Meltdown 20® at the costs of $348,376, 283,042, and $243,001 a year respectively. In fact, 97% of Abilene's expenditure went to purchase Meltdown 20®, compared to 74% for Fort Worth and 65% for Lubbock.

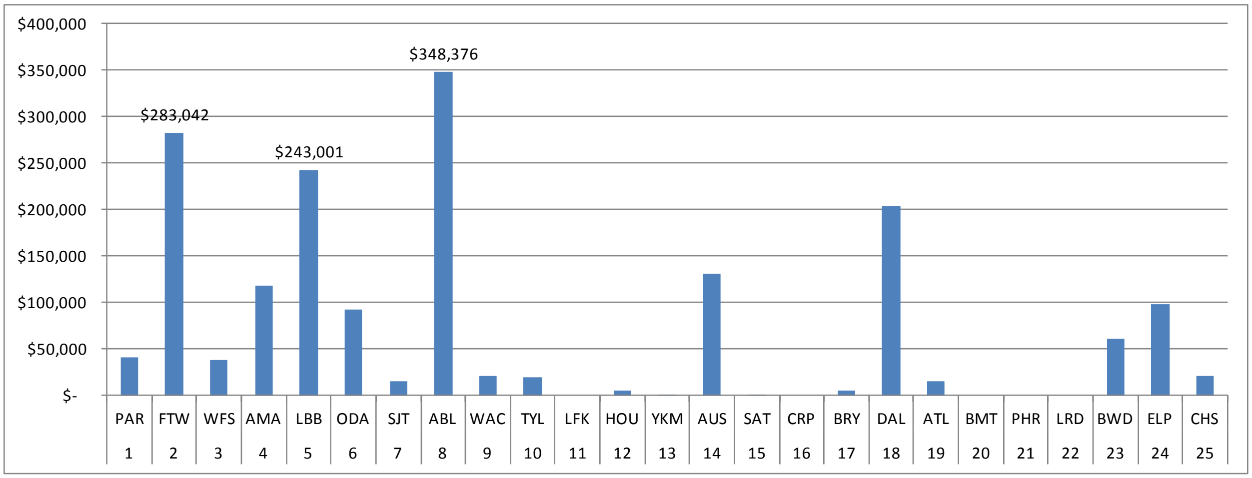


Figure 6.4 Annualized expenditure on Meltdown 20® by district (2008-2012)

The use of road salt was highly concentrated to a few districts as shown in the Figure 6.5. Childress, Amarillo, and Dallas led the group with the most expenditure while 14 districts had zero or near-zero expenditure. The Top 5 districts collectively accounted for 92% of the total spending by the department on road salt ($411,500 per year) and the Top 10 accounted for almost 100%.

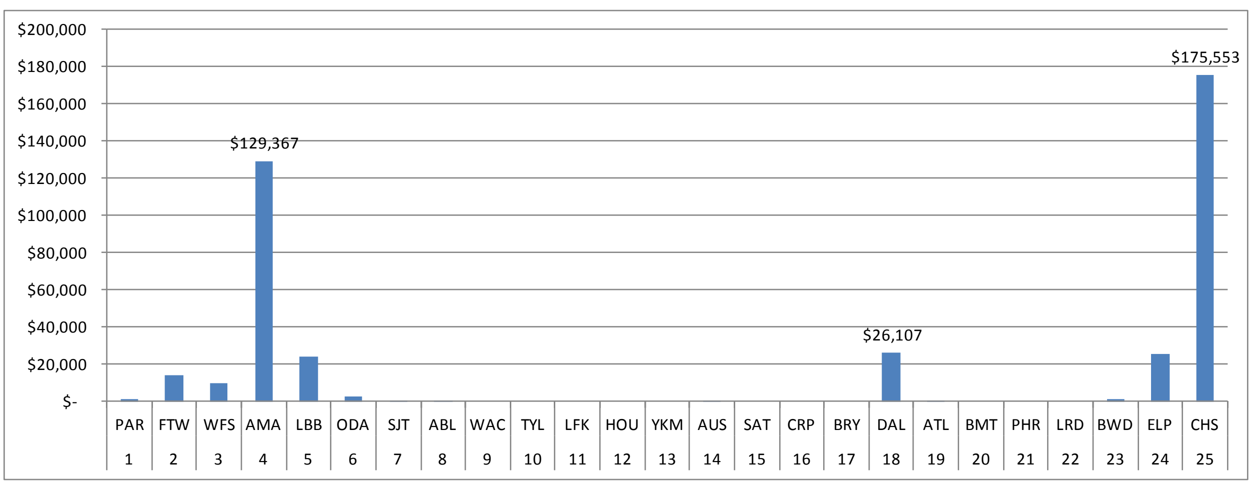


Figure 6.5 Annualized expenditure on Salt by district (2008-2012)

For Meltdown Apex™, Amarillo, Dallas and Fort Worth were among the Top 3, spending $45,079, $38,970and $30,511 respectively. Collectively, the Top 5 districts (Amarillo, Dallas, Fort Worth, El Paso, and Houston) accounted for 66% of total department expenditure whereas the Top 10 accounted for 96% (see Figure 6.6).

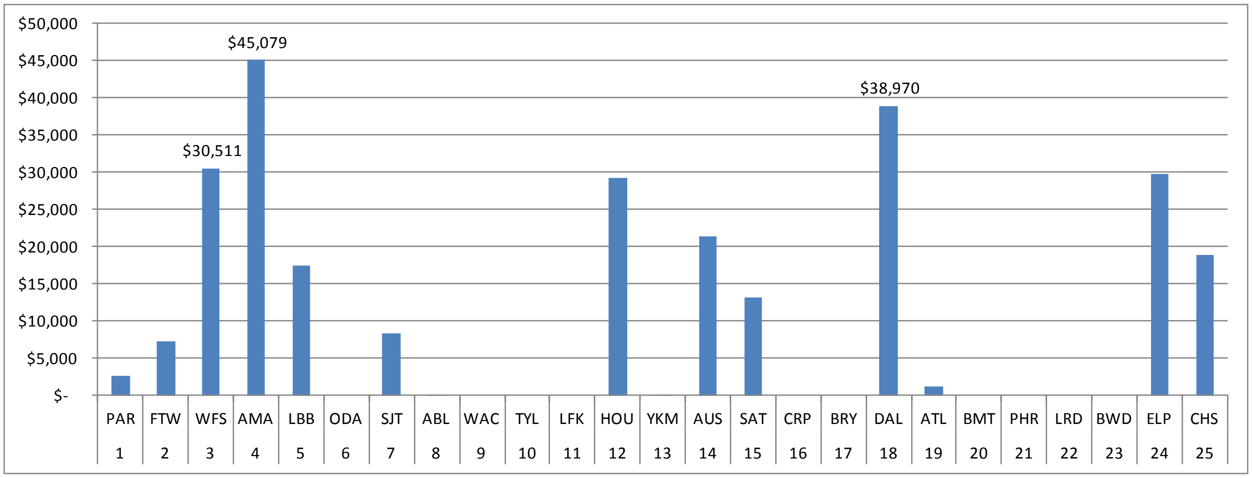


Figure 6.6 Annualized expenditure on Meltdown Apex™ by district (2008-2012)

The district-by-district expenditure on Abrasives was also tabulated over the 2008-2012 period (Figure 6.7). As Abrasives could be used during summer months for pavement treatment, the reporting on Abrasives tended to overestimate their application for snow and ice control. On average, the department spent $987,839 per year on Abrasives and Amarillo, Dallas and Wichita Falls were the three leading districts with annual expenditures of $156,090, $119,057, and $116,051 respectively. Collectively, the Top 5 districts accounted for 58% of the total department expenditures on abrasives and the Top 10 accounted for 86%.

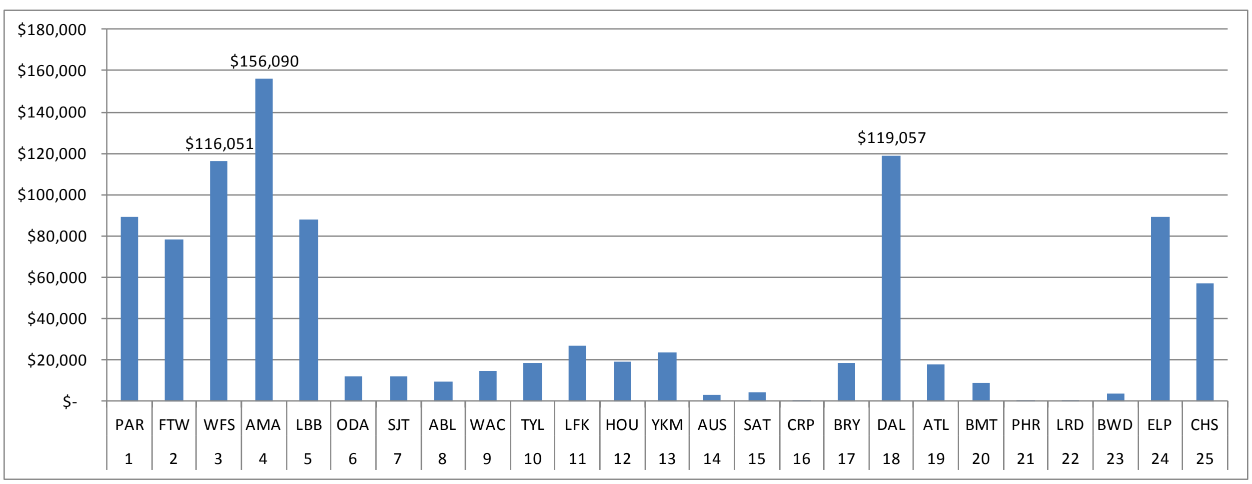


Figure 6.7: Annualized expenditure on Abrasive by district (2008-2012)

It is evident that there has been a large degree of variation in annual spending on snow and ice control materials by districts. Districts in North and West Texas often outspent their counterparts in South and East Texas although this pattern was also driven by severe weather trend that varied greatly from year to year. But a more interesting finding from the analysis was that the decision on material selection lacked consistency across the entire department. Some districts chose more proprietary products (e.g. Meltdown 20® and Meltdown Apex™) in snow and ice control applications than others without clear justifications (e.g. frequency of storms, lane-miles covered). Considering that proprietary products often cost 8 to 9 times more than road salt, there should be a need for developing a uniform method for choosing snow and ice control materials based more on documented performance and economics.

6.3. Expenditure on Snow and Ice Control Maintenance Activities by Districts

Expenditures on snow and ice control activities are captured by Function Code 811 of TxDOT's Maintenance Management Information System (MMIS). For this analysis, the MMIS data were summarized by month, district, and cost categories. This dataset provided insight to how snow and ice control activities were performed and therefore enabled a detailed analysis of the spending patterns across spatial and temporal boundaries.

First, monthly expenditures were compared using MMIS data for the same 5-year period (2008-2012). During this period, TxDOT spent $72 million in total on snow and ice control or $14.5 million per year. As shown in Figure 6.8, it is apparent that spending does not occur on a uniform basis throughout the year.

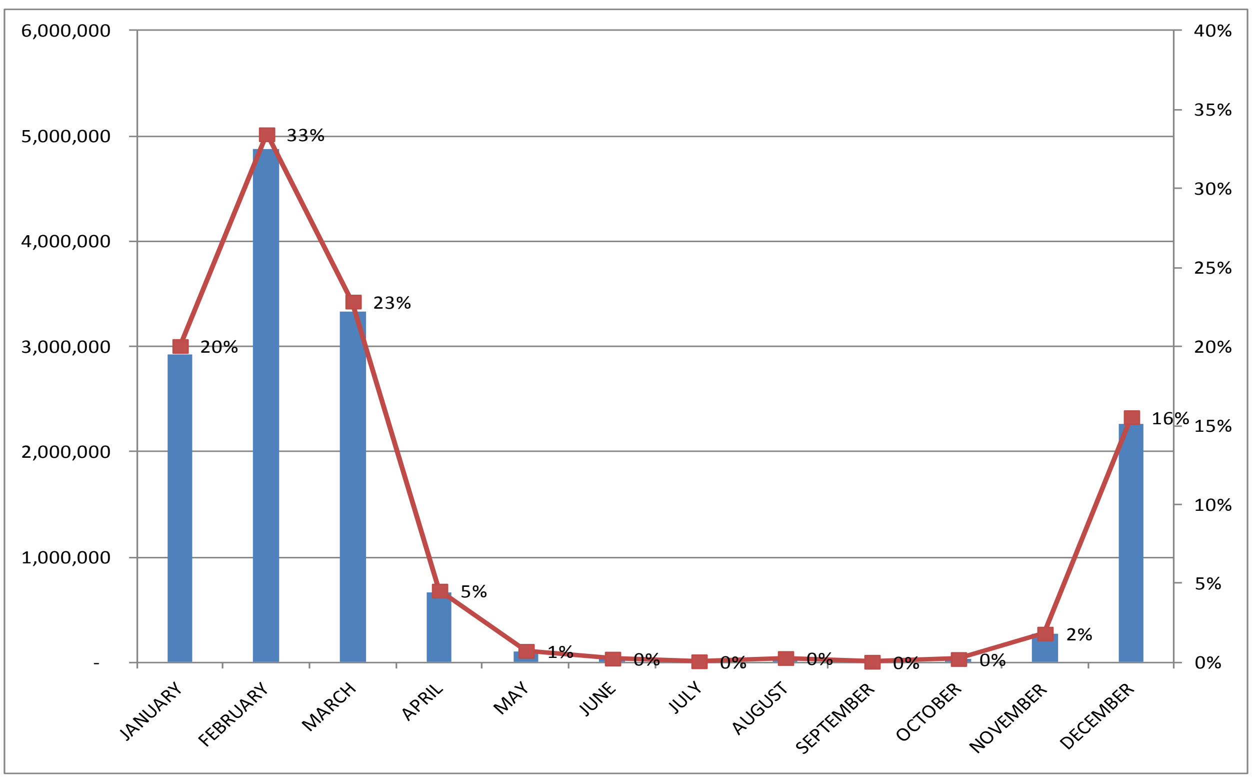


Figure 6.8. Average monthly expenditure on snow and ice control activities (2008-2012)

TxDOT spent heavily on snow and ice control in January, February, March and December and these months accounted for 20%, 33%, 23%, and 16% of the annual budget respectively. Together, they had a share of 92% of total Departmental expenditure on snow and ice control for a given year.

Similar to the pattern of spending on materials, a small number of districts accounted for the majority of Departmental expenditures for snow and ice control. The top three districts - Amarillo, Dallas, and Lubbock - spent $2,490,223, $1,511,807, and 1,415,494 a year on snow and ice control activities respectively, representing 37% of total amount by TxDOT. At the same time, the Top 10 districts (Amarillo, Dallas, Lubbock, Fort Worth, Abilene, Childress, Wichita Falls, El Paso, Paris, and Austin) collectively accounted for 80% of the total (see Figure 6.9).

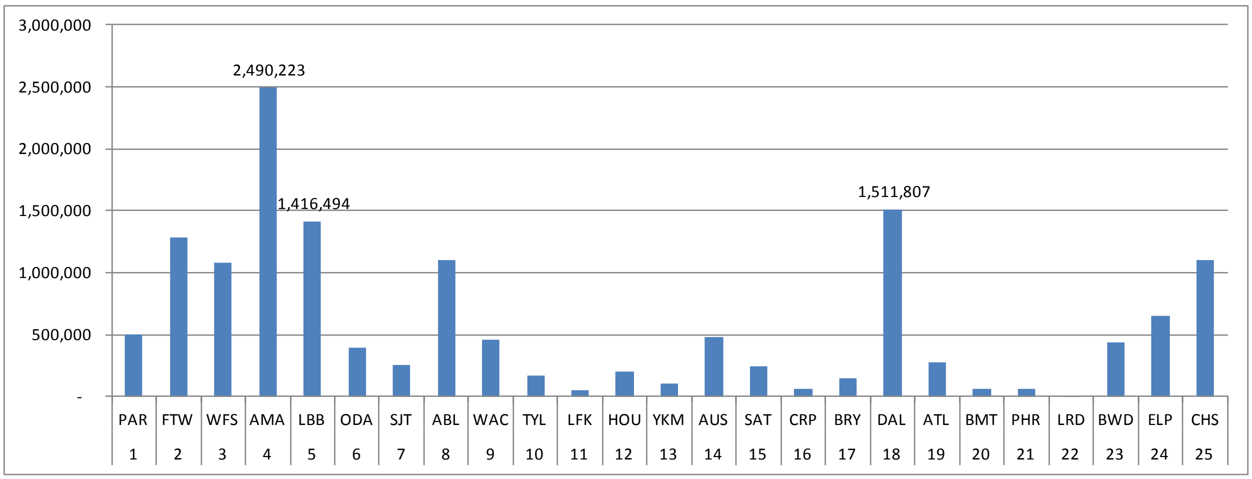


Figure 6.9: Annualized Expenditure on Snow and Ice Control Activities by Districts (2008-2012)

Total expenditure by districts on snow and ice control activities was later normalized by lane-miles maintained by each district. The normalized values were expected to better reflect each district's commitment to winter maintenance and ranged from $2 (Laredo) to $265 (Amarillo) per lane-mile (see Figure 6.10). The median value was $48 per lane-mile. Childress and Wichita Falls ranked 2nd and 3rd with $201 and $169 per lane-miles. This pattern followed closely with the classification of winter weather into three regions: mostly snow, snow and ice, and ice and freezing rain as identified in Figure 16.

While Texas as a whole ranks near the bottom among 50 states in terms of spending on snow and ice control per lane mile (see Table 2.2), it was interesting to make a comparison at the district level. The average winter maintenance costs for Amarillo, Childress, and Wichita Falls were fairly close to those for states like Tennessee ($274/lm), Kansas ($213/lm) and Arizona ($167) with the latest available data. Spending by these districts was significantly lower than that of the northern states such as Massachusetts ($10,504/lm), Rhode Island ($3,624), and New Hampshire ($3,510) as well as some bordering states including Colorado ($2,424/lm) and

Oklahoma ($307/lm). In other words, even those TxDOT districts with the most severe winter weather do not have the level exposure to snow and ice control activities comparable to many states.

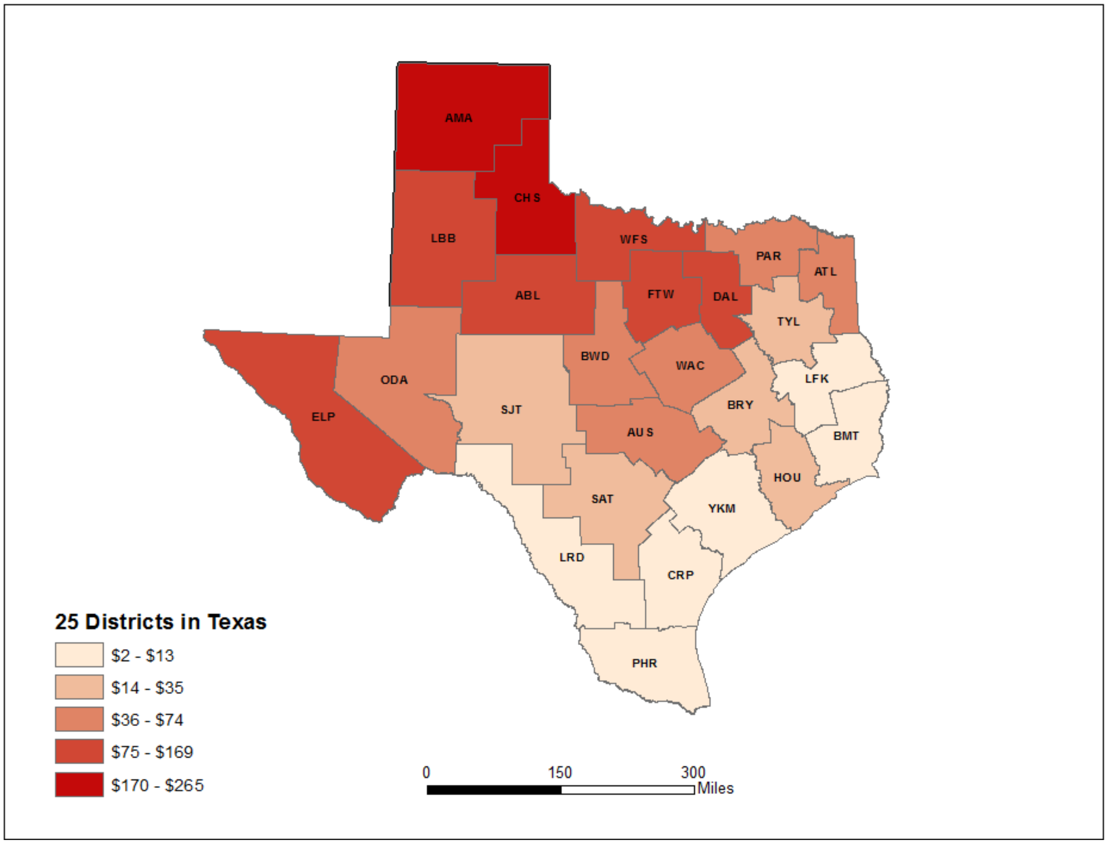


Figure 6.10. Annual expenditure on snow and ice control activities of 25 districts per lane mile

Cost data retrieved from MMIS were presented in six categories: labor, material, equipment, contractor, miscellaneous, and preparation (Figure 6.11). The majority of spending on snow and ice control went to labor (28%), material (23%), and equipment (18%) as incurred by TxDOT itself while only 2% was awarded to contractors. It is not very clear what constituted miscellaneous and preparation costs though the latter was minimal.

One measure of efficiency in construction is the operation to material (O-M) cost ratio. A lower ratio would indicate higher efficiency assuming material cost was fairly fixed. The average ratio of spending on operation (labor and equipment) to spending on material for TxDOT for snow and ice control was approximately 2 to 1. It is not surprising that the O-M ratio varied greatly by district.

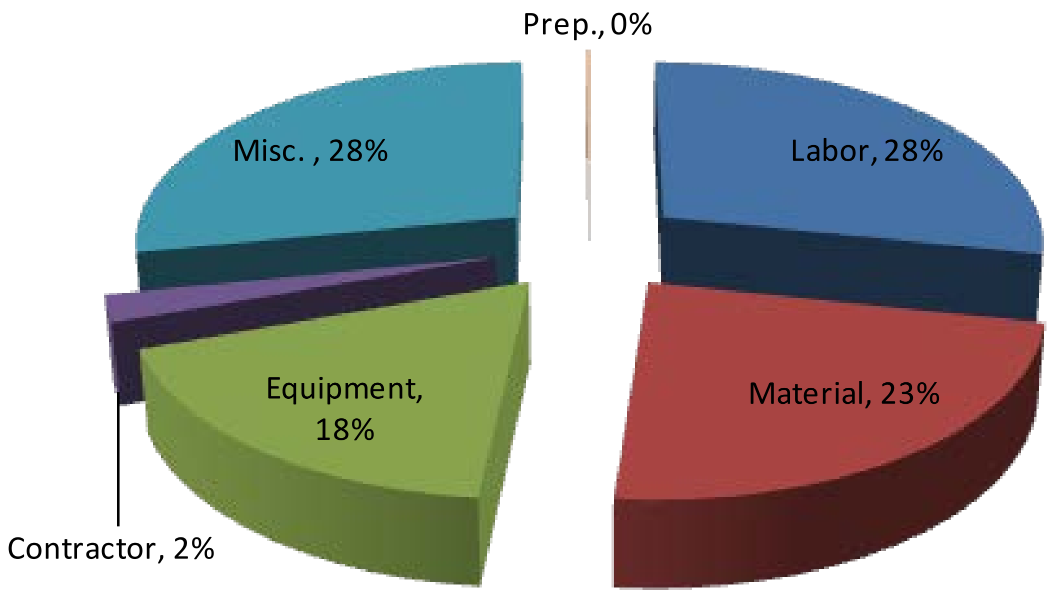


Figure 6.11: Distribution of cost categories on snow and ice control activities (2008-2012)

Figure 6.12 shows the O-M ratios for all 25 districts as compared to the Department average. The high value implied inefficiency in organizing snow and ice control activities though drawing a definitive conclusion would call for a closer examination of work orders which was beyond the scope of this project. It is noted that districts with very high values (e.g. Corpus Christi, Pharr, San Antonio, Yoakum, and Laredo) did not have much snow and ice control expenditures to start with and the abnormality could well stem from the lack of experience in planning and organizing.

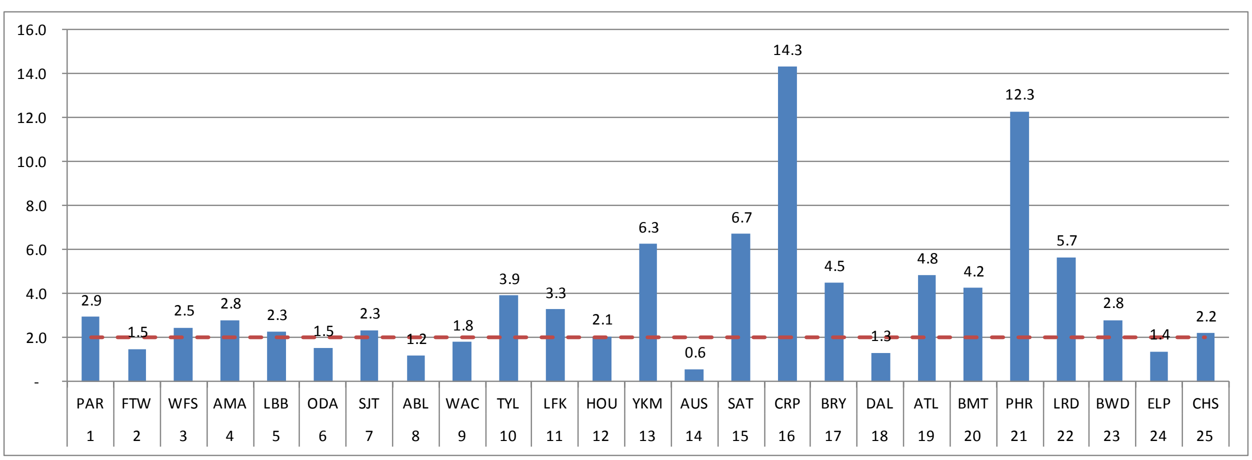


Figure 6.12: Ratio of operation to material costs by district (2008-2012). Red dashed line denotes the TxDOT average

For some heavy-spending districts such as Amarillo, Lubbock, Fort Worth and Childress, their operation to material cost ratios were fairly close to the average. At the same time, Dallas and Abilene were able to attain impressively low ratios (1.3 and 1.2 respectively) but such low numbers should not be blindly attributed to high efficiency. A closer look at the spending by Abilene revealed that the majority of their material spending (i.e. 97%) concentrated on one expensive product (Meltdown 20®), effectively increasing their material cost compared to their peers – Amarillo, Lubbock, and Fort Worth spent 26%, 65% and 74% respectively on Meltdown 20® – and consequently lowering the O-M ratio. Meantime, Dallas might deserve the credit for their low ratio as they only spent 53% of their material budget on Meltdown 20®. Therefore, a topic worth further investigation would be developing best practices for budgeting and controlling the cost of snow and ice control activities.

6.4. Primary and Secondary Materials Based on Annualized Expenditures by Districts

An analysis was conducted to examine the selection decision of snow and ice control materials by districts based on the annualized expenditures between 2008 and 2012. Table 6.1 shows the primary and secondary materials chosen by each of 25 districts.

Table 6.1: Selection of snow and ice control materials by district expenditures (2008-2012)

District		MeltDown 20®	Salt	MeltDown Apex™	Abrasive
1	PAR	**2**			**1**
2	FTW	**1**			**2**
3	WFS	**2**			**1**
4	AMA		**2**		**1**
5	LBB	**1**			**2**
6	ODA	**1**			**2**
7	SJT	**1**			**2**
8	ABL	**1**			**2**
9	WAC	**1**			**2**
10	TYL	**1**			**2**
11	LFK	**2**			**1**
12	HOU			**1**	**2**
13	YKM	**2**			**1**
14	AUS	**1**		**2**	
15	SAT			**1**	**2**
16	CRP	**2**			**1**
17	BRY	**2**			**1**
18	DAL	**1**			**2**
19	ATL	**2**			**1**
20	BMT	**2**			**1**
21	PHR	**2**			**1**
22	LRD	**2**			**1**
23	BWD	**1**			**2**
24	ELP	**1**			**2**
25	CHS		**1**		**2**

1: Primary Material; 2: Secondary Material

Overall, Table 6.1 shows that Meltdown 20® was the primary material for 11 out of 25 districts and the secondary material for 10 out of 25 districts. Salt was the primary material for 1 out of 25 districts and the secondary material for 1 out of 25 districts. Meltdown Apex™ was the primary material for 2 out of 25 districts and the secondary material for 1 out of 25 districts. Abrasives were the primary material for 11 out of 25 districts and the secondary material for 13 out of 25 districts. The primary and secondary snow and ice control materials were Meltdown 20® and Abrasives for Lubbock, and Abrasives and Salt for Amarillo.

These data (primary source by actual expenditures) were compared to findings from a study of best practices for winter weather operations by Prairie View A&M/Texas Transportation Institute (Project 0-6669) that identified the primary and secondary chemicals reported by each TxDOT District for snow and ice control (Perkins, 2012). The PVA&M/TTI study (see Table 2.8) did not separate deicing materials in the liquid form from granular form, and likely labeled Meltdown 20® and Meltdown Apex™ as $MgCl_2$. Furthermore, more than 1 product could be reported as the primary chemical and the secondary chemical. For example, Salt (NaCl), Meltdown product (20® and/or Apex™, $MgCl_2$), and Abrasive were all identified as the primary chemicals used by Lubbock and Abilene. For Amarillo, Meltdown product and Abrasive were reported as the primary chemical and Salt as the secondary one, which was somehow consistent with the expenditure data: Salt (29%), Abrasive (35%), and Meltdown product (36%). Childress reported Meltdown product and Abrasive as their primary chemical but they spent most of their budget on Salt (64%) instead of on Meltdown (14%) and Abrasive (21%). Therefore, the discrepancies between self-reported data and actual expenditures should be recognized. Besides, no data was reported for Dallas, El Paso, Fort Worth, Houston, Odessa, San Angelo, Tyler, or Waco.

6.5. Price Patterns of Snow and Ice Control Materials

The prices for the four major snow and ice control materials used in Texas - Meltdown 20®, Meltdown Apex™, Salt and Abrasive - fluctuated year to year subject to various macro and micro economic conditions and significantly affected the purchasing power of districts. The package size and order quantity also had a great effect on the unit price being paid. In the analysis, the effect of purchase unit was not considered, but the total purchase quantity made by each district was used to calculate the weighted state averages. For example, the weighted state average price for salt P_{Salt} ($/lb) in 2008 was determined by:

$$P_{Salt} = \frac{\sum_1^{25} Exp_{salt,i}}{\sum_1^{25} Qua_{salt,i}}$$

where $Exp_{Salt,i}$ ($) is the expenditure on Salt by District *i* in 2008, $Qua_{Salt,i}$ (lb) is the quantity of Salt purchased by District *i* in 2008.

The weighted value minimizes the bias from districts that paid a much higher price on small quantities.

The four panels in Figure 6.13 show yearly changes in unit prices of four materials (red lines with square markers) in comparison to RS Means Historical Cost Index (HCI, blue lines with diamond markers). The HCI used 1993 as the base year (=100) and tracked annual changes in construction costs. During the study period (2008 to 2012), HCI experienced a total increase of 7.9%.

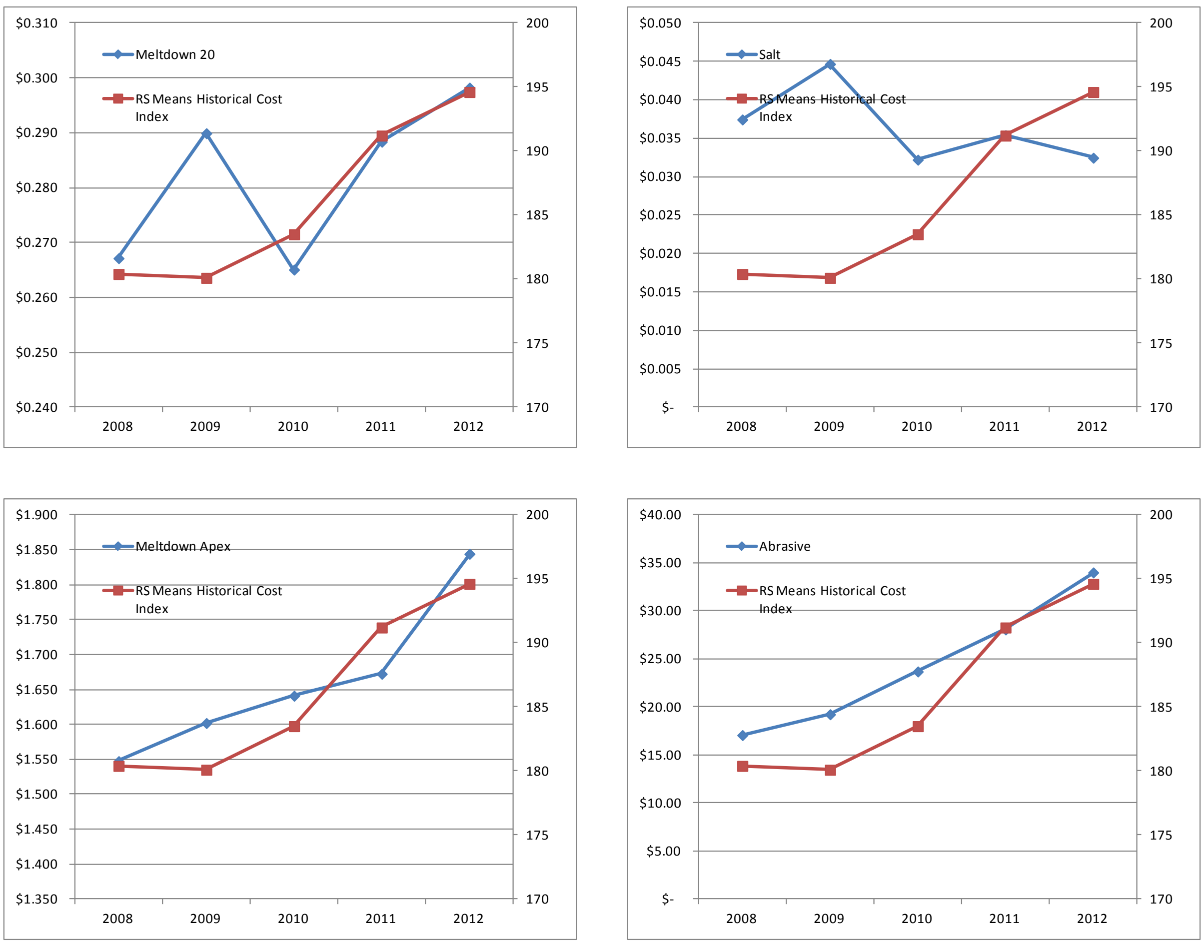


Figure 6.13: Annual change in unit prices of four snow and ice control materials in relation to construction cost in general.

For Meltdown 20®, the total price increase between 2008 and 2012 was 11.6%. The price jumped by 8.6% in 2009, from $0.267 per lb to $0.290 per lb while the HCI experienced a minor decline. In 2010, the price returned to the 2008 level and appreciated afterward similarly to HCI.

The price of salt fluctuated yearly and eventually logged a 13.5% decrease during the study period. In 2009, its price had a 21.6% increase over the previous year, from \$0.037/lb to \$0.045/lb. Since then, it dropped by 13.5% to \$0.032/lb between 2009 and 2012 while the HCI rose 8.1% during the same period.

The price trends for Meltdown Apex™ and Abrasive were more in line with that of HCI with an upward tendency. But the magnitudes were far different: Between 2008 and 2012, the price of Meltdown Apex™ changed from \$1.547/gal to \$1.844/gal, an increase of 19.2%, while the price of Abrasive changed from \$17.07/CY to \$33.99/CY, an increase of 99.1%. It showed that the unit prices of snow and ice control materials didn't respond well to the overall trend of the construction industry.

It is also observed that the unit prices for each of four snow and ice control materials were very different by district. As shown in Figure 6.14, the price range for Meltdown 20® was between \$0.212/lb (paid by Bryan) and \$0.307/lb (paid by Waco) and the average was \$0.277/lb. The Top 5 users of Meltdown 20® - Abilene, Fort Worth, Lubbock, Dallas and Austin - paid \$0.302/lb, \$0.258/lb, \$0.261/lb, \$0.294/lb, and \$0.289/lb respectively. The measure of dispersion across districts - coefficient of variation - for Meltdown 20® was 0.09.

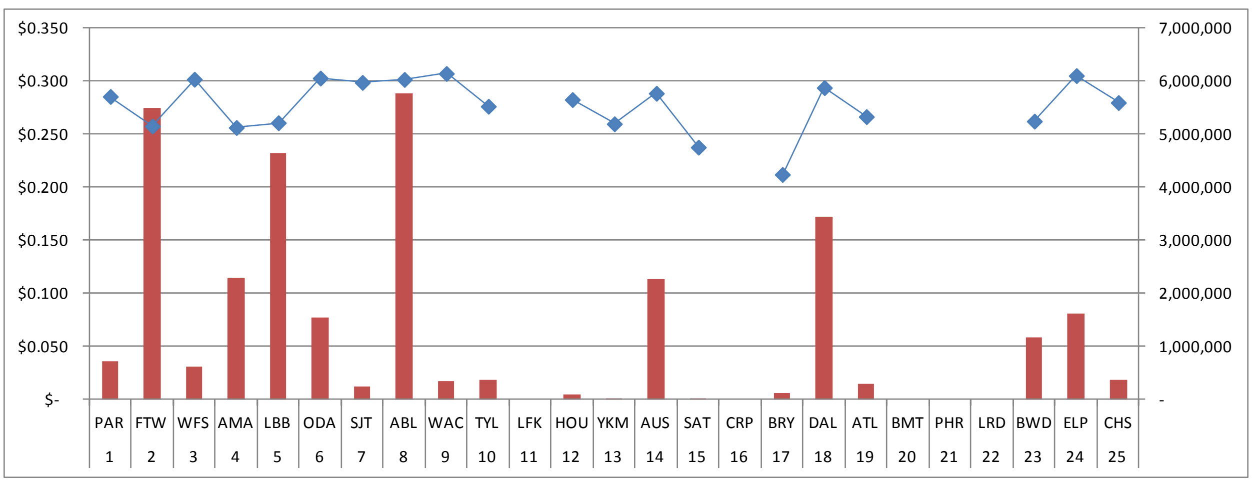


Figure 6.14 Unit prices paid by districts on Meltdown 20® (\$/lb, as denoted by blue diamond) in comparison with usage (lb, as denoted by red columns)

The unit price of Salt ranged from \$0.030/lb (paid by Abilene) to \$0.089/lb (paid by Brownwood) with the average of \$0.045/lb (see Figure 6.15). Two heavy users - Amarillo and Childress - were able to pay a lower price than other districts. The coefficient of variation for Salt was 0.34, much higher than that for Meltdown 20®. This might be attributed to salt being a common product and supplied by multiple sources. Local availability could be another factor.

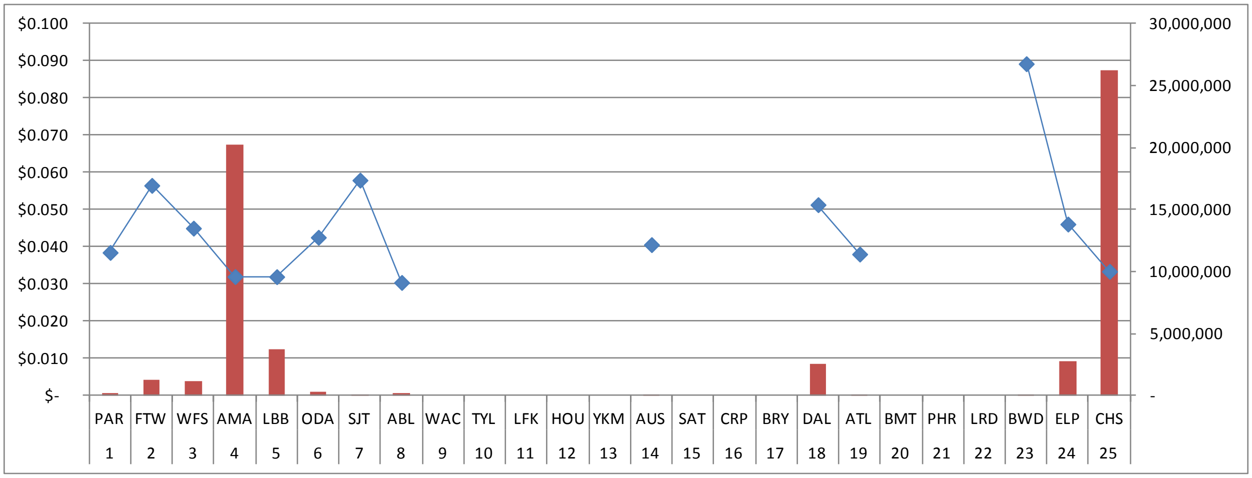


Figure 6.15. Unit prices paid by districts on salt ($/lb, as denoted by blue diamond) in comparison with usage (lb, as denoted by red columns)

The lowest, average and highest prices for Meltdown Apex™ were $1.146 (paid by Fort Worth), $1.684, and $2.208 (paid by Atlanta) per gallon (see Figure 6.16). There did not seem to be a strong correlation between unit price and usage as heavy users such as Wichita Falls, Amarillo, and Dallas all paid above-average prices. The coefficient of variation for Meltdown Apex™ was 0.17, higher than Meltdown 20® but lower than Salt.

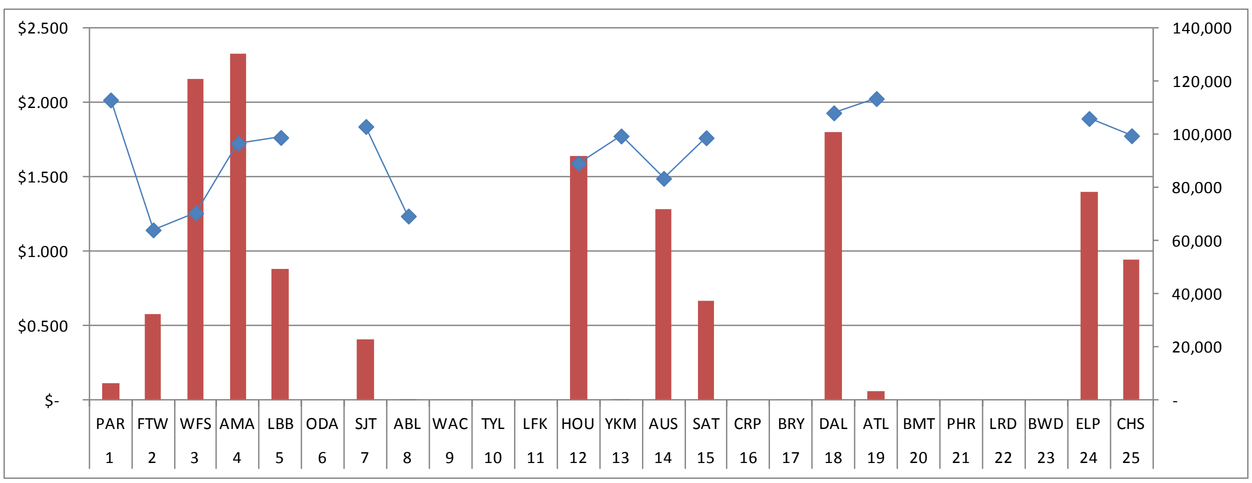


Figure 6.16 Unit prices paid by districts on Meltdown Apex™ ($/gal, as denoted by blue diamond) in comparison with usage (gal, as denoted by red columns)

The lowest, average and highest prices for Abrasive were $13.261 (paid by Brownwood), $26.977, and $53.393 (paid by El Paso) per cubic yard (see Figure 6.17). Two heavy users - Amarillo and Dallas - paid below-average prices while El Paso paid the highest and stood out as outliner. The coefficient of variation for Abrasive was 0.33. Similar to Salt, this could be attributed to multiple suppliers and local availability.

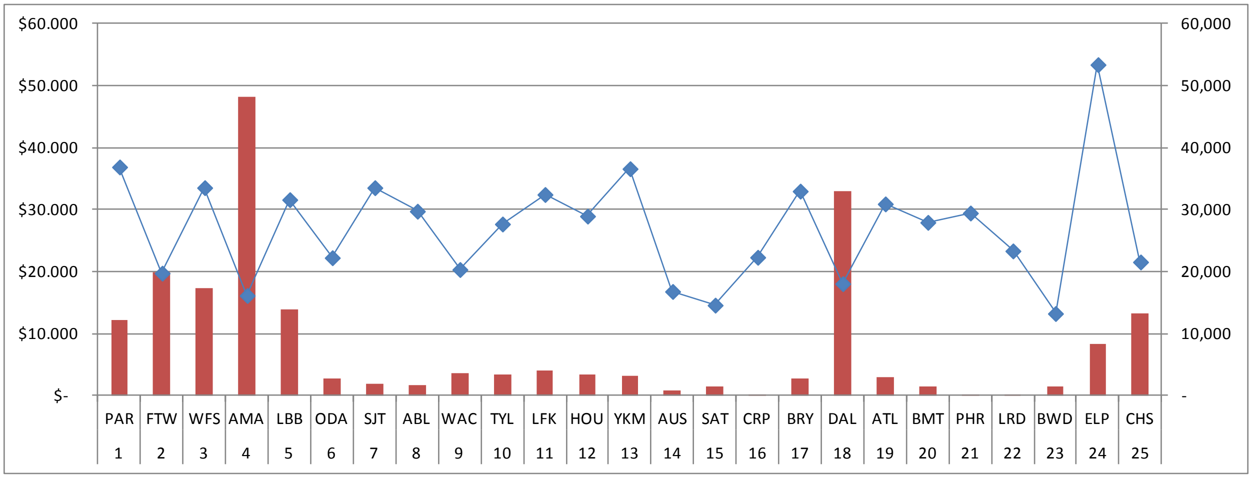


Figure 6.17 Unit prices paid by districts on abrasive ($/cy, as denoted by blue diamond) in comparison with usage (cy, as denoted by red columns)

6.6. Snow and Ice Control Expenditure in Relation to Winter Weather Patterns

The expenditure on snow and ice was closely related to weather patterns as snow and ice were removed from roadways during and after winter events. The relationship between total expenditures at the department level and the number of winter storms in a given month was plotted in Figure 6.18 for FY2007-2012 (September 2007 - August 2012).

Winter storms are defined by the National Weather Service (NWS) as weather hazards associated with freezing or frozen precipitation (freezing rain, sleet, snow) or combined effects of winter precipitation and strong winds. Typically during the period of April through November, the expenditures were minimal whereas 92% of total spending incurred in January, February, March and December. According to the data retrieved from the Storm Event Database of NOAA/NCDC, the numbers of wind storms during FY2008, 2009, 2010, 2011, and 2012 were 15, 25, 75, 88, and 18 respectively. During the same periods, the TxDOT snow and ice control expenditures were $7.9 million, $9.6 million, $22.6 million, $23.2 million, and $9.5 million which to a great extent reflected the frequency of winter storms being experienced by the state. It was found that the correlation of the snow and ice control expenditures (reported by Function Code 811 of MMIS) and the number of winter storm was 69% based on monthly data calculation, implying a strong relationship between these two variables.

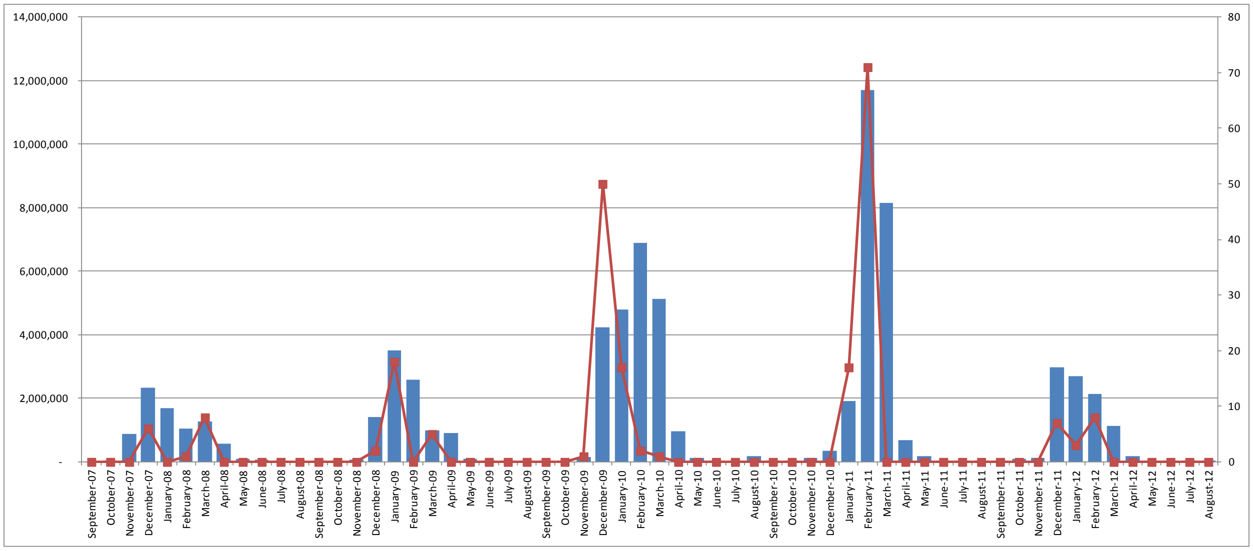


Figure 6.18 Monthly snow and ice control expenditure (Blue Columns) and the number of winter storm (Red Squares) (2008-2012)

At the same time, there were a few abnormal cases requiring attention. For example, in February of 2010, only two winter storms were reported but $6.9 million was spent on snow and ice control. Similarly, in March of 2011, no winter storm was reported but $8.1 million was spent by TxDOT. There could be several possible explanations for mismatch between snow and ice control expenditures and the number of winter storms. First, the coverage and intensity of snow precipitation might not be properly captured by the NCDC's Storm Event Database and therefore a more detailed analysis of meteorological data should be conducted with the participation of an experienced meteorologist or atmospheric scientist. Second, logging of expenses related to snow and ice control at TxDOT might not be processed in a timely manner. Discussed with TxDOT personnel in accounting could be helpful to shed light to this issue. Third, expenses may be attributed to the previous months that had heavy snowfall and subsequently required the replenishment of materials and cleanup of residuals left on roadways.

The monthly expenditure on snow and ice control activities was also examined at the district level within the weather context. According to the TTI report titled *Research on Best Practices for Winter Weather Operations*, Texas has three winter weather regions: mostly snow (MS), snow and ice (SI), and ice and freezing rain (IFR) (see Figure 2.16). Northern part of Atlanta, Amarillo, Childress, southern part of El Paso, Lubbock, northern part of Paris, and Wichita Falls fell into the most snow category. Districts including Abilene, Dallas, and Fort Worth belonged to the snow and ice categories while Austin belonged to ice and freezing rain category. Six districts were selected for the analysis including 2 MS districts (Amarillo and Lubbock), 3 SI districts (Abilene, Dallas, and Fort Worth) and 1 IFR district (Austin) all of which were in the Top 10 spenders of snow and ice control activities. The winter weather was characterized by the amount of snowfall in mm in a given month as reported by NOAA/NCDC.

Within a district, there were multiple weather stations recording snowfall and their values were averaged to represent the intensity of winter weather. These stations are presented in Figure 19.

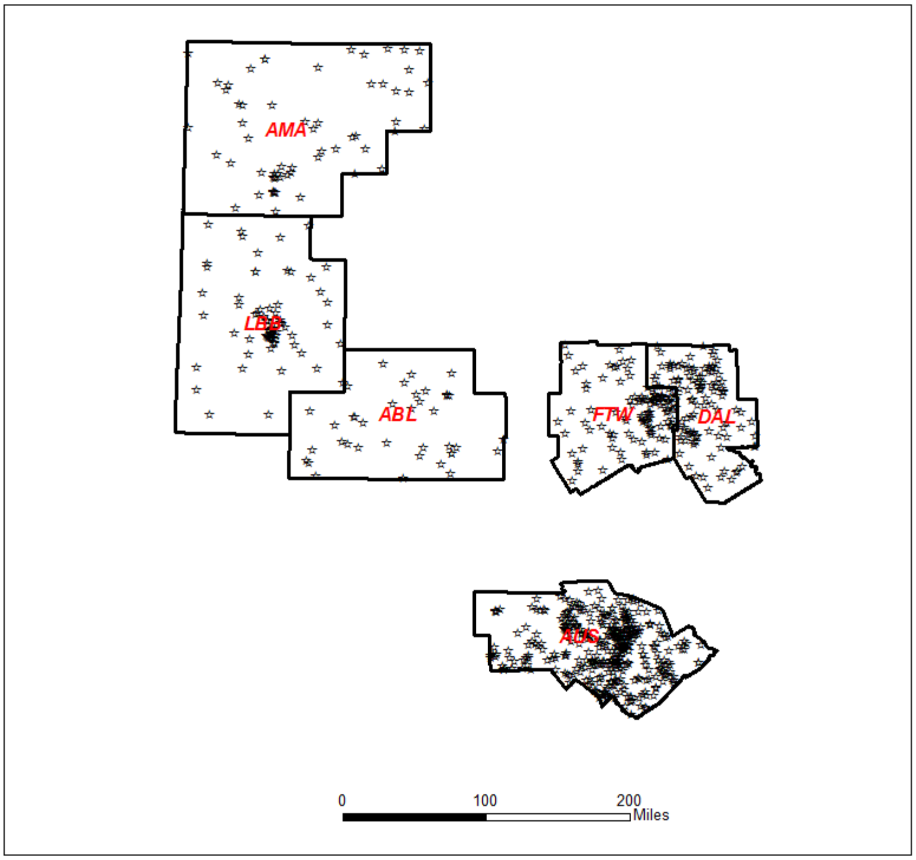


Figure 6.19 Weather stations located within Six selected TxDOT districts

The monthly snow and ice control expenditures for two mostly snow districts - Amarillo and Lubbock - are shown in Figure 6.20 and Figure 6.21. There was good degree of agreement between expenditure and snowfall as measured by correlation of 71% and 91% for these two districts respectively. In Lubbock, snowfall was a very reliable predictor for its expenditure on snow and ice control activities.

Three snow and ice districts - Abilene, Dallas, and Fort Worth - are presented in Figures 6.22 through 6.24. The correlation between the snow and ice expenditure and snowfall were 59%, 59% and 56% respectively, somewhat lower than their two counterparts in the mostly snow categories. The disagreement was more pronounced and marked by several outliers in the record. For example, the 2008/2009 winter season in Abilene received little snow but $563,490 was spent on snow and ice control in January and February. A similar pattern was observed in Dallas and Fort Worth, raising the possibility of miscoding the expenditures and/or responding to weather conditions other than snowfall. Further analysis would be required.

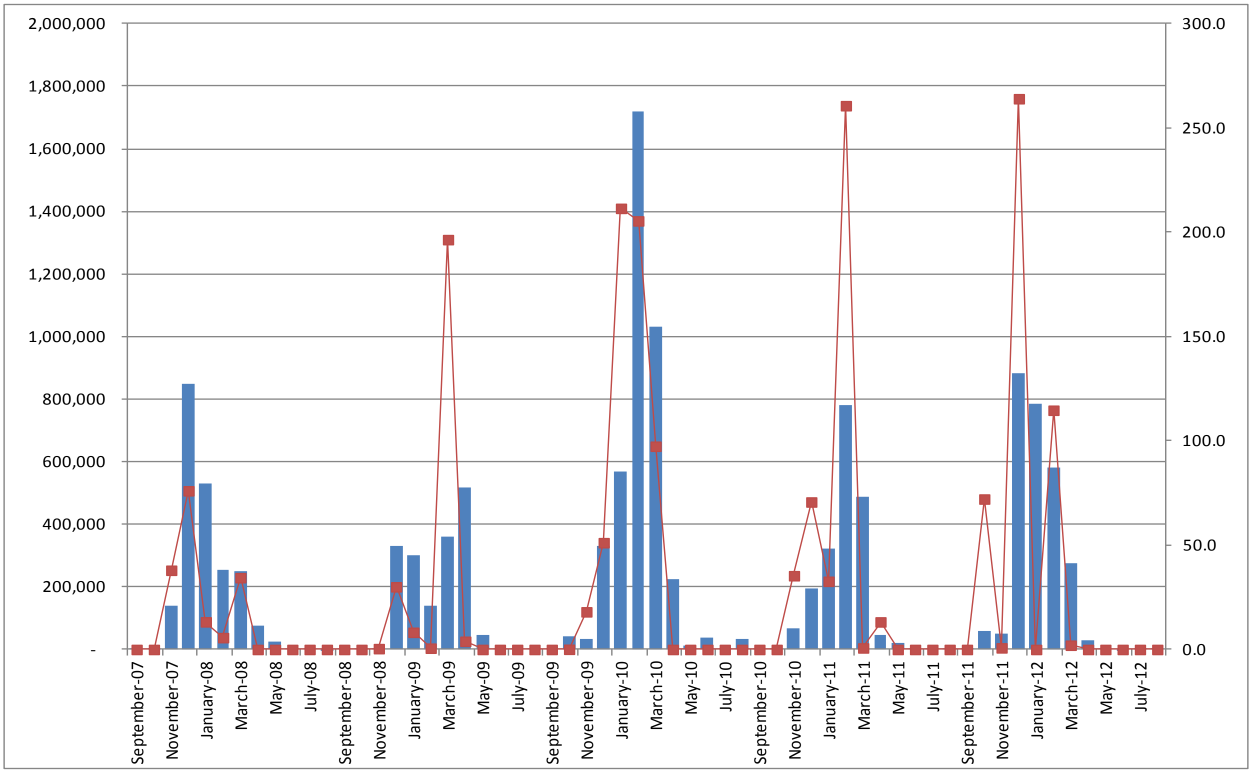


Figure 6.20. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Amarillo

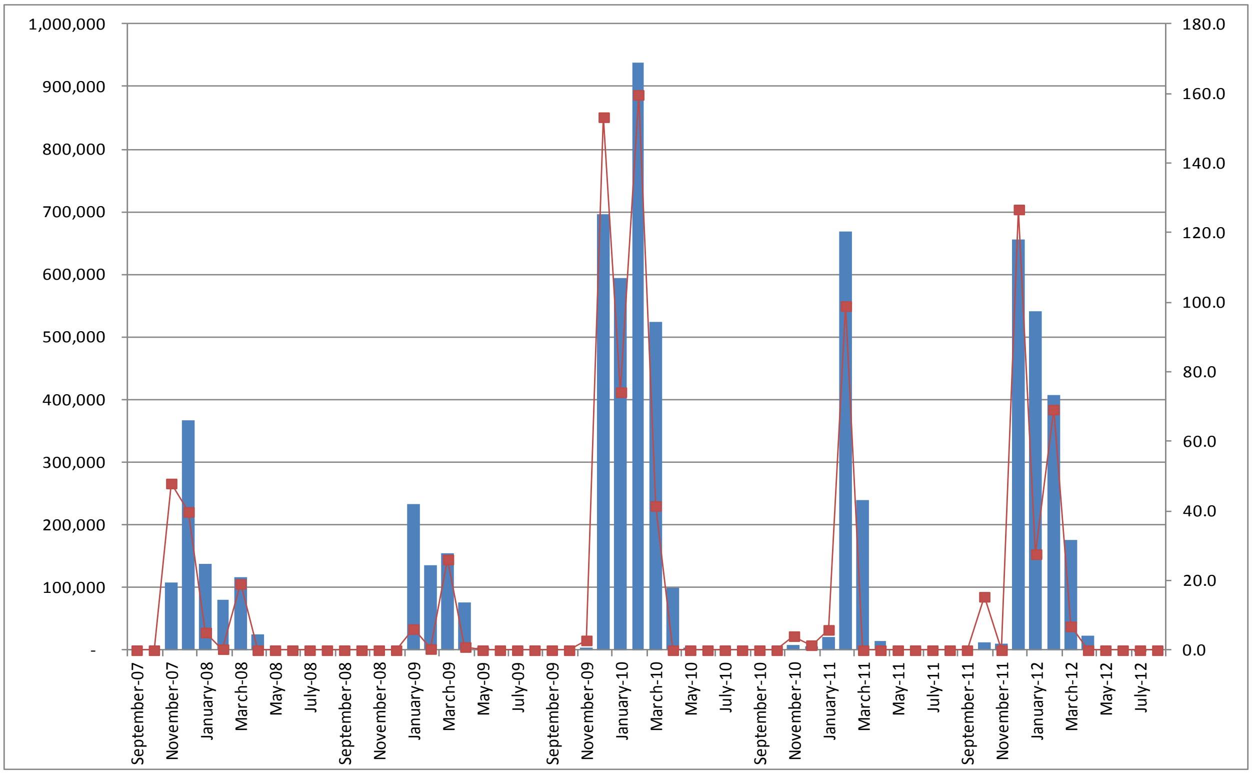


Figure 6.21. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Lubbock

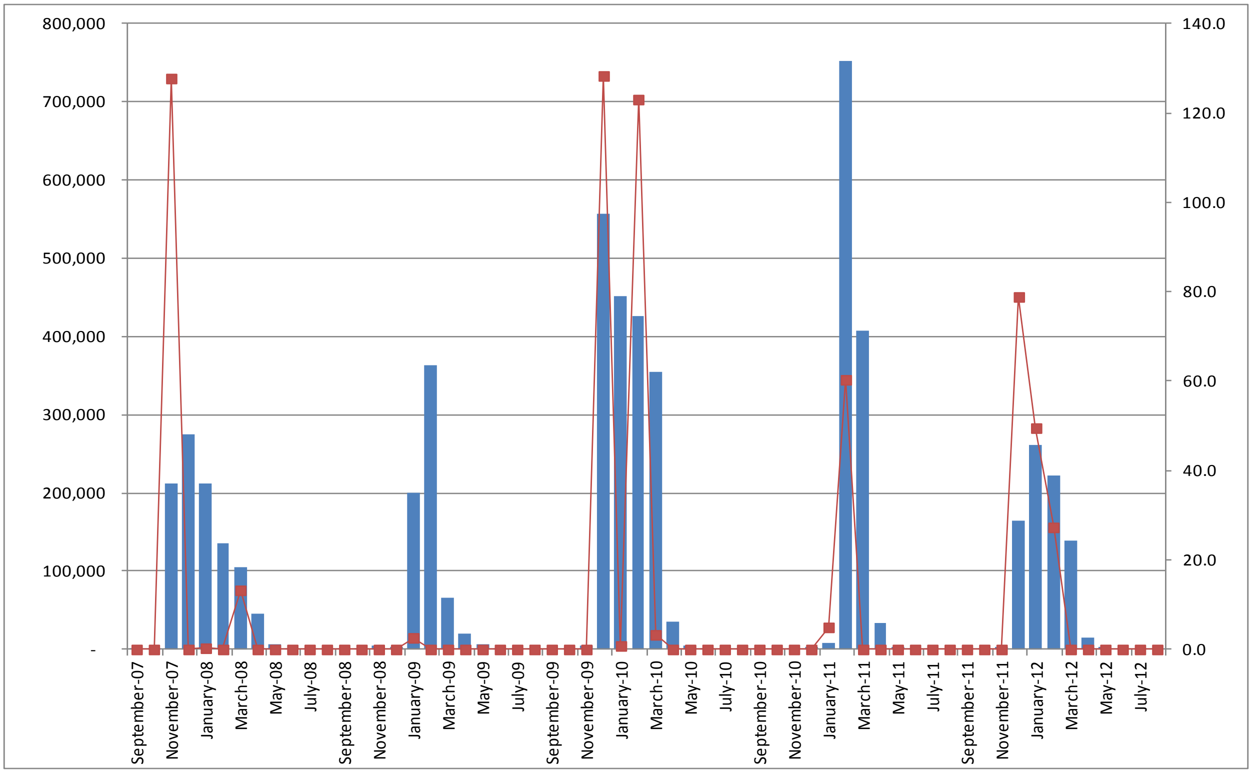


Figure 6.22. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Abilene

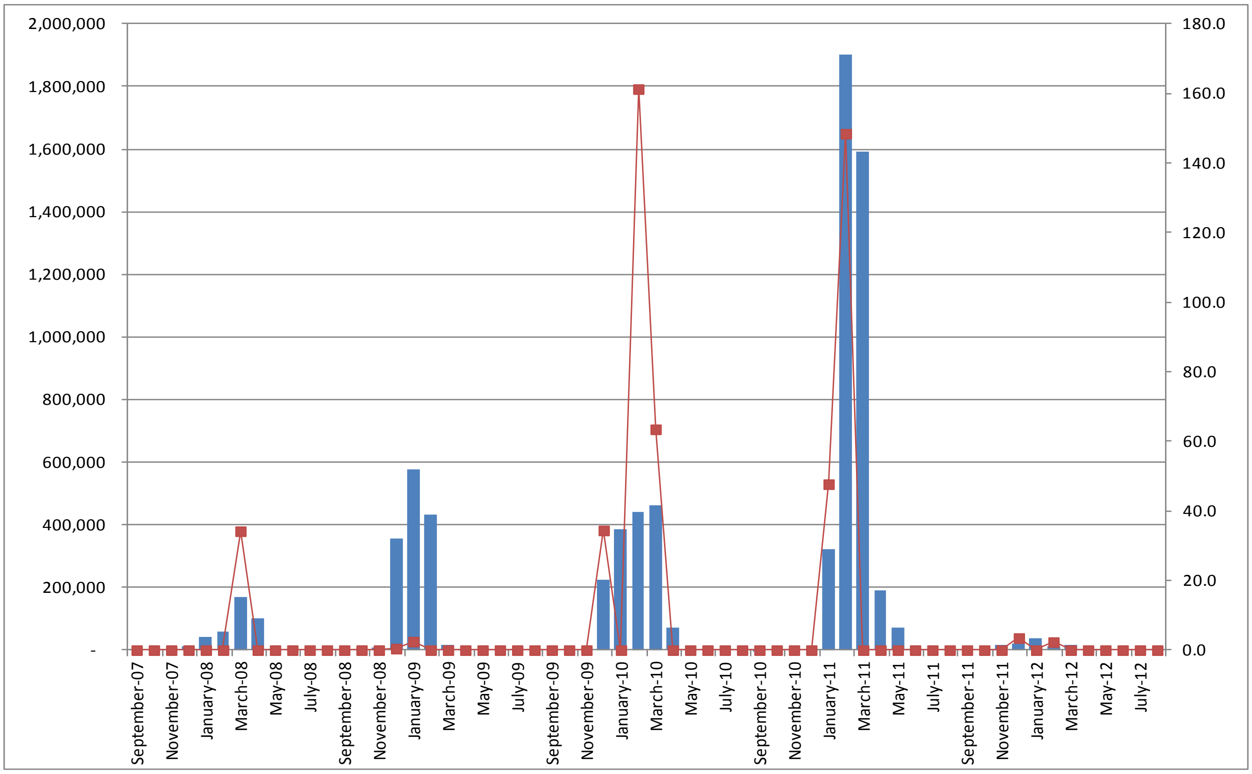


Figure 6.23. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Dallas

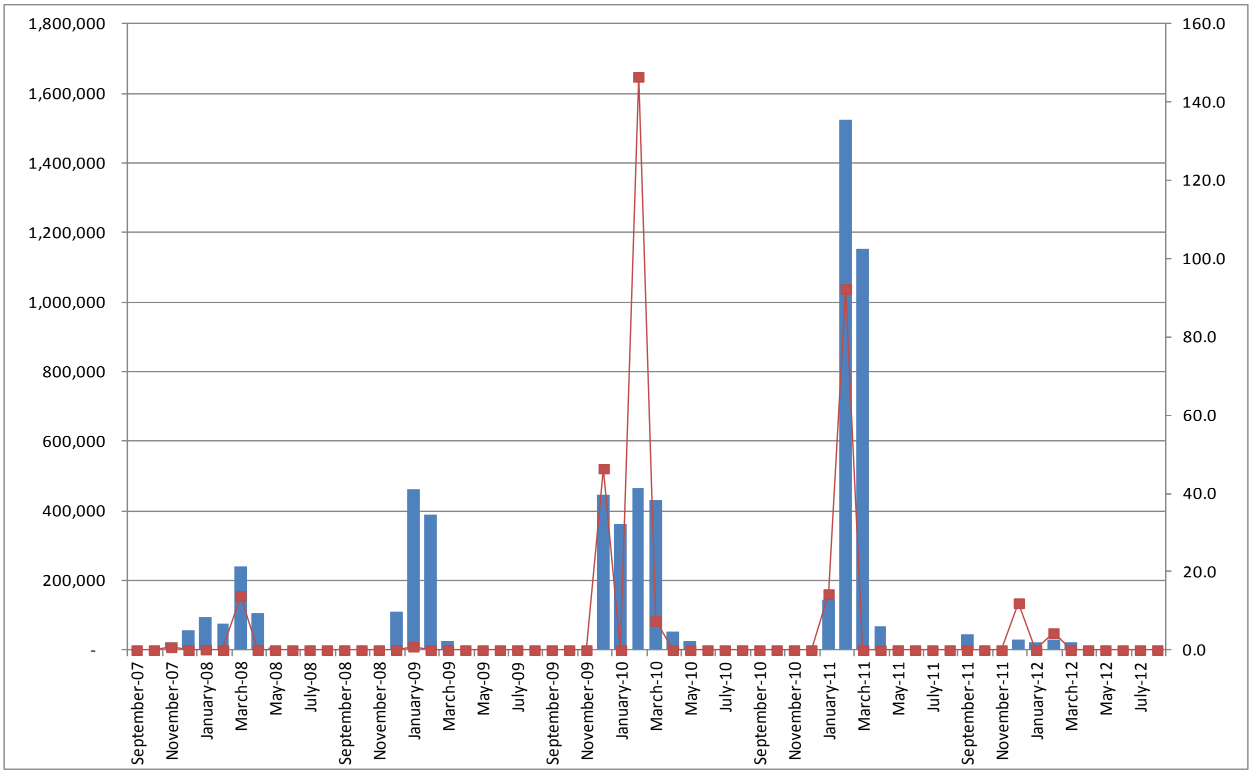


Figure 6.24. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Fort Worth

The historic February 2011 Groundhog Day Blizzard blanketed most of Texas with snow and ice during the period when Texas was hosting Superbowl XLV in the Dallas/Fort Worth Metroplex. Abilene, Dallas, and Fort Worth all spent record amounts on snow and ice control activities in February of 2011 as well as the following month on cleanups. Districts in the snow and ice region did not experience heavy snowfall and harsh winter weather on a regular basis and therefore were not as prepared as Lubbock and Amarillo. In addition, districts such as Dallas and Fort Worth served major population centers and maintained large transportation networks. The combination of less predictable weather pattern and greater exposure to severe events made Dallas and Fort Worth especially vulnerable.

The last case study focuses on Austin which is located in the ice and freezing rain region. The relationship between snow and ice control expenditure and snowfall was much weaker than for districts in the mostly snow region (e.g. Lubbock and Amarillo) with a correlation of 45% (Figure 6.25). Similar to districts in the snow and ice region (e.g. Abilene, Dallas and Fort Worth), Austin's annual expenditure was mainly driven by a few major events. Mismatch between snowfall and expenditure was observed in several instances such as the 2008 winter season during which minimal snowfall was recorded. At the same time, $154,408 (of which

$153,133 was material cost) reported in snow and ice control expenditure in August, 2010, a possible case of error.

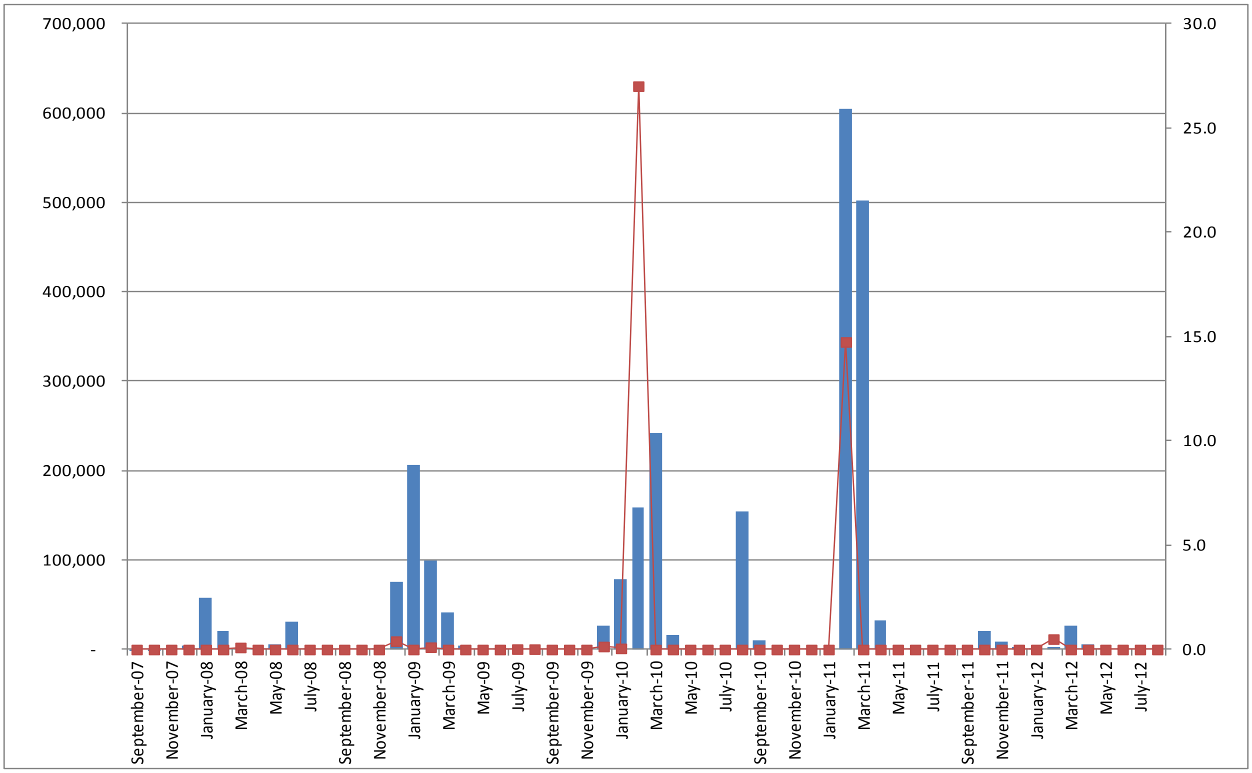


Figure 6.25. Monthly snow and ice control expenditures (in dollars, as denoted by blue columns) and amount of snowfall (in mm, as denoted by red squares) for Austin

6.7. Summary and Recommendations

The objective of the cost analysis was to establish the baseline of TxDOT snow and control expenditures and explore ways to improve efficiency and performance. The following discussions and recommendations are directed at several key areas:

6.7.1 Standardize selection of snow and ice control materials

The cost analysis identified little consistency in selecting which snow and ice control materials to use for winter roadway maintenance operations by the districts. Development of a uniform standard for TxDOT will require examination of both the performance of various products on the market and the costs (purchase, application, cleanup, and etc.). Product performance had been investigated in other tasks of this project and therefore will not be discussed in detail here. Since the project team only had access to material and operation costs (labor and equipment) aggregated to the district level, the recommendations are based on high-level observations rather than decision-making by individual TxDOT employees. Nevertheless, insight is provided for potential savings which could be attained but which might not have drawn attention before.

The following suggestions are made to better protect districts from sudden shifts in material prices:

1) Expand the list of approved products and suppliers for snow and ice control materials to improve competition

2) Establish standards on performance equivalency for intended application so that lower-priced materials can be substituted for expensive ones

3) Utilize the purchase power of the Department when negotiating with suppliers.

As an illustration, Meltdown 20® and Salt were compared to show the effect of material substitution. On average, TxDOT presently purchases 6,302,896 lbs of Meltdown 20® a year at the cost of $1,765,757. If all of the Meltdown 20® product were substituted with Salt at the ratio of 1 to 2 – the recommended application rates for deicing for Meltdown 20® and Salt are 150lb/lane-mile and 300lb/lane-mile respectively – TxDOT would have purchased 12,605,792 lb of Salt *in addition to* 11,731,254 lb they currently use at the cost of $459,144. This would represent an annual savings of $1,306,612. This comparison is based on the assumption that the costs of damage to roadways, bridges and equipment by Meltdown 20® and Salt are almost the same or the difference between them is negligible due to the low level of exposure. If better data are available on these points, the substitution ratio can be re-evaluated.

Similarly, TxDOT could achieve considerable savings by negotiating low prices with suppliers on behalf of all 25 districts. For example, the lowest and highest prices paid for Meltdown 20® were $0.212 and $0.307 per lb, with the median price at $0.281 per lb. If all districts had paid at the same low price of $0.212, the accumulated saving would be $427,795 a year for Meltdown 20® alone. The additional potential savings would be $54,307 for Salt, $81,202 for Meltdown Apex™, and $454,396 for Abrasive. Taken together, when paying the lowest prices TxDOT could have saved 30% ($1,017,699) off their annual expenditure on snow and ice control materials.

For more common materials such as Salt and Abrasives, the spread in prices paid by districts was much wider than for the proprietary products. If TxDOT leveraged its tremendous purchase power and locked in low prices on behalf of its districts before each winter season, districts wouldn't have to buy materials on the spot market and would be protected from price fluctuation. This will help districts located in the snow and ice (SI) and ice and freezing rain (IFR) regions since their usage of materials tend to be more sporadic. Consider Salt as an example. Currently, 25 districts together spent $411,500 a year and the unit prices being paid were as low as $0.030/lb and as high as $0.089/lb. If $0.030 had been a department-wide price for all districts, TxDOT would have spent $351,938 on purchasing Salt, a saving of $59,563 (14%). In the case of Abrasive, the potential saving could be as high as $454,396, or 46%.

6.7.2 Improve efficiency of snow and ice control

One measure of efficiency documented in herein was operation to material (O-M) costs ratio. Assuming material costs are fairly fixed, a lower ratio would indicate good planning and organization by districts to minimize labor and equipment expenses. Currently, only 7 districts had O-M ratios below the state average 2 to 1: Fort Worth, Odessa, Abilene, Waco, Austin, Dallas, and El Paso. If the O-M ratios for the remaining 18 lower-performing districts were brought to the state average through better training and education, the operation costs (labor and equipment) could be reduced from $6,743,865 a year to $5,501,304 a year, a saving of $1,242,561.

Another area of potential improvement is the choice between anti-icing and de-icing operations strategies. Anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice to the pavement surface by the timely application of a chemical freezing-point depressant. Anti-icing is a proactive strategy and could reduce the need and/or application rate of deicing. However, the current TxDOT MMIS did not capture anti-icing and de-icing costs in separate categories and therefore did not support an in-depth analysis on this subject. Therefore, it is recommended to create a sub-code under 811 to differentiate expenditures on anti-icing and de-icing activities.

Secondary costs of snow and ice control such as post-storm cleanup should also be better recorded in the MMIS to enable detailed analysis of TxDOT operations at the event level. When a district is hit by a major storm, costs not associated with initial responses could be long-lasting and significant. How much these costs were and over what period they occur could be important information that can be later correlated to the storm characteristics and used by districts for activity and resource planning. Therefore, it is recommended to create a sub-code under 811 to differentiate expenditures on primary and secondary snow and ice control activities.

6.7.3 Strengthen risk management practices

Winter weather, as the main driver of snow and control maintenance activities and expenditures, is inherently unpredictable. It poses a great challenge to TxDOT and its districts for making informed decisions on the appropriate level of resources allocated for a coming winter season. Especially for districts located outside the mostly snow regions, the average demand for snow and ice control was low but a severe storm (e.g. 2011 Superbowl storm) could put the whole system to its maximum stress. Risk from such low-frequency, high-impact events could be better absorbed by entities with great financial strength or distributed to a large pool of small risk-bearers.

The transfer of risk in the case of snow and ice control could be achieved in two ways. First, TxDOT may consider awarding more contracts to outside companies complementing their own capability. It is recommended that TxDOT or its districts pre-qualify contractors prior to an event and solicit bid prices from this list of contractors once an event has occurred. The solicitation for pre-qualifying contractors should define all the potential types of snow and ice control in the proposed scope of work, and the size of events for which a contract may be activated. In fact, the response to severe winter weather could be processed under the existing rules for expedited award of emergency contracts.

Second, weather risk could be transferred to large insurance companies or investors in the form of weather derivatives. Weather derivatives are financial products designed to transfer weather-related risk from individual businesses to the capital market. Such derivatives first started in the late 1990's between private parties in the over-the-counter (OTC) market. Since then, weather derivatives have been standardized and are now publicly traded on Chicago Mercantile Exchange (CME) based on a range of weather conditions in more than 45 cities in the United States, Europe, Canada, Australia and Asia. These financial products are widely used in agricultural, construction, energy and power, and insurance sectors to hedge weather risk. In Texas, temperature-based products are currently only available for Dallas.

Collaboration with meteorologists and climate scientists would enable TxDOT to better manage winter weather risks. On a short-term scale, improved forecasting of snowfall with respect to location and intensity will help districts to set up deployment plans. If the anticipated work exceeds their own capability, assistance from other districts and contractors should be requested. Over the longer term, each district should have access to a reliable outlook for the upcoming winter season and use this information to support decisions on material and equipment acquisition. For TxDOT as a whole, awareness can be raised about the future snow and ice control expenditures in the context of changing climate. How to adjust the operation to shifts in climate patterns which will alter the intensity, frequency and location of severe weather events could be a topic worth further investigation.

6.7.4 Use of performance-based models for snow and ice control

Like TxDOT’s winter maintenance practices, this cost analysis had mainly focused on input factors in terms of expenditures with the aim to make future improvements. However, the cost analyses did not address the output side which is the performance outcome resulting from snow and ice control operations. Consequently, the significant question of whether the current level of winter maintenance spending is adequate in maintaining snow and ice free roadways in Texas remains to be answered.

There are several measures of performance of transportation systems and one of them is level of service (LOS). As an example, in New York State, regular LOS should be provided to all classes of highway between 4:00 AM and 10:00 PM Monday thru Friday, and at all times on highways having Average Daily Traffic (ADT) of 50,000 vehicles per day or more. It allows a maximum accumulation of 2.0 inch during a storm and requires full width of pavement be cleared 1.5 hours after it for Highway Class A1. Modified Level of Service should be provided on all classes of highway between 10:00 PM and 4:00 AM Monday thru Friday, and all day Saturday and Sunday, except for highways with and ADT of 50,000 vehicles per day. It allows a maximum accumulation of 2.5 inch during a storm and requires full width of pavement be cleared 2.0 hours after it for Highway Class A1.

Another example is Washington State, where snow and ice operations are rated based on expected road surface conditions after the treatment. These conditions range from A (Snow or ice buildup encountered rarely. Bare pavement attained as soon as possible. Travel delays rarely experienced) to F (Compact snow buildup encountered regularly. Traveler will experience delays and slow travel).

Transition from an input-based LOS model to a performance-based LOS model for snow and ice control will yield a number of benefits to TxDOT:

- Setting clear performance goals allows TxDOT to evaluate their practices strategically and find the most cost-effective ways to utilize their resources.

- Performance-based LOS will require districts to re-evaluate their ability to meet LOS goals and adjust their budget accordingly. It will also give Districts the flexibility to deploy innovative methods in snow and control that produce better result at a lower cost.

- The public could appreciate more about TxDOT’s mission in providing safety and mobility. The concept of level of service is simple to understand and easy to communicate. In addition to surface conditions, other indicators such as traffic flow and accident count could also be included.

- Given the variability of Texas weather and Texas climate, performance-based LOS outcomes might be most appropriate to implement (at least initially) in the snowier districts where annual winter weather operations are more consistent and a more routine part of overall roadway maintenance activities.

REFERENCES

1. AASHTO. (2002). Standard Specifications for Transportation Materials and Methods of Sampling and Testing. Washington D.C: American Association of State Highway and Transportation Officials.

2. AASHTO. (2003). "Anti-Icing/Road Weather Information Systems Computer Based Training." Washington DC: American Association of State Highway and Transportation Officials. AASHTO Snow and Ice Pooled Fund Cooperative Program (SICOP).

3. ASTM International, 2013. Standard Practice for Preparation of Water Samples Using Reductive Precipitation Preconcentration Technique for ICP-MS Analysis of Trace Metals, Method D6800-12.

4. American Society for Metals. (2005). Corrosion: Materials, ASM Handbook Volume 13B. Materials Park, Ohio: ASM International Handbook Committee.

5. Andel, P., Hofman, J., Travnickova, E. (2012). "Road Salts Effects on Soil Chemical and Microbial Properties at Grassland and Forest Site in Protected Natural Areas". Research Centre for Toxic Compounds in the Environment, Faculty of Science, Masaryk University, Brno, Czech Republic

6. Arnow, Ted, Stephens, Doyle. (1990). "Hydrologic Characteristics of the Great Salt Lake, Utah: 1847-1986". United States Geological Survey, Denver, CO.

7. Baroga, E. V. (2003). Washington State Department of Transportation 2002-2003 Salt Pilot Project.

8. Benoit, D.A. (1988)." Ambient Water Quality for Chloride". Environmental Protection Agency, Duluth, MN.

9. Blackburn, R.R., K.M. Bauer, D.E. Amsler, S.E. Boselly, A.D. McElroy, (2004). *NCHRP Report 526, Snow and Ice Control: Guidelines for Materials and Methods.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

10. Bourdon, Robert H. (2001). *Best Practices of Outsources Winter Maintenance Services*. Sponsored by VMS, Inc., Richmond, VA. Report dated July 1, 2001, 67pp.

11. Brooks, R. R., Presley, B. J., and Kaplan, I. R., 1976. APDC-MIBK Extraction System for the Determination of Trace Elements in Saline Waters by Atomic-Absorption Spectrophotometry. *Talanta*, 14, 809-816.

12. CETAC Technologies, 2012. Use of the SPR-IDA Reagent for the Determination of Trace Metals in a Coastal Seawater Reference Material, Omaha, Nebraska, URL http://www.cetac.com/pdfs/SPR-IDA%20app_note.pdf, accessed September 2012.

13. CETAC Technologies, ICP-OES with the CETAC DSX-100 Preconcentration/Matrix Elimination System, Omaha, Nebraska.

14. Changnon, S. A. (2003). *Temporal and Spatial Variations of Freezing Rain in the Contiguous United States: 1948 - 2000. J. Appl. Meteor. 42, 1302 - 1315.*

15. Concrete Scaling Committee. (2002). Meeting Minutes, January 28, 2002.

16. Cuelho Eli, Jason Harwood, Michelle Akin and Ed Adams (2010). *Establishing Best Practices for Removing Snow and Ice from California Roadways.* Western Transportation Institute. California Department of Transportation Report No. CA10-1101

17. Fay, Laura., Shi, Xianming. (2012). "Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge". Water Air and Soil Pollution, Bozeman, MT.

18. Federal Highway Administration. (1997). "Is Highway Runoff a Serious Problem?". FHWA, McLean, VA.

19. Federal Highway Administration (2012). *Highway Statistics 2012.* Highway Statistics Series, Office of Highway Policy Information, U.S. Department of Transportation. Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/policyinformation/statistics/2012/ Accessed September 2015.

20. Fischel, Marion. (2001). "Evaluation of Selected Deicers Based on a Review of the Literature". The SeaCrest Group, Louisville, CO.

21. Fonnesdbech, Jens. (2001). "Ice Control Technology with 20% Brine on Highways". National Research Council, Washington, DC.

22. Guerra, K., Dahm, K, and Dundorf, S., 2011. Oil and Gas Produced Water Management and Beneficial Use in the Western United States, Science and Technology Program Report 157, U.S. Bureau of Reclamation, Denver, CO, 129 p.

23. Hackley, Keith, Kelly, Walton, Panno, Samuel. (2009). "Impacts of Road Salt on Water Resources in the Chicago Region". Southern Illinois University, Carbondale, IL.

24. Kamada, T., 2976. Selective Determination of Arsenic (III) and Arsenic (V) with Ammonium Pyrrolidinedithiocarbamate, Sodium Diethyldithioarbate and Dithizone by Means of Flameless Atomic-Absorption Spectrophotometry with a Carbon-tube Atomizer. *Talanta*, 23, 835 – 839.

25. Ketcham, S. A., L.D. Minsk, R.R. Blackburn, E.J. Fleege (1996). *Manual of Practice for an Effective Antri-Icing Program - A Guide for Highway Winter Maintenance Personnel.* Hanover, New Hampshire: U.S. Army Cold Regions Research and Engineering Laboratory, Corps of Engineers, for the Federal Highway Administration.

26. Kostick, D. S. (2011). *2010 Minerals Yearbook: Salt.* United States Department of Interior, United States Geological Survey.

27. Kotz, J. C. (2009). Chemistry & Chemical Reactivity. Belmont, CA: Thomson Brooks/Cole.

28. Kunze, A.E., Sroka, B.N. (2004). “Effects of Highway Deicing Chemicals on Shallow Unconsolidated Aquifers in Ohio- Final Report”. U.S. Geological Survey, Columbus, OH.

29. Lawson, William D. *(2012). Winter Weather Operations Training MNT812. Instructor Guide.* TxDOT Product No. FHWA/TX-12/5-9044-P3. TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX, August 2012.

30. Lawson, William D. *(2012). Winter Weather Operations Training MNT812, Student Manual.* TxDOT Product No. FHWA/TX-12/5-9044-P3. TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX, July 2012.

31. Lawson, William D. *(2012). Winter Weather Operations Training MNT812, Curriculum/Instructional Materials.* TxDOT Product No. FHWA/TX-12/5-9044-P3. TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX. July 2012.

32. Lawson, William D., (2011) *Winter Weather Management Training IPR020, Instructor Manual,* TxDOT Product No. FHWA/TX-12/5-9044-P1, TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX, September 2011.

33. Lawson, William D., (2011) *Winter Weather Management Training IPR020, Student Manual,* TxDOT Product No. FHWA/TX-12/5-9044-P1, TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX, September 2011.

34. Lawson, William D., (2011) *Winter Weather Management Training IPR020, Curriculum/Instructional Materials,* TxDOT Product No. FHWA/TX-12/5-9044-P1, TechMRT: Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, TX, September 2011.

35. Levelton Consultants, Ltd. (2006). *NCHRP Report 577: Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

36. Lewis, W.M. (1999). "Studies of Environmental Effects of Magnesium Chloride Deicer in Colorado". Western Environmental Analysts, Boulder, CO.

37. Lewis, W.M. (2000). "Preliminary Environmental Evaluation of Caliber M1000 Deicer for Use in Colorado". Western Environmental Analysts, Fort Lupton, CO.

38. Markwardt, D. (2010). TxDOT Memorandum: Summary of TxDOT Road Salt Costs.

39. Minnesota Local Research Board (2012). *Minnesota Snow and Ice Control – Field Handbook for Snowplow Operators, Second Edition.* MnDOT Office of Maintenance, St. Paul, Minnesota.

40. National Climatic Data Center. (2012). *NCDC: CLIMAPS*. Retrieved from http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl

41. National Oceanic and Atmospheric Administration. . (2001). *Climatography of the United States, No. 20, 1971 -2000.* . Asheville, North Carolina: National Climatic Data Center.

42. National Oceanic and Atmospheric Administration (2011). Snowfall Map, Groundhog Day Blizzard, January 29- February 3, 2011. http://www.noaa.gov/extreme2011/images/20110201-20110203-5.30-p.jpg Accessed September 2015.

43. National Weather Service (2007). "Winter Weather Definitions." *Directive 10-1605 "National Weather Service Instruction 10-1605: Storm Data Preparation*. National Oceanic and Atmospheric Administration, National Climatic Data Center, Storm Events Database.

44. Nixon, W.A., Williams, A.D. (2001). "A Guide for Selecting Anti-Icing Chemical". Iowa Institute of Hydraulic Research, Iowa City, IA.

45. Pacific Northwest Snowfighters. (2010). Pacific Northwest Snowfighters Snow and Ice Control Chemical Products Specifications and Test Protocols for the PNS Association of British Columbia, Colorado, Idaho, Montana, Oregon and Washington. Retrieved from http://pnsassociation.org/wp-content/uploads/PNSSPECS.pdf

46. Perkins, J.A., J. Mwakalonge, D. Jasek, J. Carson, K. Obeng-Boampong, and G. Pesti. (2012). *Research on Best Practices for Winter Weather Operations*. Prairie View A&M University and Texas Transportation Institute. Report 0-6669-1, October 2012.

47. Revie, R. W. (2008). Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering. Hoboken, NJ: Wiley-Interscience.

48. Salt Institute. (2004). "Highway Salt and our Environment". Alexandria, VA.

49. Schneider IV, W. (2014). *Evaluation and Analysis of Liquid Deicers for Winter Maintenance,* funded by the Ohio Department of Transportation (research in process).

50. Shi, Xianming, Ning Xie, Yudong Dang, Anburaj Muthumani, Jiang Huang, Adam Hagel, Shane Forsythe, Elizabeth Selig, Dustin Falk, Eli McVey, Amanda Kessel, Callie Martins, Yan Zhang, and Yida Fang (2014). *Understanding and Mitigating Effects of Chloride Deicer Exposure on Concrete*, Western Transportation Institute Final Report SPR 742. Oregon Department of Transportation Report No. FHWA-OR-RD-08.

51. Shi, X., Y. Li, S. Jungwirth, Y. Fang, N. Seeley, and E. Jackson (2013). *Identification and Laboratory Assessment of Best Practices to Protect DOT Equipment from the Corrosive Effect of Chemical Deicers.* Western Transportation Institute. Washington State Department of Transportation Report No. WA-RD 796.1.

52. Shi Xianming, Laura Fay, Chase Gallaway, Kevin Volkening, Marijean M. Peterson, Tongyan Pan, Andrew Creighton, Collins Lawlor, Stephanie Mumma, Yajun Liu, and Tuan Anh Nguyen (2009). *Evaluation of Alternate Anti-icing and Deicing Compounds Using Sodium Chloride and Magnesium Chloride as Baseline Deicers-Phase 1.* Western Transportation Institute. Colorado Department of Transportation Report No. CDOT-2009-1.

53. Shi Xianming, Laura Fay, Keith Fortune, Robert Smithlin, Matthew Johnson, Marijean M. Peterson, Andrew Creighton, Zhengxian Yang, Doug Cross (2011). *Investigating Longevity of Corrosion Inhibitors and Performance of Deicer Products under Storage or after Pavement Application*. Western Transportation Institute. Washington State Department of Transportation Report No. WA-RD 759.1

54. Shi Xianming, Yajun Liu, Matthew Mooney, Michael Berry, Barrett Hubbard, Laura Fay, and Andrea Beth Leonard (2010). *Effect of Chloride-based Deicers on Reinforced Concrete Structures*. Western Transportation Institute. Washington State Department of Transportation Report No. WA-RD 741.1

55. Silberberg, M. S. (2006). Chemistry: The Molecular Nature of Matter and Change. Boston: McGraw-Hill.

56. Speer, Scott (2012). Personal Communication. Meeting with Bill Lawson, Sanjaya Senadheera, and Scott Huson, Austin, TX: May 21, 2012.

57. Thompson, D.B., Morse, A.N., Acker, J. (2009). "Analysis of the Occurrence and Statistics of Hazardous Materials Spill Incidents Along Texas Highways and Suggestions for Mitigation of Transport-Related Spills to Receiving Waters" Center for Multidisciplinary Research in Transportation, Texas Tech University, Research Report 0-5200-1.

58. TxDOT (2014). *Maintenance Management Manual.* Texas Department of Transportation: Austin, TX.

59. TxDOT (2010). *Maintenance Operations Manual.* Texas Department of Transportation: Austin, TX.

60. TxDOT (2012). *Snow and Ice Control Operations Manual.* Texas Department of Transportation: Austin, TX.

61. U.S. Environmental Protection Agency, 1994. Method 200.8 Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Mass Spectrometry. URL: http://water.epa.gov/scitech/methods/cwa/bioindicators/upload/2007_07_10_

62. methods_method_200_8.pdf. Last accessed August 2013.

63. U.S. Environmental Protection Agency, 1994. Method 200.9 Determination of Trace Elements by Stabilized Temperature Graphite Furnace Atomic Absorption. Rev. 2.2. URL: http://water.epa.gov/scitech/methods/cwa/bioindicators/upload/2007_07_10_

64. methods_method_200_9.pdf. Last accessed August 2013.

65. U.S. Environmental Protection Agency, 2009. National Primary Drinking Water Standards. URL: http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf. Last accessed August 2013.

66. U.S. Geological Survey, 2002. Produced Waters Database, Central Energy Data Management. URL: http://energy.cr.usgs.gov/prov/prodwat/data2.htm. Last accessed June 2012.

67. Washington State DOT (2013). *Nationwide Salt Map: Salt Price Comparison and Usage Based on 2012-2013 State Survey*. http://www.wsdot.wa.gov/NR/rdonlyres/DFEBFA2B-5A42-49BA-82A9- Accessed September 2015.

68. Welch, R. and Rychel, D., 2004. Produced Water from Oil and Gas Operation in the Lower 48 States, White Paper – Phase I, U.S. Department of Energy National Energy Technology Laboratory, Contract No. DE-AD26-01NT00249, 100 p.

69. West, R. E., Hime, W. G. (1985). *Chloride Profiles*

APPENDIX A

Pacific Northwest Snow Fighters (PNS)

Qualified Product List PRODUCTS

Date of Listing: November 24, 2015

Pacific Northwest Snow Fighters (PNS) Qualified Product List - PRODUCTS
Date of Listing: November 24, 2014

Category 1 - Corrosion Inhibited Liquid Magnesium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Iceban 200*	Earth Friendly Chem.	8.4	26%	8/15/2002
Caliber M1000 AP	Envirotech Services Inc.	20.8	28%	8/2/2004
Meltdown with Shield AP	Envirotech Services Inc.	25.9	30%	8/2/2004
Hydro-Melt Green	Cargill	24.3	28.5%	8/1/2005
Meltdown APEX with Shield AP	Envirotech Services Inc.	25.1	30%	1/25/2006
FreezGard CI Plus	North American Salt	12.2	30%	8/28/2006
Ice B'Gone II HF	Sears Ecological Appl.	28.6	25%	8/9/2007
FreezGard LITE CI Plus	North American Salt	12.3	27%	6/13/2011
HydroMelt Liquid Deicer	Cargill	28	28.6%	8/15/2011
FreezGard CI Plus Sub Zero	North American Salt	14.1	27.5%	10/11/2011
Ice Ban 305	GMCO Corporation	25.3	26.6%	1/10/2013
FreezGard 0 CCI	GMCO Corporation	21.2	30.0%	1/10/2013
Meltdown Apex	Envirotech Services Inc.	22.4	30.0%	4/16/2014
Meltdown Inhibited	Envirotech Services Inc.	24.1	30.0%	4/29/2014

Note-Iceban 200 was formerly Iceban Performance Plus M
Those products marked with an asterisk (*) indicates that the stratification can be seen and agitation is required.

Category 2 - Corrosion Inhibited Liquid Calcium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Liquid Dow Armor	Dow Chemical	26	30%	6/25/1999
Winter Thaw DI	Tetra Technologies	16.5	32%	9/13/1999
Corguard TG	Tiger Calcium Services	27.7	29%	1/9/2001
Road Guard Plus	Tiger Calcium Services	16	25%	6/5/2006
Calcium Chloride with Boost (CCB)	America West	18.4	32%	4/10/2014

Category 3 - Non Corrosion Inhibited Liquid Calcium Magnesium Acetate

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Liquid CMA 25%	Cryotech	-11	25%	5/19/1998
SC CMA 25%	Sure Crop Farm Services	-2.8	25%	9/13/1999

Category 4 - Corrosion Inhibited Solid Sodium Chloride

Category 4A- Corrosion Inhibited Solid Sodium Chloride (Corrosion Percent Effectiveness of 30% or less)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Inhibited Ice Slicer	Envirotech	30	N/A	5/19/1998
CG-90 Non-Phosphate 2.8%	Cargill	27	N/A	5/19/1998
IMC CI SALT A 3.5	North American Salt	28	N/A	8/21/2001
IMC CI SALT B 4.5	North American Salt	18.6	N/A	8/21/2001
Clear Lane PNS Enhanced Deicer	Cargill	28.9	N/A	8/1/2005
Ice Slicer Elite	Envirotech	16	N/A	8/1/2005

Category 4B- Corrosion Inhibited Solid Sodium Chloride (Corrosion Percent Effectiveness 31% to 85%)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Ice Slicer RS	Redmond	80	N/A	10/13/2009
Ice Slicer Super Blend Plus	Redmond	60.4	N/A	10/13/2009

Category 5 - Corrosion Inhibited Sodium Chloride Plus 10% Magnesium Chloride (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CG-90 Surface Saver 10%	Cargill	15	N/A	5/19/1998
Meltdown 10	Envirotech	30	N/A	5/19/1998
Surface Saver PNS 10%	Cargill	27.2	N/A	8/21/2001

Category 6 - Corrosion Inhibited Sodium Chloride Plus 20% Magnesium Chloride (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CG-90 Surface Saver 22%	Cargill	26	N/A	5/19/1998
Meltdown 20	Envirotech	27	N/A	8/8/2000
Surface Saver PNS 20%	Cargill	22	N/A	8/21/2001

Category 7 - Calcium Magnesium Acetate (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CMA	Cryotech	-7	96%	5/19/1998

Category 8 - Non Corrosion Inhibited Solid Sodium Chloride

CATEGORY 8A-B Standard Gradation, Brining Salt, Insoluble Material less than 1%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
DriRox Coarse Salt*	North American Salt			9/21/2012
Bulk Coarse Solar	Morton Salt			4/21/2006
Intrepid Coarse Salt	Intrepid Potash			6/3/2010

* Product was renamed from NASC Salt (Coarse). The product has been approved since 8/2000.

CATEGORY 8A-R Standard Gradation, Road Salt, Insoluble Material less than 10%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Cargill Dry Salt	Cargill			6/1/1998
Mineral Melt	NSC Minerals			6/1/1998
DriRox Coarse Salt*	North American Salt			9/21/2012
Kayway Salt (Coarse)	Kayway Industries			12/23/2003
Bulk Coarse Solar	Morton Salt			4/26/2005
Ice Slicer Super Blend	Redmond Mineral			8/2/2006
ISCO Bulk Rock Salt	K+S			6/23/2008
Natural Alternative Ice Melt	NaturaLawn of America			5/17/2010
Intrepid Coarse Salt	Intrepid Potash			6/3/2010

* Product was renamed from NASC Salt (Coarse). The product has been approved since 8/2000.

CATEGORY 8B - Insoluble Material less than 10%, and Moisture less than 5.0%.

Product Name	Manufacturer		%Moisture	Date Approved
Ice Slicer RS	Redmond Mineral		1.95	2/9/2003
QwikSalt	North American Salt		2.54	6/30/2004
Type C Treated Salt	Broken Arrow		2.94	8/2/2004
SS-5.0	Shelton's Salt		0.90	9/16/2004
Bulk Type C Road Salt	Morton Salt		2.63	4/26/2005
ESSA Salt	ESSA		0.84	6/26/2007
Rapid Thaw	Broken Arrow		2.49	3/4/2009
Bulk Deicing Salt	Central Salt		2.39	6/24/2013

CATEGORY 8C-B Fine Gradation, Brining Salt, Insoluble Material less than 1%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Mineral Melt	NSC Minerals			3/1/2006
Quick Brine RF	NSC Minerals			3/1/2006
Rocanville Standard Road Salt	NSC Minerals			10/6/2006
Medium Solar Salt	North American Salt			8/12/2009
Mixing Solar Salt	North American Salt			8/12/2009
Intrepid Medium Salt	Intrepid Potash			6/3/2010

CATEGORY 8C-R, Fine Gradation, Road Salt, Insoluble Material less than 10% and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Mineral Melt	NSC Minerals			3/1/2006
Quick Brine VS	NSC Minerals			3/1/2006
Quick Brine RF	NSC Minerals			3/1/2006
Rocanville Standard Road Salt	NSC Minerals			10/6/2006
Medium Solar Salt	North American Salt			8/12/2009
Mixing Solar Salt	North American Salt			8/12/2009
Intrepid Medium Salt	Intrepid Potash			6/3/2010
Ice Slicer Near Zero	Redmond Minerals			12/3/2010

Category 9 - Corrosion Inhibited Liquid Sodium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Salt Brine + Brine CI	Cargill	25.4	23.3	8/12/2009
Brine with Headwaters Inhibitor	Rivertop Renewables	25.6	22.5	11/24/2014
Brine with Headwaters 10F Inhibitor	Rivertop Renewables	26.7	22.4	11/24/2014

Category 10 - Corrosion Inhibited Liquid Sodium Chloride Plus Calcium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
TC Econo*	Tiger Calcium Services	20.5	20/2 (1)	8/12/2009
Beet Heet Severe	K-Tech Specialty Coatings	21.1	15.3/5.4 (2)	7/13/2011
ESB	America West	21.0	18.8/2.3 (3)	4/14/2014
SO-CAL	Custom Spray Services	27.8	20.8/2.5 (4)	4/14/2014

1 - 20% NaCl and 2% $CaCl_2$

2 - 15.3% NaCl and 5.4% $CaCl_2$

3- 18.8% NaCl and 2.3% $CaCl_2$

4 - 20.8% NaCl and 2.5% $CaCl_2$

Category 11 - Corrosion Inhibited Liquid Chloride Blended Brines

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Road Guard Plus*	Tiger Calcium Services	16	27 (1)	8/12/2009
Road Guard TC	Tiger Calcium Services	21.3	32.1 (2)	8/12/2009
Road Guard XCEL	Tiger Calcium Services	20.3	33.2 (3)	8/12/2009
IB 7/93-Thermapoint	Millennium Roads	24	26.7 (4)	5/1/2013

1 - 25% Calcium Chloride and 2% Magnesium Chloride
1 - 27.3% Calcium Chloride and 4.8% Magnesium Chloride
2 - 28.5% Calcium Chloride and 4.7% Magnesium Chloride
4 - 17.8% Calcium Chloride, 5.4% Sodium Chloride, and 3.5% Magnesium Chloride
Those products marked with an asterisk (*) indicates that the stratification can be seen and agitation is required.

PNS Experimental Category - Approved Liquid Corrosion Inhibited Products

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CF-7	Cryotech	0.0	50[1]	6/20/2001
CMAK	Cryotech	0.0	12.5/25[2]	6/20/2001
NC 3000	Glacial Technologies	-3.5	25[3]	3/13/2002
Alpine Ice-Melt	Nachurs Alpine Sol. Ind.	-4.8	50[4]	6/23/2008
Fusion 60/40	Eco Solutions	22.1	15.0[5]	11/23/2009
Beet Heet Concentrate***	K-Tech	14.8	21.7[6]	9/26/2012
AquaSalina+	Nature's Own Source	26.4	22.5[7]	9/19/2013
Isoway	Omex Environmental	-5.1	25.0[8]	4/15/2014
Geomelt S7	SNI Solutions	25.9	18.1[9]	4/17/2014
SOS AP***	Envirotech Services	21.0	26.0[10]	4/18/2014
SOS Inhibited***	Envirotech Services	25.3	26.0[11]	8/28/2014
AQ+IceBite Liquid Brine Deicer	Nature's Own Source	11.4	20.4[12]	8/28/2014
Ecolution Liquid Deicer	State Industrial Products	26.5	24.6[13]	8/28/2014
Ice Bite S	Road Solutions Inc.	15.0	22.1[14]	10/21/2014
XO-Melt$_2$	K-Tech	22.9	24.5[15]	11/3/2014
Husker Plus***	Smith Fertilizer and Grain	10.2	36[16]	11/24/2014

1 - 50% Potassium Acetate
2 - 12.5% Calcium Magnesium Acetate and 25% Potassium Acetate
3 - The product contains a 25% Potassium Acetate concentration. The product also contains 30% Carbohydrate material which is still under consideration as an active ingredient but at this time has not be included.
4 - 50% Potassium Acetate
5 - 15.0% Sodium Chloride, blend of 60% Fusion/ 40% Salt Brine
6 - Total Chloride Salt Blend with $CaCl_2$-11.9%, $MgCL_2$- 3.4%, KCL-2.7%, NaCl-3.7% . Carbohydrate content-28.8%. ***Material approved as a pre-wet material to solid salt. Not for direct application as a liquid deicer.
7 - Total Chloride Salt Blend with $CaCl_2$-9.0%, $MgCL_2$- 2.5%, and NaCl-11.0% .
8 - 25% Potassium Acetate
9 - 18.1% Sodium Chloride, blend of 30% Geomelt 55/ 70% Salt Brine.
10 - 26.0% $MgCl_2$ with a thicking additive. ***Material approved as a pre-wet material to solid salt. Not for direct applications as a liquid deicer.
11 - 26.0% $MgCl_2$ with a thicking additive. ***Material approved as a pre-wet material to solid salt. Not for direct applications as a liquid deicer.
12 - Total Chloride Salt Blend with NaCL-13.0% and $CaCl_2$-7.4%, blended with 15% IceBite.
13 - Total Chloride Salt Blend with $CaCl_2$-9.8%, $MgCL_2$- 2.3%, and NaCl-12.5% .
14 - 22.1% Sodium Chloride.
15 - Total Chloride Salt Blend with CaCl2-12.3%, MgCL2- 2.1%, and NaCl-10.1% .
16 - 36% Mixed Matrix Organic Salt Compounds derived from Sugar. ***Material approved as a pre-wet material to solid salt. Not for direct application as a liquid deicer.

Pacific Northwest Snow Fighters (PNS) Qualified Product List - INHIBITORS
Date of Listing: July 18, 2014

Category A1 - Corrosion Inhibitor for Sodium Chloride Brine (Minimum 21% NaCl)

Product Name	Manufacturer	% NaCl		% Additive	Class	% Effectiveness	Date Approved
ArctiClear CI Plus	North American Salt	21.2		5	1	21.3	12/3/2010
Headwaters Corrosion Inhibitor	Rivertop Renewables	22.5		3.5	1	24.9	4/15/2014
Shield GLT Plus	Paradigm Chemical	22.6		5	1	28.7	4/15/2014
Headwaters 10F Corrosion Inhibitor	Rivertop Renewables	22.4		4.5	1	26.7	7/18/2014

Category A2 - Corrosion Inhibitor for Sodium Chloride and Calcium Chloride Brine (Minimum 15% NaCl & 2% $CaCl_2$)

Product Name	Manufacturer	% NaCl	% $CaCl_2$	% Additive	Type/Class	% Effectiveness	Date Approved
Boost SB	America West	18.8	2.3	20	I / 2	21.0	4/14/2014

Category A3 - Corrosion Inhibitor for Sodium Chloride (Minimum 15% NaCl)

Product Name	Manufacturer	% NaCl		% Additive	Class	% Effectiveness	Date Approved
ArtiClear Gold	North American Salt	18.8		15	2	26.6	12/3/2010
Beet 55 Concentrate	Smith Fertilizer & Grain	17.2		35	2	23.1	9/19/2013
Geomelt 55	SNI Solutions	18.1		30	2	25.9	4/17/2014

APPENDIX B

Characteristics of Typical Snow and Ice Control Chemicals

Characteristics of Sodium Chloride

SODIUM CHLORIDE			
Symbol	**Eutectic Temperature**	**Effective Temperature**	**Cost***
NaCl	-6°F at 23.3% by weight	20°F	\$40 - \$50 per ton

Form	Solid colorless crystals or white granules	**Surface Effects**	Dries completely; endothermic

Environmental and Infrastructure Concerns

Human

- Potential for minor eye, skin, respiratory, and gastrointenstinal effects
- Low acute oral toxicity (assuming concentrations less than 230 ppm)

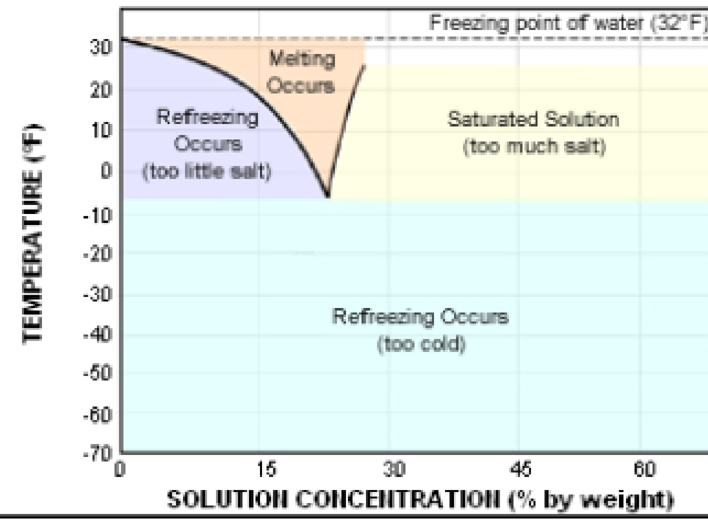
Plants, Animals and Aquatic Life

- May damage vegetation
- May decrease stability of some types of soil
- Increases salinity of soil and water
- May attract wildlife onto roads contributing to road kills
- Low toxicity to aquatic life (assuming concentrations less than 230 ppm)

Infrastructure Impact

- Spalling of concrete
- Corrosive to steel

Phase Diagram



Characteristics of Magnesium Chloride

MAGNESIUM CHLORIDE

Symbol	Eutectic Temperature	Effective Temperature	Cost*
$MgCl_2$	-28°F at 21.6% by weight	-10°F	$120 per ton

Form	Typically liquid (30%); white crystals also available	Surface Effects	Significant residual; exothermic

Environmental and Infrastructure Concerns

Human

- Potential for minor eye, skin, respiratory, and gastrointestinal effects
- Low acute oral toxicity (dependent on concentration)

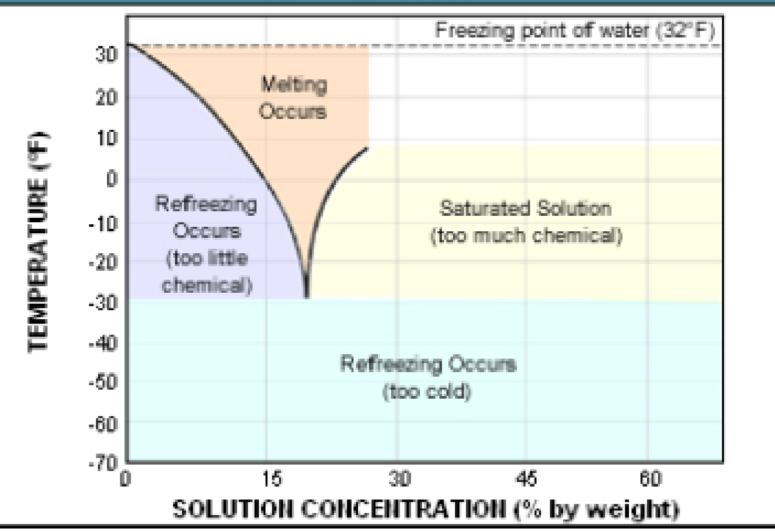
Plants, Animals and Aquatic Life

- Damage to vegetation
- Low toxicity to aquatic life (dependent on concentration)
- Increases salinity of soil and water

Infrastructure Impact

- Minimal spalling to concrete
- Potential negative effects on aluminum

Phase Diagram



Characteristics of Calcium Chloride

CALCIUM CHLORIDE

Symbol	Eutectic Temperature	Effective Temperature	Cost*
$CaCl_2$	-59°F at 29.8% by weight	-20°F	$130 per ton

Form	Flakes (70-80%), pellets (92-98%), liquid (32%+)	Surface Effects	Leaves moist film; exothermic

Environmental and Infrastructure Concerns

Human

- Potential for minor eye, skin, respiratory, and gastrointestinal effects
- Low acute oral toxicity (dependent on concentration)

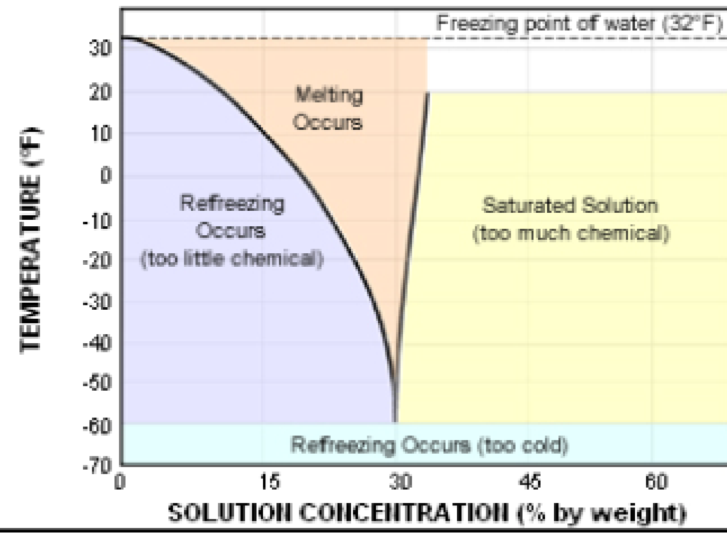
Plants, Animals and Aquatic Life

- Damage to vegetation
- Low toxicity to aquatic life (depending on concentration)
- Increases salinity of soil and water

Infrastructure Impact

- Minimal spalling to concrete
- Slightly corrosive to steel
- Potential for increased nitrates in drinking water

Phase Diagram



Characteristics of Calcium Magnesium Acetate

CALCIUM MAGNESIUM ACETATE

Symbol	Eutectic Temperature	Effective Temperature	Cost*
CMA	-17.5°F at 32.5% by weight	20°F	$1150 per ton

Form	White pellets or granular	Surface Effects	Has residual effect; endothermic

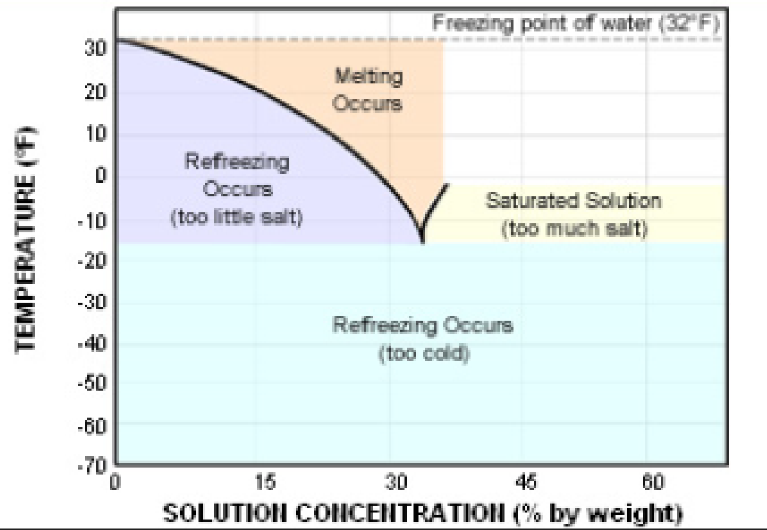
Environmental and Infrastructure Concerns

Human
- Potential for minor eye, skin, respiratory, and gastrointestinal effects
- Low acute oral toxicity (dependent on concentration)

Plants, Animals and Aquatic Life
- Minimal damage to vegetation
- Low toxicity to aquatic life (dependent on concentration)
- Potential for oxygen depletion in soil and water

Infrastructure Impact
- Non-corrosive

Phase Diagram



Characteristics of Potassium Acetate

POTASSIUM ACETATE			
Symbol	**Eutectic Temperature**	**Effective Temperature**	**Cost***
KAc	-76°F at 50% by weight	-13°F	$1000 per ton

Form	Typically liquid (50%); crystals & flakes available	**Surface Effects**	Slight slippery effect; endothermic

Environmental and Infrastructure Concerns

Human

- Potential for minor eye, skin, respiratory, and gastrointestinal effects
- Low acute oral toxicity (dependent on concentration)

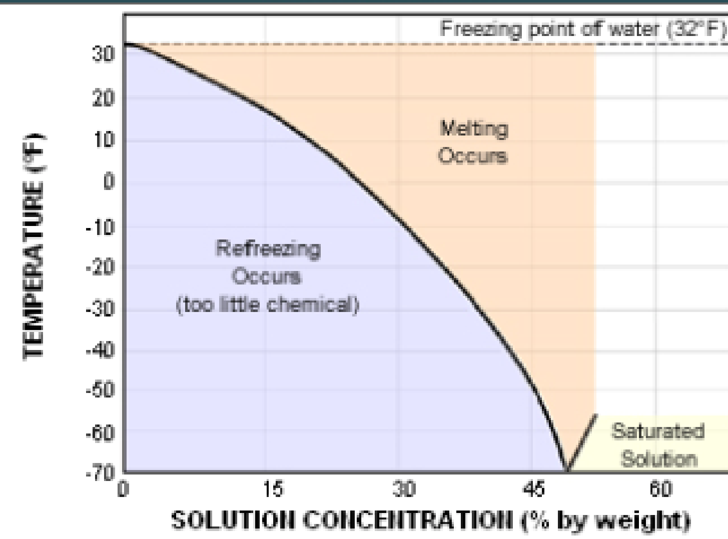
Plants, Animals and Aquatic Life

- Minimal damage to vegetation
- Moderate toxicity to aquatic life (dependent on concentration)
- Potential for oxygen depletion in soil and water

Infrastructure Impact

- No corrosion to steel if corrosion inhibitors added

Phase Diagram



Melting Potential Examples for Standard Snow and Ice Control Materials[1]

Temperature		NaCl		$CaCl_2$		$MgCl_2$		CMA		KAc	
		BC[2] (%) =23		BC (%) =32		BC (%) =30		BC (%) =25		BC (%) =50	
°F	°C	EC[3] (%)	MP[4]	EC (%)	MP	EC (%)	MP	EC (%)	MP	EC (%)	MP
30	-1.1	1.9	11.3	2.5	11.7	2.1	13.4	5.0	4.0	5.0	9.0
29	-1.7	2.8	7.2	3.7	7.7	3.0	8.9	6.0	3.2	6.0	7.3
28	-2.2	3.7	5.2	4.8	5.7	3.9	6.7	7.0	2.6	7.0	6.1
27	-2.8	4.6	4.0	5.7	4.6	4.7	5.4	8.0	2.1	8.0	5.3
26	-3.3	5.4	3.2	5.7	4.6	5.3	4.7	9.0	1.8	9.0	4.6
25	-3.9	6.3	2.7	6.4	4.0	6.0	4.0	10.0	1.5	10.0	4.0
24	-4.4	7.1	2.2	7.0	3.6	6.7	3.5	11.0	1.3	11.0	3.5
23	-5.0	7.9	1.9	8.0	3.0	7.3	3.1	11.9	1.1	12.0	3.2
22	-5.6	8.7	1.7	9.0	2.6	8.1	2.7	12.7	1.0	13.0	2.8
21	-6.1	9.4	1.4	9.5	2.4	8.6	2.5	13.5	0.9	13.5	2.7
20	-6.7	10.1	1.3	10.0	2.2	9.0	2.3	14.4	0.7	14.0	2.6
19	-7.2	10.8	1.1	10.5	2.0	9.5	2.2	15.0	0.7	15.0	2.3
18	-7.8	11.5	1.0	11.0	1.9	10.0	2.0	15.8	0.6	16.0	2.1
17	-8.3	12.2	0.9	11.5	1.8	10.4	1.9	16.5	0.5	16.5	2.0
16	-8.9	12.8	0.8	12.0	1.7	10.8	1.8	17.2	0.5	17.0	1.9
15	-9.4	13.4	0.7	12.5	1.6	11.1	1.7	17.7	0.4	17.5	1.9
14	-10.0	14.1	0.6	13.0	1.5	11.4	1.6	18.3	0.4	18.0	1.8
13	-10.6	14.6	0.6	13.5	1.4	11.9	1.5	18.8	0.3	19.0	1.6
12	-11.1	15.2	0.5	14.0	1.3	12.3	1.4	19.4	0.3	19.5	1.6
11	-11.7	15.8	0.5	14.5	1.2	12.7	1.4	19.9	0.3	20.0	1.5
10	-12.2	16.3	0.4	15.3	1.1	13.1	1.3	20.6	0.2	20.5	1.4
9	-12.8	16.8	0.4	15.6	1.1	13.4	1.2	21.3	0.2	21.0	1.4
8	-13.3	17.3	0.3	16.0	1.0	13.7	1.2	21.8	0.1	21.5	1.3
7	-13.9	17.9	0.3	16.3	1.0	13.9	1.2	22.3	0.1	22.0	1.3
6	-14.4	18.3	0.3	16.7	0.9	14.2	1.1	22.8	0.1	22.5	1.2
5	-15.0	18.8	0.2	17.0	0.9	14.5	1.1	23.3	0.1	23.0	1.2
4	-15.6	19.3	0.2	17.3	0.8	14.8	1.0	23.8	0.1	23.5	1.1
3	-16.1	19.7	0.2	17.8	0.8	5.2	1.0	24.3	0.0	24.0	1.1
2	-16.7	20.2	0.1	18.2	0.8	15.5	0.9	24.8	0.0	24.5	1.0
1	-17.2	20.6	0.1	18.5	0.7	15.8	0.9	NA	NA	25.0	1.0
0	-17.8	21.0	0.1	18.7	0.7	16.1	0.9	NA	NA	25.0	1.0
-1	-18.3	21.4	0.1	19.0	0.7	16.3	0.8	NA	NA	25.9	0.9
-2	-18.9	21.8	0.1	19.3	0.7	16.6	0.8	NA	NA	26.3	0.9
-3	-19.4	22.2	0.0	19.7	0.6	16.8	0.8	NA	NA	27.7	0.8
-4	-20.0	22.6	0.0	20.0	0.6	17.1	0.8	NA	NA	28.1	0.8
-5	-20.6	22.9	0.0	20.3	0.6	17.4	0.7	NA	NA	28.6	0.8
-6	-21.2	23.3	(0.0)	20.5	0.6	17.6	0.7	NA	NA	29.0	0.7
-7	-21.7	NA	NA	20.8	0.5	17.8	0.7	NA	NA	28.4	0.8
-8	-22.2	NA	NA	21.0	0.5	18.1	0.7	NA	NA	28.8	0.7
-9	-22.8	NA	NA	21.3	0.5	18.3	0.6	NA	NA	29.2	0.7
-10	-23.3	NA	NA	21.5	0.5	18.5	0.6	NA	NA	29.6	0.7
-11	-23.9	NA	NA	21.8	0.5	18.7	0.6	NA	NA	30.0	0.7
-12	-24.4	NA	NA	22.0	0.5	19.0	0.6	NA	NA	30.6	0.6
-13	-25.0	NA	NA	22.3	0.4	19.2	0.6	NA	NA	30.7	0.6
-14	-25.6	NA	NA	22.5	0.4	19.4	0.5	NA	NA	31.1	0.6
-15	-26.1	NA	NA	22.8	0.4	19.6	0.5	NA	NA	31.5	0.6
-16	-26.7	NA	NA	23.0	0.4	19.8	0.5	NA	NA	31.8	0.6
-17	-27.2	NA	NA	23.3	0.4	20.0	0.5	NA	NA	32.2	0.6
-18	-27.8	NA	NA	23.5	0.4	20.2	0.5	NA	NA	32.6	0.5
-19	-28.3	NA	NA	23.8	0.3	20.4	0.5	NA	NA	32.9	0.5
-20	-28.9	NA	NA	24.0	0.3	20.6	0.5	NA	NA	33.3	0.5

[1] From NCHRP Project 06-16 Phase II – Decision Tool, Purchase Specification and Quality Assurance Monitoring Program, Table 2-21, pp. 29-30.
[2] BC: Beginning Concentration (percent)
[3] EC: Ending Concentration (percent)
[4] MP: Melting Potential

Temperature		NaCl		$CaCl_2$		$MgCl_2$		CMA		KAc	
		BC (%) =23		BC (%) =32		BC (%) =30		BC (%) =25		BC (%) =50	
°F	°C	EC (%)	MP	EC (%)	MP	EC (%)	MP	EC (%)	MP	EC (%)	MP
-21	-29.4	NA	NA	24.2	0.3	20.8	0.4	NA	NA	33.6	0.5
-22	-30.0	NA	NA	24.4	0.3	20.9	0.4	NA	NA	34.0	0.5
-23	-30.6	NA	NA	24.6	0.3	21.1	0.4	NA	NA	34.3	0.5
-24	-31.3	NA	NA	24.8	0.3	21.6	0.4	NA	NA	34.7	0.4
-25	-31.7	NA	NA	25.0	0.3	22.0	0.4	NA	NA	35.0	0.4
-26	-32.2	NA	NA	25.2	0.3	NA	NA	NA	NA	35.3	0.4
-27	-32.8	NA	NA	25.3	0.3	NA	NA	NA	NA	35.7	0.4
-28	-33.3	NA	NA	25.5	0.3	NA	NA	NA	NA	36.0	0.4
-29	-33.9	NA	NA	25.7	0.2	NA	NA	NA	NA	36.3	0.4
-30	-34.4	NA	NA	25.8	0.2	NA	NA	NA	NA	36.7	0.4
-31	-35.0	NA	NA	26.0	0.2	NA	NA	NA	NA	37.0	0.4
-32	-35.6	NA	NA	26.2	0.2	NA	NA	NA	NA	37.3	0.3
-33	-36.1	NA	NA	26.3	0.2	NA	NA	NA	NA	37.7	0.3
-34	-36.7	NA	NA	26.5	0.2	NA	NA	NA	NA	38.0	0.3
-35	-37.2	NA	NA	26.6	0.2	NA	NA	NA	NA	38.3	0.3
-36	-37.8	NA	NA	26.8	0.2	NA	NA	NA	NA	38.7	0.3
-37	-38.3	NA	NA	26.9	0.2	NA	NA	NA	NA	39.0	0.3
-38	-38.9	NA	NA	27.1	0.2	NA	NA	NA	NA	39.3	0.3
-39	-39.4	NA	NA	27.2	0.2	NA	NA	NA	NA	39.7	0.3
-40	-40.0	NA	NA	27.4	0.2	NA	NA	NA	NA	40.0	0.3
-41	-40.6	NA	NA	27.5	0.2	NA	NA	NA	NA	40.3	0.2
-42	-41.1	NA	NA	27.6	0.2	NA	NA	NA	NA	40.6	0.2
-43	-41.7	NA	NA	27.8	0.2	NA	NA	NA	NA	41.9	0.2
-44	-42.2	NA	NA	27.9	0.1	NA	NA	NA	NA	41.3	0.2
-45	-42.8	NA	NA	28.1	0.1	NA	NA	NA	NA	41.6	0.2
-46	-43.3	NA	NA	28.2	0.1	NA	NA	NA	NA	41.9	0.2
-47	-43.9	NA	NA	28.3	0.1	NA	NA	NA	NA	42.2	0.2
-48	-44.4	NA	NA	28.4	0.1	NA	NA	NA	NA	42.5	0.2
-49	-45.0	NA	NA	28.6	0.1	NA	NA	NA	NA	42.8	0.2
-50	-45.6	NA	NA	28.7	0.1	NA	NA	NA	NA	43.1	0.2
-51	-46.1	NA	NA	28.7	0.1	NA	NA	NA	NA	43.4	0.2
-52	-46.7	NA	NA	28.8	0.1	NA	NA	NA	NA	43.8	0.1
-53	-47.2	NA	NA	28.9	0.1	NA	NA	NA	NA	44.1	0.1
-54	-47.8	NA	NA	29.1	0.1	NA	NA	NA	NA	44.4	0.1
-55	-48.3	NA	NA	29.2	0.1	NA	NA	NA	NA	44.7	0.1
-56	-48.9	NA	NA	29.3	0.1	NA	NA	NA	NA	45.0	0.1
-57	-49.4	NA	NA	29.4	0.1	NA	NA	NA	NA	45.3	0.1
-58	-50.0	NA	NA	29.5	0.1	NA	NA	NA	NA	45.5	0.1
-59	-50.6	NA	NA	29.6	0.1	NA	NA	NA	NA	45.8	0.1
-60	-51.1	NA	NA	NA	NA	NA	NA	NA	NA	46.0	0.1
-61	-51.7	NA	NA	NA	NA	NA	NA	NA	NA	46.3	0.1
-62	-52.2	NA	NA	NA	NA	NA	NA	NA	NA	46.5	0.1
-63	-53.8	NA	NA	NA	NA	NA	NA	NA	NA	46.8	0.1
-64	-53.3	NA	NA	NA	NA	NA	NA	NA	NA	47.0	0.1
-65	-53.9	NA	NA	NA	NA	NA	NA	NA	NA	47.3	0.1
-66	-54.4	NA	NA	NA	NA	NA	NA	NA	NA	47.5	0.1
-67	-55.0	NA	NA	NA	NA	NA	NA	NA	NA	47.8	0.0
-68	-55.6	NA	NA	NA	NA	NA	NA	NA	NA	48.0	0.0
-69	-56.1	NA	NA	NA	NA	NA	NA	NA	NA	48.3	0.0
-70	-56.7	NA	NA	NA	NA	NA	NA	NA	NA	48.5	0.0

APPENDIX C

OPERATIONS GUIDE FOR MAINTENANCE FIELD PERSONNEL

from

MANUAL OF PRACTICE FOR AN EFFECTIVE ANTI-ICING PROGRAM

A Guide for Highway Winter Maintenance Personnel

Ketcham, et al. 1996

APPENDIX C. OPERATIONS GUIDE FOR MAINTENANCE FIELD PERSONNEL

C.1 INTRODUCTION

This appendix is a guide to highway anti-icing operations for maintenance field personnel. Its purpose is to suggest maintenance actions for *preventing* the formation or development of packed and bonded snow or bonded ice during a variety of winter weather events. It is intended to complement the decision-making and management practices of a systematic anti-icing program so that roads can be efficiently maintained in the best possible condition.

The guidance is based upon the results of four years of anti-icing field testing conducted by 15 State highway agencies and supported by the Strategic Highway Research Program (SHRP) and the Federal Highway Administration (FHWA). It has been augmented with practices developed outside the U.S., where necessary, for completeness. The recommendations are subject to refinement as U.S. highway agencies gain additional experience with anti-icing operations. Final decisions for their implementation rests with management personnel.

C.2 GUIDANCE FOR ANTI-ICING OPERATIONS

Guidance for anti-icing operations is presented in Tables 8 to 13 for six distinctive winter weather events. The six events are:

- Light Snow Storm
- Light Snow Storm with Period(s) of Moderate or Heavy Snow
- Moderate or Heavy Snow Storm
- Frost or Black Ice
- Freezing Rain Storm
- Sleet Storm

The tables suggest the appropriate maintenance action to take during an initial or subsequent (follow-up) anti-icing operation for a given precipitation or icing event. Each action is defined for a range of pavement temperatures and an associated temperature trend. For some events the operation is dependent not only on the pavement temperature and trend, but also upon the pavement surface or the traffic condition at the time of the action. Most of the maintenance actions involve the application of a chemical in either a dry solid, liquid, or prewetted solid form. Application rates ("spread rates") are given for each chemical form where appropriate. These are suggested values and should be adjusted, if necessary to achieve increased effectiveness or efficiency, for local conditions. *The rates given for liquid chemicals are the equivalent dry chemical rates*. Application rates in volumetric units such as L/lane-km (or gal/lane-mi) must be calculated from these dry chemical rates for each chemical and concentration.

Comments and notes are given in each table where appropriate to further guide the maintenance field personnel in their anti-icing operations.

C.3 GLOSSARY OF TERMS

Black ice. Popular term for a very thin coating of clear, bubble-free, homogeneous ice which forms on a pavement with a temperature at or slightly above $0^{o}C$ ($32^{o}F$) 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.

Dry chemical spread rate. The chemical application rate. For solid applications it is simply the weight of the chemical applied per lane kilometer (or mile). For liquid applications it is the weight of the dry chemical in solution applied per lane kilometer (or mile).

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.

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 of ice formed directly from water vapor at a temperature below $0^{o}C$ ($32^{o}F$) (sublimation).

Light snow. Snow falling at the rate of less than 12 mm (1/2 in) per hour; visibility is not affected adversely.

Liquid chemical. A chemical solution; the weight of the dry chemical in solution applied per lane kilometer (or mile) is the chemical application rate – the “dry chemical spread rate” – used in this appendix.

Moderate or heavy snow. Snow falling at a rate of 12 mm (1/2 in) per hour or greater; visibility may be reduced.

Sleet. A mixture of rain and of snow which has been partially melted by falling through an atmosphere with a temperature slightly above freezing.

Slush. Accumulation of snow which 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.

Table 8. Weather event: light snow storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	pavement surface at time of initial operation	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
			liquid	solid or prewetted solid		liquid	solid or prewetted solid	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent;	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow as needed; reapply liquid or solid chemical when needed	28 (100)	28 (100)	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement temperature drops below -5°C (23°F) 3) Do not apply liquid chemical onto heavy snow accumulation or packed snow
ALSO **-7 to 0°C (20 to 32°F)**, remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)				
-10 to -7°C (15 to 20°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed		55 (200)	If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 9. Weather event: light snow storm with period(s) of moderate or heavy snow.

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**				**SUBSEQUENT OPERATIONS**					**COMMENTS**
	pavement surface at time of initial operation	**maintenance action**	**dry chemical spread rate, kg/lane-km (lb/lane-mi)**		**maintenance action**	**dry chemical spread rate, kg/lane-km (lb/lane-mi)**				
			liquid	**solid or prewetted solid**		**liquid**		**solid or prewetted solid**		
						light snow	**heavier snow**	**light snow**	**heavier snow**	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments					1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent; *ALSO* **-4 to 0°C (25 to 32°F)**, remaining in range	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow as needed; reapply liquid or solid chemical when needed	28 (100)	55 (200)	28 (100)	55 (200)	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow 3) After heavier snow periods and during light snow fall, reduce chemical rate to 28 kg/lane-km (100 lb/lane-mi); continue to plow and apply chemicals as needed
	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)						
-10 to -4°C (15 to 25°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed			55 (200)	70 (250)	1) If sufficient moisture is present, solid chemical without prewetting can be applied 2) Reduce chemical rate to 55 kg/lane-km (200 lb/lane-mi) after heavier snow periods and during light snow fall; continue to plow and apply chemicals as needed
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow as needed					1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) *Anticipate increases in snowfall intensity. Apply higher rate treatments prior to or at the beginning of heavier snowfall periods to prevent development of packed and bonded snow*. (3) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 10. Weather event: moderate or heavy snow storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	pavement surface at time of initial operation	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
			liquid	solid or prewetted solid		liquid	solid or prewetted solid	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent; *ALSO* **-1 to 0°C (30 to 32°F)**, remaining in range	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow accumulation and reapply liquid or solid chemical as needed	28 (100)	28 (100)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 55 kg/lane-km (200 lb/lane-mi) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)				
-4 to -1°C (25 to 30°F), remaining in range	Dry	Apply liquid or prewetted solid chemical	55 (200)	42-55 (150-200)	Plow accumulation and reapply liquid or solid chemical as needed	55 (200)	55 (200)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 110 kg/lane-km (400 lb/lane-mi) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply liquid or solid chemical	55 (200)	42-55 (150-200)				
-10 to -4°C (15 to 25°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow accumulation and reapply prewetted solid chemical as needed		70 (250)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 140 kg/lane-km (500 lb/lane-mi) to accommodate longer operational cycles 2) If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow accumulation as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow -- *timing and frequency of subsequent applications will be determined primarily by plowing requirements*. (2) Apply chemical ahead of traffic rush periods occurring during storm.
PLOWING. *Plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 11. Weather event: frost or black ice.

PAVEMENT TEMPERATURE RANGE, TREND, AND RELATION TO DEW POINT	TRAFFIC CONDITION	INITIAL OPERATION			SUBSEQUENT OPERATIONS			COMMENTS
		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
			liquid	solid or prewetted solid		liquid	solid or prewetted solid	
Above 0°C (32°F), steady or rising	Any level	None, see comments			None, see comments			Monitor pavement temperature closely; begin treatment if temperature starts to fall to 0°C (32°F) or below and is at or below dew point
-2 to 2°C (28 to 35°F), remaining in range or falling to 0°C (32°F) or below, *and* equal to or below dew point	Traffic rate less than 100 vehicles per h	Apply prewetted solid chemical		7-18 (25-65)	Reapply prewetted solid chemical as needed		7-18 (25-65)	1) Monitor pavement closely; if pavement becomes wet or if thin ice forms, reapply chemical at higher indicated rate 2) Do not apply liquid chemical on ice so thick that the pavement can not be seen
	Traffic rate greater than 100 vehicles per h	Apply liquid or prewetted solid chemical	7-18 (25-65)	7-18 (25-65)	Reapply liquid or prewetted solid chemical as needed	11-32 (40-115)	7-18 (25-65)	
-7 to -2°C (20 to 28°F), remaining in range, *and* equal to or below dew point	Any level	Apply liquid or prewetted solid chemical	18-36 (65-130)	18-36 (65-130)	Reapply liquid or prewetted solid chemical when needed	18-36 (65-130)	18-36 (65-130)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency 3) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement temperature drops below -5°C (23°F)
-10 to -7°C (15 to 20°F), remaining in range, *and* equal to or below dew point	Any level	Apply prewetted solid chemical		36-55 (130-200)	Reapply prewetted solid chemical when needed		36-55 (130-200)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency
Below -10°C (15°F), steady or falling	Any level	Apply abrasives			Apply abrasives as needed			It is not recommended that chemicals be applied in this temperature range

Notes

TIMING. (1) Conduct initial operation in advance of freezing. Apply liquid chemical up to 3 h in advance. Use longer advance times in this range to effect drying when traffic volume is low. Apply prewetted solid 1 to 2 h in advance. (2) In the absence of precipitation, liquid chemical at 21 kg/lane-km (75 lb/lane-mi) has been successful in preventing bridge deck icing when placed up to 4 days before freezing on higher volume roads and 7 days before on lower volume roads.

Table 12. Weather event: freezing rain storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION		SUBSEQUENT OPERATIONS		COMMENTS
	maintenance action	chemical spread rate, kg/lane-km (lb/lane-mi)	maintenance action	chemical spread rate, kg/lane-km (lb/lane-mi)	
Above 0ºC (32ºF), steady or rising	None, see comments		None, see comments		1) Monitor pavement temperature closely for drops toward 0ºC (32ºF) and below 2) Treat icy patches if needed with prewetted solid chemical at 21-28 kg/lane-km (75-100 lb/lane-mi)
Above 0ºC (32ºF), 0ºC (32ºF) or below is imminent	Apply prewetted solid chemical	21-28 (75-100)	Reapply prewetted solid chemical as needed	21-28 (75-100)	Monitor pavement temperature and precipitation closely
-7 to 0ºC (20 to 32ºF), remaining in range	Apply prewetted solid chemical	21-70 (75-250)	Reapply prewetted solid chemical as needed	21-70 (75-250)	1) Monitor pavement temperature and precipitation closely 2) Increase spread rate toward *higher indicated rate* with decrease in pavement temperature or increase in intensity of freezing rainfall 3) Decrease spread rate toward *lower indicated rate* with increase in pavement temperature or decrease in intensity of freezing rainfall
-10 to -7ºC (15 to 20ºF), remaining in range	Apply prewetted solid chemical	70-110 (250-400)	Reapply prewetted solid chemical as needed	70-110 (250-400)	1) Monitor precipitation closely 2) Increase spread rate toward *higher indicated rate* with increase in intensity of freezing rainfall 3) Decrease spread rate toward *lower indicated rate* with decrease in intensity of freezing rainfall
Below -10ºC (15ºF), steady or falling	Apply abrasives		Apply abrasives as needed		It is not recommended that chemicals be applied in this temperature range

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* glaze ice conditions. (2) Apply chemical ahead of traffic rush periods occurring during storm.

Table 13. Weather event: sleet storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION		SUBSEQUENT OPERATIONS		COMMENTS
	maintenance action	**chemical spread rate, kg/lane-km (lb/lane-mi)**	**maintenance action**	**chemical spread rate, kg/lane-km (lb/lane-mi)**	
Above 0ºC (32ºF), steady or rising	None, see comments		None, see comments		1) Monitor pavement temperature closely for drops toward 0ºC (32ºF) and below 2) Treat icy patches if needed with prewetted solid chemical at 35 kg/lane-km (125 lb/lane-mi)
Above 0ºC (32ºF), 0ºC (32ºF) or below is imminent	Apply prewetted solid chemical	35 (125)	Plow as needed, reapply prewetted solid chemical when needed	35 (125)	Monitor pavement temperature and precipitation closely
-2 to 0ºC (28 to 32ºF), remaining in range	Apply prewetted solid chemical	35-90 (125-325)	Plow as needed, reapply prewetted solid chemical when needed	35-90 (125-325)	1) Monitor pavement temperature and precipitation closely 2) Increase spread rate toward *higher indicated rate* with increase in sleet intensity 3) Decrease spread rate toward *lower indicated rate* with decrease in sleet intensity
-10 to -2ºC (15 to 28ºF), remaining in range	Apply prewetted solid chemical	70-110 (250-400)	Plow as needed, reapply prewetted solid chemical when needed	70-110 (250-400)	1) Monitor precipitation closely 2) Increase spread rate toward *higher indicated rate* with decrease in pavement temperature or increase in sleet intensity 3) Decrease spread rate toward *lower indicated rate* with increase in pavement temperature or decrease in sleet intensity
Below -10ºC (15ºF), steady or falling	Plow as needed		Plow as needed		1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* the sleet from bonding to the pavement. (2) Apply chemical ahead of traffic rush periods occurring during storm.

APPENDIX D

Using Road and Weather Information to Make Chemical Ice Control Treatment Decisions

from

NCHRP Report 526

SNOW AND ICE CONTROL: GUIDELINES FOR MATERIALS AND METHODS

Blackburn, et al. 2004

ATTACHMENT 1

USING ROAD AND WEATHER INFORMATION TO MAKE CHEMICAL ICE CONTROL TREATMENT DECISIONS

This Attachment contains recommended steps for using road and weather information to make snow and ice control treatment decisions. Its purpose is to define a step-by-step procedure that winter maintenance field personnel can follow in determining an appropriate treatment action to take in response to a variety of conditions.

Snow and ice control material rate guidelines are presented. These application rates are based upon results of three winters of field testing various strategy/tactic combinations by 24 highway agencies. The recommended rates apply to both state and local highway agencies engaged in snow and ice control operations on highways, roads, and streets. Appropriate application rates for solid, prewetted solid, and liquid sodium chloride are given as a function of pavement temperature range, adjusted dilution potential level, and the presence or absence of ice/pavement bond. The adjusted dilution potential level accounts for precipitation type and rate, snow and ice conditions on the road, and treatment cycle time and traffic volume conditions. The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) prior to the next anticipated treatment.

Implicit in the recommended treatment steps is the requirement that plowing, if needed, should be performed before chemical applications are made. This is necessary so that any excess snow, slush, or ice is removed and the pavement surface is wet, slushy, or lightly snow covered when treated.

When applying solid, prewetted solid, or liquid snow and ice control chemicals, the usual intent is to achieve or maintain an unbonded, bare, or wet pavement condition. The following procedure will provide a generally successful result.

STEP 1

The first step in the procedure is to determine the pavement temperature at the time of treatment and the temperature trend after treatment. A judgment, either estimated or predicted by modeling techniques, will need to be made of what the pavement temperature will be in the near term, 1 to 2 hours after treatment. This is one aspect of what is commonly called “nowcasting.” Nowcasting refers to the use of real-time data, or best information available, for very short-term forecasting. It relies on the rapid transmittal of data from RWIS installations, weather radar, patrols, and other information sources for making a judgment of the probable weather and pavement condition/temperature over the next hour or two. Nowcasts can be provided by a private weather service or performed within the maintenance agency.

The end result of this step in the procedure will be the determination of the “pavement temperature and trend.”

STEP 2

The second step in the procedure is to establish the dilution potential that a chemical treatment must: (1) endure before another treatment is made during a winter weather event, or (2) produce a satisfactory result in the absence of precipitation at the end of an event. The establishment of the dilution potential for each treatment includes consideration of precipitation type and rate (including none), precipitation trend, the presence of various wheel path area conditions, treatment cycle time, and traffic speed and volume.

The dilution potential for the precipitation at the time of treatment and its anticipated trend in the short-term is determined from Table A-1. The level of precipitation dilution potential will be either low, medium, or high. In the absence of precipitation, the dilution potential is determined from the wheel path area condition and is shown in Table A-2.

STEP 3

In the third step, an adjustment to the precipitation dilution potential shown in Table A-1 may have to be made for various wheelpath area conditions. These adjustments are given in Table A-3.

STEP 4

In the fourth step, an additional adjustment to the precipitation dilution potential may have to be made for treatment cycle time. This is the time between anticipated successive treatment passes. In the case of pretreating, it is the time between the onset of precipitation and the next anticipated treatment. These adjustments are given in Table A-4.

STEP 5

In the fifth step, an extra adjustment to the precipitation dilution potential may have to be made for traffic speeds greater than 35 mph and traffic volume greater than 125 vehicles per hour. These adjustments are also given in Table A-4. No adjustment is made for traffic volume when traffic speeds are 35 mph or below.

When making additional level adjustments to the precipitation dilution potential, an adjustment level of 1 would change a low level to a medium level or a medium level to a high level. An adjustment level of 2 would change a low level to a high level. The end result of adding various factor adjustment levels to the precipitation dilution potential is termed "adjusted dilution potential." The final adjusted dilution potential level cannot exceed "high."

STEP 6

The sixth and final step in the procedure is to make a judgment of whether an ice/pavement bond condition exists. This determination (yes or no) is made based on field observations or sensor data.

TABLE A-1 Precipitation dilution potential in the presence of precipitation

	Precipitation type	Precipitation rate			
		Light	Moderate	Heavy	Unknown
1.	Snow 1 (powder)	Low	Low	Medium	Low
2.	Snow 2 (ordinary)	Low	Medium	High	Medium
3.	Snow 3 (wet/heavy)	Medium	High	High	High
4.	Snow U (unknown)	–	Medium	–	–
5.	Rain	Low	Medium	High	Medium
6.	Freezing rain	Low	Medium	High	Medium
7.	Sleet	Low	Medium	High	Medium
8.	Blowing snow	–	Medium	–	–
9.	Snow with blowing snow	(Same as type of snow)			
10.	Freezing rain with sleet	Low	Medium	High	Medium

TABLE A-2 Precipitation dilution potential in the absence of precipitation for various wheel path area conditions

Precipitation	Wheel path area condition	Precipitation dilution potential
None	Dry or damp	Not applicable ("NA")
	Wet	Low
	Frost or black ice (thin ice)	Low
	Slush or loose snow	Medium
	Packed snow or thick ice	High

TABLE A-3 Adjustment table to precipitation dilution potential for the presence of various wheel path area conditions

Precipitation	Wheel path condition	Increase precipitation dilution potential by number of levels
Yes	Bare	0
	Frost or thin ice	0
	Slush, loose snow, packed snow, or thick ice	1

TABLE A-4 Cycle time and traffic volume adjustments to precipitation dilution potential (final level not to exceed "high")

Cycle time, hours	Increase precipitation dilution potential by number of levels:
0 – 1.5	0
1.6 – 3.0	1
More than 3.0	2
For traffic speeds > 35 mph Traffic volume (vehicles per hour)	
Less than 125	0
More than 125	1

The appropriate application rates for solid, prewetted solid, and liquid sodium chloride can then be determined from Table A-5 using the results from the previously described steps.

Calculations were performed to develop application rate data for calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KAc), and calcium magnesium acetate (CMA), that were normalized with respect to the application rate data for dry solid NaCl. The ice melting characteristics of each chemical were used in the computations. The equivalent application rates for each of the five ice control chemicals are given in Table A-6 for a range of pavement temperatures. The application rates are normalized to 100 lb/LM of dry solid NaCl.

A word of caution is in order concerning the use of the application rates in Table A-6. The equivalent application rates for a 23-percent concentration solution of NaCl determined from the use of Table A-6 are more conservative (larger) than those in Table A-5 for unbonded ice-pavement conditions. The liquid application rate data in Table A-6 were derived from freezing point (ice melting) data of the five chemical solutions. The liquid application rate data in Table A-5 for unbonded ice-pavement conditions were derived from field test data and include the influence of such variables as precipitation type and rate, pavement wheel path conditions, maintenance treatment cycle time, and traffic volume. As such, the equivalent application rates for the five ice control chemicals in Table A-6 should be considered as starting points in determining the appropriate rates for snow and ice control operations. Local experience should refine these values.

Two forms were developed to assist in the process of selecting an appropriate treatment chemical application rate. Form 1 shown in Figure A-1 is a weather and pavement condition sheet. Here, all relevant weather and pavement data are arrayed for various points in time of interest. These time points may be:

- shortly before a winter weather event begins
- at the onset of precipitation
- at the beginning of each treatment cycle
- at the end of an event
- at various points in time after the winter weather event

The data may come from a variety of sources. The form is intended to display all relevant weather and pavement condition data in one convenient location and format. The form could be used as a format for private sector weather forecasters to deliver their products.

Form 2 shown in Figure A-2 is a snow and ice control treatment design worksheet. It was developed to assist in determining an appropriate treatment and application rate by arraying the necessary data in a logical order.

Both forms could be easily computerized to assist in the treatment decision-making process in support of level of service requirements. An example of how to select a treatment using the treatment design procedure is given in Attachment 2.

TABLE A-5 Application rates for solid, prewetted solid, and liquid sodium chloride

Pavement Temperature (°F)	Adjusted dilution potential	Ice pavement bond	Application rate	
			Solid (1) lb/LM	Liquid (2) gal/LM
Over 32° F	Low	No	90 (3)	40 (3)
		Yes	200	NR (4)
	Medium	No	100 (3)	44 (3)
		Yes	225	NR (4)
	High	No	110 (3)	48 (3)
		Yes	250	NR (4)
32 to 30	Low	No	130	57
		Yes	275	NR (4)
	Medium	No	150	66
		Yes	300	NR (4)
	High	No	160	70
		Yes	325	NR (4)
30 to 25	Low	No	170	74
		Yes	350	NR (4)
	Medium	No	180	79
		Yes	375	NR (4)
	High	No	190	83
		Yes	400	NR (4)
25 to 20	Low	No	200	87
		Yes	425	NR (4)
	Medium	No	210	92
		Yes	450	NR (4)
	High	No	220	96
		Yes	475	NR
20 to 15	Low	No	230	NR
		Yes	500	NR
	Medium	No	240	NR
		Yes	525	NR
	High	No	250	NR
		Yes	550	NR
15 to 10	Low	No	260	NR
		Yes	575	NR
	Medium	No	270	NR
		Yes	600	NR
	High	No	280	NR
		Yes	625	NR
Below 10°F	A. If unbonded, try mechanical removal without chemical. B. If bonded, apply chemical at 700 lb/LM. Plow when slushy. Repeat as necessary. C. Apply abrasives as necessary.			

NR = Not recommended.

Specific Notes:

1. Values for "solid" also apply to prewet solid and include the equivalent dry chemical weight in prewetting solutions.
2. Liquid values are shown for the 23-percent concentration solution.
3. In unbonded, try mechanical removal without applying chemicals. If pretreating, use this application rate.
4. If very thin ice, liquids may be applied at the unbonded rates.

General Notes:

5. These application rates are starting points. Local experience should refine these recommendations.
6. Prewetting chemicals should allow application rates to be reduced by up to about 20% depending on such primary factors as spread pattern and spreading speed.
7. Application rates for chemicals other than sodium chloride will need to be adjusted using the equivalent application rates shown in Table A-6.
8. Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible.

TABLE A-6 Equivalent application rates for five ice control chemicals

Temperature (°F)	NaCl 100%* Solid lb/LM	NaCl 23%* Liquid gal/LM	$CaCl_2$ 90-92%* Solid lb/LM	$CaCl_2$ 32%* Liquid gal/LM	$MgCl_2$ 50%* Solid lb/LM	$MgCl_2$ 27%* Liquid gal/LM	KAc 100%* Solid lb/LM	KAc 50%* Liquid gal/LM	CMA 100%* Solid lb/LM	CMA 25%* Liquid gal/LM
31.5	100	45	109	32	90	31	159	30	159	69
31	100	46	111	32	91	32	161	31	161	72
30.5	100	47	111	33	91	32	155	30	155	71
30	100	48	107	33	94	33	158	31	158	74
29	100	49	109	34	91	33	155	31	155	79
28	100	52	109	34	91	33	152	31	152	81
27	100	54	109	35	90	34	153	31	153	86
26	100	56	104	34	96	36	161	33	161	95
25	100	57	102	34	99	35	167	35	167	108
24	100	61	108	38	102	41	167	35	167	114
23	100	62	112	41	102	41	164	35	164	117
22	100	65	110	41	102	42	160	35	160	121
21	100	68	107	40	101	42	155	35	155	125
20	100	70	108	42	98	42	150	34	150	129
15	100	90	103	44	96	44	142	34	142	170
10	100	120	101	49	95	47	138	35	138	265
5	100	165	104	57	96	51	139	37	139	630

NaCl: Sodium chloride.
$CaCl_2$: Calcium chloride.
$MgCl_2$: Magnesium chloride.
KAc: Potassium acetate.
CMA: Calcium magnesium acetate.

* Typical percent concentrations of the solid and liquid forms with the balance being largely water.

General Notes:

1. The above application rates are normalized to 100 lb/LM of dry solid NaCl. The application rates corresponding to a dry solid NaCl rate other than 100 lb/LM are determined by multiplying the equivalent chemical application rates for a given temperature by the ratio of the desired dry solid NaCl rate to 100 lb/LM. For example, if a 200 lb/LM of dry solid NaCl application rate were recommended at a temperature of 20°F, then switching to a 90 to 92 percent concentration of solid $CaCl_2$ would require a slightly higher application rate of 216 lb/LM.
2. The above application rate data were derived from the freezing point (ice melting) data of the five chemical solutions. As such, the data are more conservative (larger) than field data would suggest for anti-icing operations.

APPENDIX E

Application Rate Guidelines

from

MINNESOTA SNOW AND ICE CONTROL:

FIELD HANDBOOK FOR SNOWPLOW OPERATORS

Minnesota Department of Transportation 2005

HANDBOOK

Manual Number 2005-01

Minnesota Snow and Ice Control

Field Handbook for Snowplow Operators

University of Minnesota
Center for Transportation Studies

Minnesota Department of Transportation

Minnesota Local Road Research Board

Application Rate Guidelines

Develop your own application rates using the guidelines on pages 16–18 as a starting point and modify them incrementally over time to fit your needs. You can summarize information gathered from your truck logs into application rates for your area. Be aware, though, that sample rate charts vary greatly from one area to another, and most are very high. Make it a goal to reduce application rates while keeping our roads safe. You can reduce rates by following anti-icing and other strategies covered in this field handbook.

Salt spray damages roadside vegetation.

Guidelines for Determining Application Rates

- Sand/salt mix isn't advised but may help in some situations such as freezing rain.
- Always plow before applying chemical. For reapplication, start with the lowest rate in the range.
- High traffic volume will work salt into the snow and aid in melting—so use a lower rate.
- Higher traffic speeds will blow salt off the road and hinder melting—so increase use of prewetted materials.
- Use sand for short-term traction only. It will never melt anything.
- For application on a single lane, cut rates in half. For an 18-foot-wide road, use ¾ of the listed rate (i.e., multiply rate by 0.75).
- It is usually not cost-efficient to apply salt (sodium chloride) at pavement temperatures below 15˚ F.

Anti-icing Application Rate Guidelines

These guidelines are a starting point. Reduce or increase rates incrementally based on your experience.

Condition	Gallons/Lane Mile		Other Products
	$MgCl_2$	Salt Brine	
1. Regularly scheduled applications	15 – 25	20 – 40	Follow manufacturers' recommendations.
2. Prior to frost or black ice event	15 – 25	20 – 40	
3. Prior to light or moderate snow	15 – 25	20 – 50	

Pounds of Ice Melted Per Pound of Salt

Pavement Temp. °F	One Pound of Salt (NaCl) melts	Melt Times
30	46.3 lbs of ice	5 min.
25	14.4 lbs of ice	10 min.
20	8.6 lbs of ice	20 min.
15	6.3 lbs of ice	1 hour
10	4.9 lbs of ice	Dry salt is ineffective and will blow away before it melts anything.
5	4.1 lbs of ice	
0	3.7 lbs of ice	
-6	3.2 lbs of ice	

It is not cost-efficient to apply salt (sodium chloride) at pavement temperatures less than 15° F.

Deicing Application Rate Guidelines

24' of pavement (typical two-lane road)

These rates are not fixed values, but rather the middle of a range to be selected and adjusted by an agency according to its local conditions and experience.

			Lbs/ two-lane mile			
Pavement Temp. (°F) and Trend (↑↓)	Weather Condition	Maintenance Actions	Salt Prewetted/ Pretreated With Salt Brine	Salt Prewetted/ Pretreated With Other Blends	Dry Salt*	Winter Sand (abrasives)
>30° ↑	Snow	Plow, treat intersections only	80	70	100*	Not recommended
	Frz. rain	Apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
30° ↓	Snow	Plow & apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30° ↑	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30° ↓	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25° ↑	Snow or frz. rain	Plow & apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25° ↓	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↑	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↓	Snow or Frz. rain	Plow & apply chemical	240 – 320	210 – 280	300 – 400*	500 for frz. rain
0 to 15° ↑↓	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	300 – 400	Not recommended	500 – 750 spot treat as needed
< 0°	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	400 – 600**	Not recommended	500 – 750 spot treat as needed

*Dry salt is not recommended. It is likely to blow off the road before it melts ice.

**A blend of 6 – 8 gal/ton $MgCl_2$ or $CaCl_2$ added to NaCl can melt ice as low as -10°.

Application Rate Guidelines

How to use the table on page 17:

1. Select the row with the appropriate pavement temperature, temperature trend, and weather conditions.
2. Select the column that has the type of material you are using.
3. Find the box where the row and columns intersect to find the application rate. These rates are not fixed values, but rather the middle of a range to be selected and adjusted by your agency according to your local conditions and experience.
4. Compare those values to the calibration chart for your truck.
5. Dial the correct setting for the rate indicated on the Application Rate Guidelines.
6. If you are not treating a 24-foot-wide road (typical two-lane road), adjust the rate as follows: for application on a single lane, cut rates in half. For an 18-foot-wide road, use ¾ of the listed rate (i.e., multiply rate by 0.75).

APPENDIX F

Material Safety Data Sheets for Selected Chemicals

ENVIROTECH® SERVICES, INC.

MATERIAL SAFETY DATA SHEET

SECTION I: PRODUCT, COMPANY AND SHIPPER IDENTIFICATION

Product Name:	**MeltDown® 20 Granular Deicer**	
Chemical Name:	*Complex Chloride—Sodium Chloride, Potassium Chloride, Magnesium Chloride, Calcium Chloride with corrosion inhibition*	
Manufacturer:	*Redmond Minerals, Inc.* *PO Box 219* *Redmond, UT 84652*	*(801) 423-1622*
Shipper/Distributor:	*EnviroTech Services, Inc.* *910 54th Avenue, Suite 230* *Greeley, CO 80634*	*(970) 346-3900*
Chemtrec:	*(800) 424-9300*	

SECTION II: COMPOSITION / INFORMATION ON INGREDIENTS

Ingredients	CAS Number	Percent
Sodium Chloride	*7647-14-5*	*90 - 98*
Magnesium Chloride	*7791-18-6*	*0.06 – 0.20*
Potassium Chloride	*7447-40-7*	*0.03 – 0.20*
Calcium Chloride	*10043-52-4*	*0.30 – 1.40*
Corrosion Inhibitor	*None Exists*	*Proprietary*

SECTION III: HAZARDS INDENTIFICATION

Emergency Overview: *This MSDS has been compiled as a response to customer requests to address the safe handling of the product.*
THIS PRODUCT IS NOT REGULATED UNDER OSHA.
It does not contain any hazardous components.
CAUTION – MAY CAUSE EYE IRRITATION

Potential Health Effects

- Route(s) Of Entry: *Eye, Inhalation, Ingestion, Skin Contact*
- Eyes: *May cause mild irritation.*
- Inhalation: *May cause respiratory tract irritation.*
- Ingestion: *May cause GI irritation.*
- Skin: *May cause mild irritation.*

Chronic Effects: *None known.*

SECTION IV: FIRST AID MEASURES

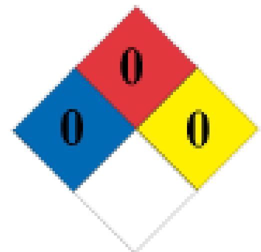
Ingestion: *Non toxic, rinse mouth with water, do not give an unconscious person something to ingest.*

Skin: *Flush with water, wash with mild soap and water, and practice reasonable and ordinary hygiene.*

Eyes: *Look for and remove contact lenses. Irrigate with water.*

Inhalation: *If inhaled, remove to fresh air, if not breathing, give artificial respiration. Obtain medical attention if irritation occurs.*

SECTION V: FIRE AND EXPLOSION HAZARD DATA



Flammable Limits: *N/A Not Flammable*
LEL: *N/A*
UEL: *N/A*
Extinguishing Media: *None, non-flammable*
Flash Point: *None*
Special Fire Fighting Procedures: *None*
Unusual Fire and Explosion Hazards: *None*

NFPA Classification: *Health = 0* *Flammability = 0* *Reactivity = 0*

SECTION VI: ACCIDENTAL RELEASE MEASURES

Spill or Leak Procedure:

Sweep up. Store in a dry area.

SECTION VII: HANDLING AND STORAGE

Precautions to be taken in Handling and Storage:

KEEP OUT OF THE REACH OF CHILDREN
Material can be corrosive to some metals; care should be taken when stored for long periods in metal containers.
Avoid contact with eye, skin or clothing.
Wash thoroughly after handling.
Practice reasonable care and precautions.
Wear safety glasses and rubber or other impervious gloves
Store in a dry area.

Other Precautions:

Not for food or drug use. Do not take internally.

SECTION VIII: EXPOSURE CONTROLS / PERSONAL PROTECTION

Respiratory Protection:	*None*
Ventilation:	*Local Exhaust: Not required*
	Mechanical (General): Not required
Protective Gloves:	*Rubber or other impervious gloves recommended.*
Eye Protection:	*Safety glasses or goggles with splash shields recommended.*
Other:	*None*

SECTION IX: PHYSICAL AND CHEMICAL PROPERTIES

Boiling Point:	*Solid Material, N/A*	Specific Gravity:	*Solid Material, N/A*
Vapor Pressure:	*Solid Material, N/A*	Melting Point:	*1474 °F*
Vapor Density:	*Solid Material, N/A*	Evaporation Rate:	*Not Determined*
Solubility in Water:	*92 - 99%*		

Appearance and Odor: *Reddish to white, no odor.*

SECTION X: STABILITY AND REACTIVITY

Stability: *Stable*
Incompatibilities: *None known*
Hazardous Decomposition: *None known.*
Hazardous Polymerization: *Will not occur*
Conditions to Avoid: *None established*

SECTION XI: TOXICOLOGICAL INFORMATION

Description: *Not Listed*

SECTION XII: ECOLOGICAL INFORMATION

Environmental Effects: *Not Available*
Ecotoxicity: *Not Available*

SECTION XIII: DISPOSAL CONSIDERATIONS

Disposal Method:

If a waste is identified it must be disposed of in accordance with federal, state and local regulations.

SECTION XIV: TRANSPORTATION INFORMATION

U.S. Department of Transportation:

Not regulated as dangerous goods. Not regulated as hazardous.

Transportation of Dangerous Goods (TDG – Canada):

Not regulated as dangerous goods. Not regulated as hazardous.

SECTION XV: REGULATORY INFORMATION

OSHA Status:	*Not Listed*
TSCA Status:	*Not Listed*
CERCLA reportable quantity:	*None*
SARA Section 302 Extremely Hazardous Substances:	*Not Listed*
SARA Section 311/312 Hazard Category:	*Not an OSHA hazardous material.*
SARA Section 313 Toxic Chemical:	*Not an OSHA hazardous material.*
RCRA Status:	*Not Listed*

SECTION XVI: OTHER INFORMATION

Disclaimer: *This Material Data Safety Sheet (MSDS) is provided in response to customer requests to address the safe handling of the product. All statements, technical information and recommendations contained herein are the best of our knowledge, reliable and accurate. This MSDS is not intended to make any representation as to how the product will perform when used for its intended purpose by a user. In that regards the product is sold "AS IS" and nothing in this MSDS should be deemed to be a representation or warranty of any injury, loss, or damage, of any kind or nature, which are sustained by or arise from the use of the product. Nothing in this MSDS is intended to be a representation or warranty by the manufacturer of the accuracy, safety, or usefulness for any purpose of any technical information, materials, techniques, or practices.*

Issue Date: September 1st, 2011
Supersedes Date: All Previous Versions

The information contained in this Material Safety Data Sheet is, to the best of our knowledge, accurate and reliable. This information should be provided to all individuals handling this product. Federal, state, and local regulations should be followed when handling this product.

MATERIAL SAFETY DATA SHEET

SECTION I: PRODUCT, COMPANY AND SHIPPER IDENTIFICATION

Product Name:	**MeltDown® Apex**	
Chemical Name:	*Magnesium Chloride Solution plus Proprietary Additive*	
Manufacturer:	*EnviroTech Services, Inc.* *910 54th Avenue, Suite 230* *Greeley, CO 80634*	*(970) 346-3900*
Shipper/Distributor: (if different than Manufacturer)		
Chemtrec:	*(800) 424-9300*	

SECTION II: COMPOSITION / INFORMATION ON INGREDIENTS

Ingredients	CAS Number	Percent
Magnesium Chloride	*7791-18-6*	*25 – 35*
Water	*7732-18-5*	*65 – 75*
Shield AP Corrosion Inhibitor	*None Exists*	*Proprietary*
Proprietary Additive	*None Exists*	*Proprietary*

SECTION III: HAZARDS INDENTIFICATION

Emergency Overview: *This MSDS has been compiled as a response to customer requests to address the safe handling of the product.*
THIS PRODUCT IS NOT REGULATED UNDER OSHA.
It does not contain any hazardous components.
CAUTION – MAY CAUSE EYE IRRITATION

Potential Health Effects

- Route(s) Of Entry: *Eye, Inhalation, Ingestion, Skin Contact*
- Eyes: *May cause mild irritation.*
- Inhalation: *May cause respiratory tract irritation.*
- Ingestion: *May cause GI irritation.*
- Skin: *May cause mild irritation.*

Chronic Effects: *None known.*

SECTION IV: FIRST AID MEASURES

Ingestion: *Non toxic, do not induce vomiting, rinse mouth with water, do not give an unconscious person something to ingest.*

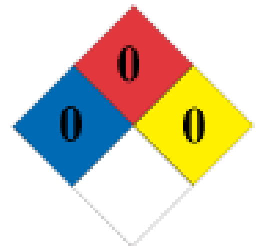
Skin: *Flush with water, wash with mild soap and water, and practice reasonable and ordinary hygiene.*

Eyes: *Look for and remove contact lenses. Irrigate with water.*

Inhalation: *Normally not applicable. If inhaled, remove to fresh air, if not breathing, give artificial respiration. Obtain medical attention if irritation occurs.*

SECTION V: FIRE AND EXPLOSION HAZARD DATA

Flammable Limits: *N/A Not Flammable*
LEL: *N/A*
UEL: *N/A*
Extinguishing Media: *None, non-flammable*
Flash Point: *None*
Special Fire Fighting Procedures: *None*
Unusual Fire and Explosion Hazards: *None*



NFPA Classification: *Health = 0* *Flammability = 0* *Reactivity = 0*

SECTION VI: ACCIDENTAL RELEASE MEASURES

Spill or Leak Procedure:

Contain spills to prevent access to waterways, sewers and basements.
Flush with water.

SECTION VII: HANDLING AND STORAGE

Precautions to be taken in Handling and Storage:

KEEP OUT OF THE REACH OF CHILDREN
Material can be corrosive to some metals; care should be taken when stored for long periods in metal containers.
Avoid contact with eye, skin or clothing.
Wash thoroughly after handling.
Practice reasonable care and precautions.
Wear safety glasses and rubber or other impervious gloves.

Other Precautions:

Not for food or drug use. Do not take internally. May cause leather to shrink.

SECTION VIII: EXPOSURE CONTROLS / PERSONAL PROTECTION

Respiratory Protection:	*None*
Ventilation:	*Local Exhaust: Not required* *Mechanical (General): Not required*
Protective Gloves:	*Rubber or other impervious gloves recommended.*
Eye Protection:	*Safety glasses or goggles with splash shields recommended.*
Other:	*None*

SECTION IX: PHYSICAL AND CHEMICAL PROPERTIES

Boiling Point:	*225°F*	Specific Gravity:	*1.24 – 1.34*
Vapor Pressure:	*N/A*	Melting Point:	*N/A*
Vapor Density:	*N/A*	Evaporation Rate:	*Not Determined*
Solubility in Water:	*100%*	pH:	*4 – 9 as shipped* 6 – 9 in a 1:4 dilution

Appearance and Odor: *Liquid, Clear to Slight Yellow, Very Low or No Odor*

SECTION X: STABILITY AND REACTIVITY

Stability: *Stable*

Incompatibilities: *Strong oxidizers, concentrated acids (i.e. nitric acid)*

Hazardous Decomposition: *Hydrogen chloride, halogenated compounds. Thermal decomposition above temperatures of 570° F may release chlorine gas.*

Hazardous Polymerization: *Will not occur*

Conditions to Avoid: *Avoid contact and storage with above listed compounds or materials.*

SECTION XI: TOXICOLOGICAL INFORMATION

Description: *Not Listed*

SECTION XII: ECOLOGICAL INFORMATION

Environmental Effects: *Not Available*

Ecotoxicity: *Not Available*

SECTION XIII: DISPOSAL CONSIDERATIONS

Disposal Method:

If a waste is identified it must be disposed of in accordance with federal, state and local regulations.

SECTION XIV: TRANSPORTATION INFORMATION

U.S. Department of Transportation:

Not regulated as dangerous goods. Not regulated as hazardous.

Transportation of Dangerous Goods (TDG – Canada):

Not regulated as dangerous goods. Not regulated as hazardous.

SECTION XV: REGULATORY INFORMATION

OSHA Status:	*Not Listed*
TSCA Status:	*Not Listed*
CERCLA reportable quantity:	*None*
SARA Section 302 Extremely Hazardous Substances:	*Not Listed*
SARA Section 311/312 Hazard Category:	*Not an OSHA hazardous material.*
SARA Section 313 Toxic Chemical:	*Not an OSHA hazardous material.*
RCRA Status:	*Not Listed*

SECTION XVI: OTHER INFORMATION

Disclaimer: *This Material Data Safety Sheet (MSDS) is provided in response to customer requests to address the safe handling of the product. All statements, technical information and recommendations contained herein are the best of our knowledge, reliable and accurate. This MSDS is not intended to make any representation as to how the product will perform when used for its intended purpose by a user. In that regards the product is sold "AS IS" and nothing in this MSDS should be deemed to be a representation or warranty of any injury, loss, or damage, of any kind or nature, which are sustained by or arise from the use of the product. Nothing in this MSDS is intended to be a representation or warranty by the manufacturer of the accuracy, safety, or usefulness for any purpose of any technical information, materials, techniques, or practices.*

Issue Date: September 1st, 2011
Supersedes Date: All Previous Versions

The information contained in this Material Safety Data Sheet is, to the best of our knowledge, accurate and reliable. This information should be provided to all individuals handling this product. Federal, state, and local regulations should be followed when handling this product.

APPENDIX G

Winter Weather Definitions

Winter Weather Definitions from the National Weather Service (NWS) Directive 10-1605 "The Collection and Dissemination of Storm Data"

7.3 **Blizzard (Z).** A winter storm which produces the following conditions for 3 hours or longer: (1) sustained winds or frequent gusts 30 knots (35 mph) or greater, and (2) falling and/or blowing snow reducing visibility frequently to less than 1/4 mile, on a widespread or localized basis.

7.16 **Freezing Fog (Z).** Fog which freezes on contact with exposed objects and forms a coating of rime and/or glaze, on a widespread or localized basis, resulting in an impact on transportation, commerce, or individuals. Freezing fog can occur with any visibility of 6 miles or less. Even small accumulations of ice can have an impact.

7.17 **Frost/Freeze (Z).** A surface air temperature of 32 degrees Fahrenheit (F) or lower, or the formation of ice crystals on the ground or other surfaces, over a widespread or localized area for a period of time long enough to cause human or economic impact, during the locally defined growing season.

7.22 **Heavy Snow (Z).** Snow accumulation meeting or exceeding locally/regionally defined 12 and/or 24 hour warning criteria, on a widespread or localized basis. This could mean such values as 4, 6, or 8 inches or more in 12 hours or less; or 6, 8, or 10 inches in 24 hours or less. In some heavy snow events, structural damage, due to the excessive weight of snow accumulations, may occur in the few days following the meteorological end of the event. The preparer should include this damage as part of the original event and give details in the narrative.

7.26 **Ice Storm (Z).** Ice accretion meeting or exceeding locally/regionally defined warning criteria (typical value is 1/4 or 1/2 inch or more), on a widespread or localized basis.

7.47 **Winter Storm (Z).** A winter weather event which has more than one significant hazard (i.e., heavy snow and blowing snow; snow and ice; snow and sleet; sleet and ice; or snow, sleet and ice) and meets or exceeds locally/regionally defined 12 and/or 24 hour warning criteria for at least one of the precipitation elements, on a widespread or localized basis. Normally, a winter storm would pose a threat to life or property. In cases of winter storms, the preparer should be careful to classify the event properly *in Storm Data*.

In general, the event should be classified as a Winter Storm event (rather than an Ice Storm event or a Heavy Snow event) only if more than one winter precipitation type presented a significant hazard.

7.48 **Winter Weather (Z).** A winter precipitation event that causes a death, injury, or a significant impact to commerce or transportation but does not meet locally/regionally defined warning criteria. A Winter Weather event could result from one or more winter precipitation types (snow, or blowing/drifting snow, or freezing rain/drizzle), on a widespread or localized basis

7.36 **Sleet (Z).** Sleet accumulations meeting or exceeding locally/regionally defined warning criteria (typical value is ½ inch or more). The *Storm Data* preparer should include in the narrative the times that sleet accumulation began, met criteria, and ended.

APPENDIX H

SNOW AND ICE CONTROL CHEMICAL PRODUCT SPECIFICATION

from

2010
PACIFIC NORTHWEST SNOWFIGHTERS
SNOW AND ICE CONTROL CHEMICAL PRODUCTS
SPECIFICATIONS
AND TEST PROTOCOLS
FOR THE PNS ASSOCIATION OF
BRITISH COLUMBIA, COLORADO, IDAHO, MONTANA,
OREGON AND WASHINGTON

(ABRIDGED)

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I. GENERAL SPECIFICATIONS

To bid a product, that product shall be on the most current Qualified Products List (QPL), or the product is currently being evaluated for qualification as part of this bid process if the offer to submit samples is made by the agency. To submit a product for the qualification process, contact any of the PNS members for information. In the case of a request for bid, please contact the agency requesting the bid for information on how to become a qualified bidder.

The PNS Association of British Columbia, Idaho, Montana, Oregon, and Washington have developed the Qualified Products List. The list is composed of products that have been tested and found to be in conformance with these specifications. Any material changes to a product that is listed on the QPL by either the manufacturer or the bidder, which in any way makes the product different from the original qualified material, shall be grounds for disqualifying the product from the list. The new product will have to be re-qualified before it will be allowed to be placed back on the QPL.

The bidder of any product that is delivered and/or applied, which is found to be contaminated and is cause for environmental concerns, shall be responsible for all clean up expenses. This includes but is not limited to clean up measures as needed for the following: storage facility, yard, equipment, and roadside.

The bidder shall be liable, as determined by the purchaser for causing any unanticipated extraordinary damages to equipment used in the storage or distribution of the chemical products.

The PNS has the right to qualify or disqualify, accept or reject products based on the materials used to produce the product. The products will be assessed for the potential of causing a decrease in the public safety. The right to qualify or disqualify, accept or reject a product based on manufactured composition rest solely with the PNS. The PNS assessment shall be final and in the best interest of the PNS.

Each bidder submitting a sample will be notified whether the sample passes or fails to meet the specifications. Copies of the complete lab reports will be available upon request.

All submitted products shall be tested to the specified limits contained within these specifications and as per the products' specific category classifications. A product that passes the required specification testing limits and has passed the PNS review shall be placed onto the PNS Qualified Products List. A product that fails to meet the standard limits as specified will not be placed onto the Qualified Products List and the bid will be disqualified.

A. A submitted product that contains any constituent in excess of the following established total concentration limits as tested in accordance with the listed test methodology from Section VI shall be not be acceptable. Results are stated as **parts per million (ppm)**.

Arsenic	5.0
Barium	100.0
Cadmium	0.20
Chromium	1.0
Copper	1.0
Lead	1.0
Mercury	0.05
Selenium	5.0
Zinc	10.00
Phosphorus	2500.
Cyanide	0.20

Note: Liquid products shall be tested as received. Solid Salts are to be diluted to a 25% (W/V) concentration and then tested as if the material was a liquid sample. Report only the values determined from the 25% solution for all of the parameters as compared to the specification limits. Do not back calculate the concentration of the parameters to the dry weight of the material.

B. No bid will be accepted on any corrosion inhibited product that has not successfully completed the National Association of Corrosion Engineers (NACE) Standard TM0169-95, as modified by the PNS, and found to have a Corrosion Value of at least 70% less than that of Sodium Chloride (salt).

C. The manufacturer shall also supply the following analyses for information purposes for liquid products or solid products that will be converted into a liquid product for application purposes. Testing of the following parameters will be done by the listed testing methodology from Section VI.

Ammonia - Nitrogen
Total Kjeldahl Nitrogen
Nitrate and Nitrite - Nitrogen
Biological Oxygen Demand
Chemical Oxygen Demand
Frictional Analysis
Toxicity Testing
- Rainbow Trout or Fathead Minnow Toxicity Test
- Ceriodaphnia Dubia Reproductive and Survival Bioassay
- Selenastrum Capricornutum Algal Growth

II. SAMPLE SUBMITTALS

A. If a product that is currently listed on the Qualified Products List is to be bid no sample submission or information packet is required. If a new product is being submitted for evaluation during a bidding opportunity the bid shall be accompanied by **two** one gallon (4 liter) containers of the product along with the chemical, biological, and physical analyses of the product by a qualified laboratory. See "Product Sample Checklist" for complete instructions "as to how to provide required samples and information. All samples must be marked with an easily distinguishable name and the associated paper work must be clearly marked as such so that the samples and the submitted product information can be easily identified and matched up. **<u>Failure to supply the required samples and product information will be cause for disqualification.</u>** These samples will be used to establish a database for future fingerprinting of all approved products when delivered to any of the PNS locations and for future bid comparisons. Any products purchased in the future will be expected to meet specifications as established in the bid process. All test data that is submitted with each product sample is subject to verification by one or more of the PNS laboratories. Results of the testing from the PNS's laboratories shall be verifiable and final. Information and laboratory results shall be submitted according to the general and specific product specification contained within this document. The following results and information are mandatory at the time of submission and shall be verified from the Product Sample Check List.

1. Corrosion test data obtained according to NACE Standard TM0169-95 as modified by PNS.

2. pH (liquid products only) - The pH of submitted liquid chemical products shall be within the specified limits as designated in the appropriate categories. The pH of liquid chemical products that contains organic matter as one of it constituents may be waived by the PNS for each of the liquid categories that require adherence to a specified pH range. The right to waive the pH will be at the discretion of the PNS. The PNS decision to waive the pH requirement shall be in the best interest of the PNS and shall be final.

   NOTE: Recent testing has concluded that brines inhibited with organic matter exhibit lower pH values than do brines with non-organic matter inhibitors. Organic matter, such as peat, routinely exhibits low pH values because they generate weak organic acids. These weak organic acids are prevalent in the ecology system and are necessary to maintain a healthy environment. Our main concern, in addressing pH, was to limit the amount of excess inorganic acidity or alkalinity that brine could carry. Corrosion testing has shown that these weak organic acids do not have a detrimental effect but seem to enhance the corrosion inhibiting power of the products. Due to this, the pH parameter on brines that contain organic matter may be waived by the PNS. The organic matter information shall be included in the Product Information section of the Bid Schedule and bidder may apply for the pH waiver. The bidder must also provide documentation as to what the organic material consists off, and the minimum concentration that it will be added to their product. The PNS reserves the right to use any and all testing procedures necessary to verify bidder data.

3. Analytical results of all constituents for which limits have been set by the General Specifications in Section I, Part A. **The analytical results shall reflect testing to the specified limit or below. For example the specified limit for Cadmium is 0.20 ppm, therefore the supplied analytical results need to reflect testing to that limit or below. A submitted value of less than 1.00 ppm is not acceptable.**

4. All biological, chemical, toxicology and friction test results as listed in Section I Part C. Friction testing shall be conducted on all liquid samples and may be required on solid products per the discretion of the PNS.

5. Specific gravity chart (liquid products only) with correlating weight percentage and freeze point information presented in 1% increments beginning with a five percent solution. The chart must contain information up to, including, and exceeding, ***by 5% (or the solubility limits of your product)*** the concentration being submitted for evaluations.

6. Detailed information on the corrosion inhibitor, the minimum concentration of the corrosion inhibitor contained in the product, complete and precise laboratory procedures for verifying inhibitor concentrations **SHALL** be included with the bid document. Failure to provide sufficient detail to address all specification requirements may result in bid disqualification. Proprietary information must be included and will be held confidential by the PNS. Mark and submit in a separate sealed envelope all the proprietary information to maintain confidentiality.

B. Bids shall be accompanied with the most recent detailed product specification sheet and Material Safety Data Sheet (MSDS) including the MSDS of the inhibitor. **All documents must be clearly legible.**

C. Most chemical products after successfully completing the PNS's initial screening process and corrosion tests may then be required to successfully complete field application/effectiveness tests. The decision as to whether or not to require a supplier to furnish an ample supply of their product (at no charge including shipping) for field-testing lies solely with the PNS. If the product requested for field-testing is not furnished, or if an inadequate amount is supplied, or if product performance is not satisfactory, the product will not be placed on the approved product list.

Field application/effectiveness testing of some products may be waived based on the chemical constituents of the product. The PNS has laboratory and field-tested many variations of these products. The results of the field tests should be predictable based on the percentage of the active chemical constituent. The option to waive field application/effectiveness tests lies solely with the PNS.

III. ORDERS, DELIVERIES, AND INVOICING OF PRODUCTS

ATTENTION: PLEASE REFER TO EACH INDIVIDUAL AGENCIES SPECIFICATIONS REGARDING ORDERING AND DELIVERING PRODUCTS.

A. Bidder will be responsible for all necessary equipment to transfer liquid chemical products to purchasers' storage tanks. Purchaser's storage tanks will be fitted with a three-inch male pipe fitting to allow for unloading of product.

B. Each shipment shall be accompanied by a current and clearly legible MSDS.

C. An anti-foaming agent will be available from the Bidder for use as needed, at no additional charge to the Purchaser, to control foaming during loading, unloading, and agitation of liquid chemical products.

D. The bill of lading for each shipment must contain the following information.

1. Name of product.
2. Supplier and manufacturer of product.
3. Delivery Destination.
4. Total number of units being delivered.
5. Total weight of delivery using a certified scale ticket or certified flow meter. As an option on liquid deliveries only, the bidder can use a legibly printed certified ticket from a flow meter that has been tested and certified by an approved PNS member's agency of Weight and Measures. The certification of the meter shall not be older than one year. Any PNS member can request that the meter be retested and certified again during the delivery year if the data from the meter is in question. This retesting and certification shall be done at no extra charge to the PNS member. Reciprocity among the PNS members for meter calibration may be employed. **The bidder shall provide a copy of the certification and product information about the flow meter at the time of bid.** The PNS member may at any time choose to spot check a delivery of liquid product by having the load weighed on certified scales before and after delivery to insure the accuracy of the flow meter. No additional cost will be charged to the PNS member for spot-checking deliveries of liquid products.
6. Lot Number for the product being delivered. The Lot Number is a specific number assigned to that particular product as delivered. This number must be denoted as the "**LOT NUMBER**" on the bill of lading and shall be clearly legible. The lot number must enable purchaser to track a delivered product back to its manufacture point, date of manufacture and specific batch. **Failure to have a defined LOT NUMBER that appears on the Bill of Lading is grounds for rejection of the load.**
7. Transport information--Name of transporting company, tank, trailer or rail car number, point and date of origin.

8. For liquid products include the Bidder Quoted Concentration and Specific Gravity.

E. The Agency will not process invoices for payment until the bidder has met all requirements under this section. The invoice shall include the following:

1. A copy of the original bill of lading.
2. Contract unit of measure.
3. Total number of units delivered.
4. Contract unit price for product delivered.
5. Total price for units delivered.

IV. FIELD INSPECTION, UNLOADING, SAMPLING AND TESTING

All material is subject to field inspection, sampling, and testing on an as delivered base. Sampling and field-testing is the prerogative of the Purchaser. The bidder shall not off load any material without affording the Purchaser an opportunity to conduct the field inspection, sampling or the testing. Off loading of material without affording the Purchaser an opportunity to conduct said work shall deem the delivered material non-compliant and is subject to total rejection. The bidder shall only off load material without field inspection, testing and sampling by the Purchaser when the agency representative grants prior written approval.

A. FIELD INSPECTION

BEFORE ALLOWING ANY PRODUCT TO BE UNLOADED AGENCY PERSONNEL WILL ADHERE TO THE FOLLOWING PROCEDURES:

1. Document and maintain records on all deliveries, including those that are rejected.
2. Check to assure that the product is being delivered according to the terms of the contract. This may include but is not limited to the following:
    a. Date of the order.
    b. Date and time of delivery.
    c. Verification of advance delivery notification.
    d. Delivered within allowable times.
    e. Name of Delivery Company and license plate numbers.
    f. Is any price adjustment assessments required?
    g. Is the product being delivered what you ordered?
    h. Document all procedures prior to unloading of product.
    i. Verify that all papers required of a delivery are present, complete, and legible.
        1. Accurate, complete, and legible bill of lading and/or invoice.
        2. Legible and current MSDS sheet.
        3. Certified weight slip.
3. Verify separation or non-separation of product.
4. Visually inspect the load to determine if there are any obvious reasons why the load should be rejected.

5. No precipitate or flocculation in liquid products shall be allowed in excess of the specification limits. Material portraying these or other uncharacteristic traits when delivered may be immediately rejected at the option of the agency or their representative at the delivery location.
6. Any problems must be noted at the point of delivery by agency personnel, documented, and relayed to their agency representative for action.

B. UNLOADING

1. Provided that all the required information is in place and the material appears to be the correct material as ordered, document the amount of product currently in storage prior to unloading and begin the unloading process.

2. The delivery truck shall unload solid materials in a windrow.

3. For liquid products, visually inspect the discharge valve prior to unloading for the presence of any foreign material.

4. Visually inspect the delivered product again while unloading. If problems are noted that are a cause for rejection of the load, immediately halt the unloading process. Take photos if applicable and record any pertinent information. Conduct the following procedures if the material is to be rejected.

   a. If material fails the field inspection or testing, reload the product and reject the load.
   b. If reloading can't be done, (mixed with previous material) note the amount of product (liquid only) pumped into the tank and total product now present in the tank.
   c. Circulate the tank and then pull two one-gallon (4 Liter) samples of the contaminated chemical material now in the tank
   d. Check and record the specific gravity of the samples.
   e. Take appropriate action as needed to assure the integrity of product on hand if possible. Will all products on hand have to be removed?
   f. Send samples directly to the Agency's designated testing laboratory.
   g. Immediately advise the Agency's Representative of any ordering, delivery, storage, or product quality issues.

C. SAMPLING AND TESTING

One sample, of the liquid or dry product being delivered, may be taken from the delivered shipment for laboratory testing after the shipment has passed the initial inspection and is approved for unloading. This sample will be used for testing and/or fingerprinting at the agency's expense to insure product quality. Clearly, label samples for identification. Send the sample directly to the appropriate agency testing laboratory. Be sure the Transmittal form is placed in the box and contains at least the following information; Manufacture or bidders name, name of product, lot number of product, shipping date, date received, name of delivery point, quantity of material delivered, and name and phone number of person who received the load and took the samples. Test results from the appropriate Laboratory will be final and in the best interest of the Purchaser.

1. If the load is liquid, a one-gallon sample will be taken from the transfer hose in three equal parts. Each part will be compositely mixed together with the other parts to make up the one-gallon sample that will be submitted to the laboratory for testing. The samples will be collected during unloading as the first third, the second third and the last third of the product that is being delivered. If the trailer or pup has compartments the three equal samples shall be taken from only one of the compartments to complete the sample. Check and record the specific gravity of the samples.

2. If the load is solid, the delivery truck shall unload the solid material in a windrow. Samples of the windrow materials should be obtained from the complete cross section of the windrow. Portions of the sample shall be taken from the top, center, and bottom in proportion to the cross section area at that point and well within the stack each time. It is best practice to cut completely through the stack if practical. Fine material sifts to the bottom. Care should be taken to obtain a complete and representative sample. The sample shall be placed into a wide mouth 1-gallon container with a screw top lid as soon as the sample has been taken to avoid exposing the sample unduly to atmospheric moisture.

3. Samples sent to the Laboratory will be tested for conformance to specification during the year. Each type of product may be tested for those parameters listed in the General Specifications and in the appropriate Category requirements.

V. CHEMICAL PRODUCT AND INHIBITOR PRODUCT CATEGORIES

Chemical Product Category 1

Corrosion Inhibited
Liquid Magnesium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 25% magnesium chloride.

   Test Method: Number 1

2. Weight per gallon will be established according to the specific gravity and percentage of magnesium chloride contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. Product will contain the corrosion control inhibitor in quantities not less than those indicated by the bidder. The finished deicing product, including corrosion inhibitors, must be completely accomplished at the original manufacturing plant location. Post adding of corrosion inhibitors or any other ingredients and splash mixing is unacceptable after the product has left the original manufacturing plant.

   Test Method: Number 3

4. The pH must be 6.0 - 9.0

   Test Method: Number 4

5. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at -17.8°C +/- 1°C (0°F +/- 2°F) for 168 hours (Seven days).

   Test Method: Number 6

Chemical Product Category 2

Corrosion Inhibited
Liquid Calcium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 25% calcium chloride.

   Test Method: Number 1

2. Weight per gallon will be established according to the specific gravity and percentage of calcium chloride contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. Product will contain corrosion control inhibitor in quantities not less than those indicated by the bidder. The finished deicing product, including corrosion inhibitors, must be completely accomplished at the original manufacturing plant location. <u>Post adding of corrosion inhibitors or any other ingredients and splash mixing is unacceptable after the product has left the original manufacturing plant.</u>

   Test Method: Number 3

4. The pH must be 6.0 - 10.0

   Test Method: Number 4

5. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have ninety nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at <u>-29°C +/- 1°C (-20°F +/- 2°F)</u> for 168 hours (Seven days).

   Test Method: Number 6

Chemical Product Category 3

Liquid Calcium Magnesium Acetate
CMA Specifications (Bidder Manufactured)

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 25% calcium magnesium acetate (CMA).

   Test Method: Number 1

2. Weight per gallon will be established according to the specific gravity and percentage of CMA contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. The pH must be 8.0 – 10.0

   Test Method: Number 4

4. This chemical product shall not contain greater than 4.0 % (V/V) Total Settleable Solids and shall have ninety nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at -12°C +/- 1°C (+10°F +/- 2°F) for 168 hours (Seven days).

   Test Method: Number 6

5. Calcium to magnesium mole ratio shall be 3 to 7.

   Test Method: Number 1

6. Residual base shall be a maximum of 0.30 meq (milliequivalents) base per gram of sample.

   Test Method: Number 11

Chemical Product Category 4

Corrosion Inhibited
Solid Sodium Chloride Specifications

CATEGORIES 4A AND 4B

The Categories shall be defined as follows:

1. Category 4A — Corrosion Percent Effectiveness of 30% or less
   Gradation – ASTM D 632 Type I, Grade 2
2. Category 4B — Corrosion Percent Effectiveness of 31% to 85%
   Gradation ASTM D 632 Type I, Grade - Modified

In addition to the General Specifications the following requirements shall also apply:

1. Gradation - Test Method: Number 13

CATEGORY 4A		CATEGORY 4B	
Sieve Size	Wt. % Passing	Sieve Size	Wt. % Passing
3/4"	100	3/4"	100
#4	20 - 100	1/4"	75 - 85
#8	10 - 60	#8	50 - 70
#30	0 - 15	#30	10 – 20

2. Anti-Caking agent will be included to insure that the material remains free from hard caking and suitable for its intended purpose.

   Test Method: Number 14

   NOTE: Salt for highway use is usually treated with either Ferric Ferrocyanide, also known as Prussian Blue, or Sodium Ferrocyanide, also known as Yellow Prussiate of Soda (YPS), to prevent the salt from caking. The amount of Prussian Blue added is 70 to 165 parts per million (ppm), equivalent to 0.33 to 1.14 pounds per ton of salt. YPS is added in the amount of 50 to 250 ppm, equivalent to 0.1 to 0.5 pounds per ton of salt. YPS is also used as an anti-caking agent in table salt, and has approval of the U.S. Food and Drug Administration. Based on exhaustive testing no evidence of toxicity was demonstrated. If used, the presence of these products will not be assessed towards the total cyanide concentration when testing this product. However, the total cyanide concentration of the original material must meet specifications. Information may be obtained from the Salt Institutes Highway Digest Publication.

   Bidder may bid this product with or without the anti-caking agent. Bidders must note on the Sample Checklist if the sample does contain anti-caking agent or not. If the Bidder chooses not to add the anti-caking agent it does not prevent the bidder from assuring that the delivered product is in a free-flowing state.

3. Material must be clean and free from extraneous matter. The material must be homogenous or manufactured in such a manner to assure that the corrosion inhibitor, anti-caking agent and the chemical product does not segregate.

Test Method: Number 14

4. Moisture Content

Category 4A
The salt shall be dried to a maximum moisture content of 0.5 % (percent by weight). Water in excess of 0.5% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 0.5% shall be computed as follows:

Pay Weight = (100.5 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

NOTE: The moisture content is judged as available free water. Organic Bases Corrosion Inhibitors that are used in the processes of making this product that impart a loss in weight (Organic Matter Weight Loss) when ran according to the prescribe test method but do not reflect the loss of available free water shall be limited to a maximum of 3% by weight. Products that exceed the 3% by weight limit shall be subject to the same equation as above with the limit being adjusted to 3%. Additionally, the use of said inhibitors may be used provided that the material remain free flowing, will not clump, cause hard caking and remains suitable for use. The use of these types of inhibitors may require additional testing to be provided by the bidder at the request of the PNS before approval to the qualified products list is granted. The amount of available water in the inhibitor and the base salt will be required along with a mass balance analysis of the two products to show the theoretical amount of free water that is available in the finished product.

Test Method: Number 12

Category 4B
The salt shall not exceed a maximum moisture content of 5.0 % (percent by weight). Water in excess of 5.0% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 5.0% shall be computed as follows:

Pay Weight = (105.0 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

Chemical Product Category 4---Continued

5. Pay Weight Schedule for Insoluble Residue

Category 4B

The salt shall have a maximum insoluble residue of 10.0 % (percent by dry weight). Insoluble residue in excess of 10.0% of dry salt weight will not be paid for. The amount of salt to be paid for, when the insoluble residue exceeds 10.0% shall be computed as follows:

Pay Weight = (110.0 x Dry Wt. of Salt) divided by (100 + Percent Insoluble Residue)

6. Corrosion Control Inhibitor and Concentration

Test Method: Number 3

Chemical Product Category 5

Corrosion Inhibited
Sodium Chloride Plus 10% Magnesium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

The bidder must state the use of solid or liquid magnesium chloride. For liquid applications the manufacturer shall use at a minimum a 28% concentration of magnesium chloride. The manufacturer shall supply information as to what concentration of the magnesium chloride was used in the process.

1. Gradation of product shall be Type 1, Grade 2, for Sodium Chloride.

    Test Method: Number 13

PHYSICAL REQUIREMENTS AND TOLERANCES

Sieve Size	Wt. % Passing
3/4"	100
#4	20 - 100
#8	10 - 60
#30	0 - 15

2. Anti-Caking agent will be included to insure that the material remains free from hard caking and suitable for its intended purpose.

    Test Method: Number 14

    NOTE: Salt for highway use is usually treated with either Ferric Ferrocyanide, also known as Prussian Blue, or Sodium Ferrocyanide, also known as Yellow Prussiate of Soda (YPS), to prevent the salt from caking. The amount of Prussian Blue added is 70 to 165 parts per million (PPM), equivalent to 0.33 to 1.14 pounds per ton of salt. YPS is added in the amount of 50 to 250 PPM, equivalent to 0.1 to 0.5 pounds per ton of salt. YPS is also used as an anti-caking agent in table salt, and has approval of the U.S. Food and Drug Administration. Based on exhaustive testing no evidence of toxicity was demonstrated. If used, the presence of these products will not be assessed towards the total cyanide concentration when testing this product. However, the total cyanide concentration of the original material must meet specifications. Information may be obtained from the Salt Institutes Highway Digest Publication.

    Bidder may bid this product with or without the anti-caking agent. Bidders must note on the Sample Checklist if the sample does contain anti-caking agent or not. If the Bidder chooses not to add the anti-caking agent it does not prevent the bidder from assuring that the delivered product is in a free-flowing state.

Chemical Product Category 5---Continued

3. Material must be clean and free from extraneous matter. The material must be homogenous or manufactured in such a manner to assure that the corrosion inhibitor, anti-caking agent and the chemical product does not segregate.

Test Method: Number 14

4. Moisture Content Of Sodium Chloride Only.

A. Sodium Chloride Only

The salt shall be dried to a maximum moisture content of 0.5 % (percent by weight). Water in excess of 0.5% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 0.5% shall be computed as follows:

Pay Weight = (100.5 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

Test Method: Number 12

B. Magnesium Chloride Hexahydrate Only

The total moisture content of the magnesium chloride (both free and bound) shall not exceed 56%.

*Unbound water is defined as that water that is not a normal part of the ingredients and becomes part of the product due to hygroscopic action.

Test Method: Number 12

NOTE: The moisture content is judged as available free water. Organic Bases Corrosion Inhibitors that are used in the processes of making this product that impart a loss in weight (Organic Matter Weight Loss) when ran according to the prescribe test method but do not reflect the loss of available free water shall be limited to a maximum of 3% by weight. Products that exceed the 3% by weight limit shall be subject to the same equation as above with the limit being adjusted to 3%. Additionally, the use of said inhibitors may be used provided that the material remain free flowing, will not clump, cause hard caking and remains suitable for use. The use of these types of inhibitors may require additional testing to be provided by the bidder at the request of the PNS before approval to the qualified products list is granted. The amount of available water in the inhibitor and the base salt will be required along with a mass balance analysis of the two products to show the theoretical amount of free water that is available in the finished product.

5. Corrosion Control Inhibitor and Concentration

Test Method: Number 3

Chemical Product Category 5---Continued

6. Product Must Contain No Less Than 10% Magnesium Chloride Hexahydrate by Weight.

This product will consist of 10% magnesium chloride hexahydrate ($MgCl_2$ +6H2O) as specified by weight. Weight of the magnesium chloride shall be calculated as a percent of the total mixture with zero percent unbound water *. The manufacture shall establish unit densities and correlating weight for the product based on the zero percent of unbound water content at time of manufacturing. The required percentage of magnesium chloride ($MgCl_2$) in the total mixture shall be based on the weight of magnesium chloride hexahydrate ($MgCl_2$ +6H2O).

Test Method: Number 1

Chemical Product Category 6

Corrosion Inhibited
Sodium Chloride Plus 20% Magnesium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

The bidder must state the use of solid or liquid magnesium chloride. For liquid applications the manufacturer shall use at a minimum a 28% concentration of magnesium chloride. The manufacturer shall supply information as to what concentration of the magnesium chloride was used in the process.

1. Gradation of product shall be Type 1, Grade 2, for Sodium Chloride.

   Test Method: Number 13

PHYSICAL REQUIREMENTS AND TOLERANCES

Sieve Size	Wt. % Passing
3/4"	100
#4	20 - 100
#8	10 - 60
#30	0 - 15

2. Anti-Caking agent will be included to insure that the material remains free from hard caking and suitable for its intended purpose.

   Test Method: Number 14

   NOTE: Salt for highway use is usually treated with either Ferric Ferrocyanide, also known as Prussian Blue, or Sodium Ferrocyanide, also known as Yellow Prussiate of Soda (YPS), to prevent the salt from caking. The amount of Prussian Blue added is 70 to 165 parts per million (PPM), equivalent to 0.33 to 1.14 pounds per ton of salt. YPS is added in the amount of 50 to 250 PPM, equivalent to 0.1 to 0.5 pounds per ton of salt. YPS is also used as an anti-caking agent in table salt, and has approval of the U.S. Food and Drug Administration. Based on exhaustive testing no evidence of toxicity was demonstrated. If used, the presence of these products will not be assessed towards the total cyanide concentration when testing this product. However, the total cyanide concentration of the original material must meet specifications. Information may be obtained from the Salt Institutes Highway Digest Publication.

   Bidder may bid this product with or without the anti-caking agent. Bidders must note on the Sample Checklist if the sample does contain anti-caking agent or not. If the Bidder chooses not to add the anti-caking agent it does not prevent the bidder from assuring that the delivered product is in a free-flowing state.

Chemical Product Category 6---Continued

3. Material must be clean and free from extraneous matter. The material must be homogenous or manufactured in such a manner to assure that the corrosion inhibitor, anti-caking agent and the chemical product does not segregate.

   Test Method: Number 14

4. Moisture Content Of Sodium Chloride Only.

   A. Sodium Chloride Only

   The salt shall be dried to a maximum moisture content of 0.5 % (percent by weight). Water in excess of 0.5% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 0.5% shall be computed as follows:

   Pay Weight = (100.5 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

   Test Method: Number 12

   B. Magnesium Chloride Hexahydrate Only

   The total moisture content of the magnesium chloride (both free and bound) shall not exceed 56%.

   *Unbound water is defined as that water that is not a normal part of the ingredients and becomes part of the product due to hygroscopic action.

   Test Method: Number 12

NOTE: The moisture content is judged as available free water. Organic Bases Corrosion Inhibitors that are used in the processes of making this product that impart a loss in weight (Organic Matter Weight Loss) when ran according to the prescribe test method but do not reflect the loss of available free water shall be limited to a maximum of 3% by weight. Products that exceed the 3% by weight limit shall be subject to the same equation as above with the limit being adjusted to 3%. Additionally, the use of said inhibitors may be used provided that the material remain free flowing, will not clump, cause hard caking and remains suitable for use. The use of these types of inhibitors may require additional testing to be provided by the bidder at the request of the PNS before approval to the qualified products list is granted. The amount of available water in the inhibitor and the base salt will be required along with a mass balance analysis of the two products to show the theoretical amount of free water that is available in the finished product.

5. Corrosion Control Inhibitor and Concentration

   Test Method: Number 3

Chemical Product Category 6---Continued

6. Product Must Contain No Less Than 20% Magnesium Chloride Hexahydrate by Weight.

This product will consist of 20% magnesium chloride hexahydrate ($MgCl_2$ +6H2O) as specified by weight. Weight of the magnesium chloride shall be calculated as a percent of the total mixture with zero percent unbound water *. The manufacture shall establish unit densities and correlating weight for the product based on the zero percent of unbound water content at time of manufacturing. The required percentage of magnesium chloride ($MgCl_2$) in the total mixture shall be based on the weight of magnesium chloride hexahydrate ($MgCl_2$ +6H2O).

Test Method: Number 1

Chemical Product Category 7

Solid Calcium Magnesium Acetate Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product will consist of Calcium Magnesium Acetate (CMA)

   Only those ingredients that are normally found in high quality CMA will be acceptable. Any products that do not meet this requirement during the bid process will be immediately rejected unless scientific data shows the additional ingredients/ingredients result in an improvement to the product.

   Test Method: Number 14

2. Calcium to magnesium mole ratio shall be 3 to 7

   Test Method: Number 1

3. This product when liquefied at or near a 25% concentration shall not contain greater than 4.0 % (V/V) settleable solids and shall have ninety nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at -12°C +/- 1°C (-10°F +/- 2°F) for 168 hours (Seven days).

   Test Method: Number 6

4. Moisture (free and hydration) shall not exceed 10%.

   Test Method: Number 12

5. Product attrition shall be less than 2.5% with minimum dust generated on handling.

   Test Method: Number 14 and any other tests deemed necessary.

6. Residual base shall be 0.30 milliequivalents base per gram of sample.

   Test Method: Number 11

7. The pH of product in a 10% solution shall be 8 to 10.

   Test Method: Number 4 except in this case a 10% solution will be used.

Chemical Product Category 8

Non Corrosion Inhibited
Solid Sodium Chloride Specifications

CATEGORIES 8A, 8B, and 8C

The Categories shall be defined as follows:

1. Category 8A	Dry Salt, Standard Gradation
A. Category 8A-B	Brining Salt
B. Category 8A-R	Road Salt
2. Category 8B	Wet Salt, Standard Gradation
3. Category 8C	Dry Salt, Fine Gradation
A. Category 8C-B	Brining Salt
B. Category 8C-R	Road Salt

In addition to the General Specifications, the following requirements shall apply.

1. Moisture Content – Test Method No. 12
   Category 8A – 0.5% Maximum
   Category 8B – 5.0% Maximum
   Category 8C – 0.5% Maximum

2. Insoluble Material- Test Method No. 22
   Category 8A-R – 10.0 % Maximum
   Category 8B - 10.0% Maximum
   Category 8C-R - 10.0 % Maximum
   Category 8A-B – 1.0% Maximum
   Category 8C-B – 1.0% Maximum

3. Gradation – Test Method No. 13

Type 1, Grade 2, with the following Gradation for each Sodium Chloride Category.

Category 8A and 8B

Sieve Size	Wt. % Passing
3/4"	100
#4	20 - 100
#8	10 - 60
#30	0 - 15

Category 8C

Sieve Size	Wt. % Passing
#4	100
#100	0 - 3

4. Anti-Caking agent will be included to insure that the material remains free from hard caking and suitable for its intended purpose.

Chemical Product Category 8---Continued

Test Method: Number 14

NOTE: Salt for highway use is usually treated with either Ferric Ferrocyanide, also known as Prussian Blue, or Sodium Ferrocyanide, also known as Yellow Prussiate of Soda (YPS), to prevent the salt from caking. The amount of Prussian Blue added is 70 to 165 parts per million (PPM), equivalent to 0.33 to 1.14 pounds per ton of salt. YPS is added in the amount of 50 to 250 PPM, equivalent to 0.1 to 0.5 pounds per ton of salt. YPS is also used as an anti-caking agent in table salt, and has approval of the U.S. Food and Drug Administration. Based on exhaustive testing no evidence of toxicity was demonstrated. If used, the presence of these products will not be assessed towards the total cyanide concentration when testing this product. However, the total cyanide concentration of the original material must meet specifications. Information may be obtained from the Salt Institutes Highway Digest Publication.

Bidder may bid this product with or without the anti-caking agent. Bidders must note on the Sample Checklist if the sample does contain anti-caking agent or not. If the Bidder chooses not to add the anti-caking agent it does not prevent the bidder from assuring that the delivered product is in a free-flowing state.

5. Material must be clean and free from extraneous matter. The material must be homogenous or manufactured in such a manner to assure that the corrosion inhibitor, anti-caking agent and the chemical product does not segregate.

   Test Method: Number 14

6. Pay Weight Schedule for Excessive Moisture

Category 8A and 8C

The salt shall be dried to a maximum moisture content of 0.5 % (percent by weight). Water in excess of 0.5% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 0.5% shall be computed as follows:

Pay Weight = (100.5 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

Category 8B

The salt shall be dried to a maximum moisture content of 5.0 % (percent by weight). Water in excess of 5.0% of dry salt weight will not be paid for. The amount of salt to be paid for, when moisture exceeds 5.0% shall be computed as follows:

Pay Weight = (105.0 x Wet Wt. of Salt) divided by (100 + Percent of Moisture)

Chemical Product Category 8---Continued

7. Pay Weight Schedule for Insoluble Residue

   Category 8A-R, 8B, and 8C-R

   The salt shall have a maximum insoluble residue of 10.0 % (percent by dry weight). Insoluble residue in excess of 10.0% of dry salt weight will not be paid for. The amount of salt to be paid for, when the insoluble residue exceeds 10.0% shall be computed as follows:

   Pay Weight = (110.0 x Dry Wt. of Salt) divided by (100 + Percent Insoluble Residue)

   Category 8A-B and 8C-B

   The salt shall have a maximum insoluble residue of 1.0 % (percent by dry weight). Insoluble residue in excess of 1.0% of dry salt weight will not be paid for. The amount of salt to be paid for, when the insoluble residue exceeds 1.0% shall be computed as follows:

   Pay Weight = (101.0 x Dry Wt. of Salt) divided by (100 + Percent Insoluble Residue)

Chemical Product Category 9

Corrosion Inhibited
Liquid Sodium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 21% sodium chloride.

   Test Method: Number 1 (Adapted to measure Sodium by emission spectroscopy.)
   Number 23

2. Weight per gallon will be established according to the specific gravity and percentage of sodium chloride contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. Product will contain the corrosion control inhibitor in quantities not less than those indicated by the bidder. The finished deicing product, including corrosion inhibitors, must be completely accomplished at the original manufacturing plant location. Post adding of corrosion inhibitors or any other ingredients and splash mixing is unacceptable after the product has left the original manufacturing plant.

   Test Method: Number 3

4. The pH must be 6.0 - 9.0

   Test Method: Number 4

5. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at -17.8°C +/- 1°C (0°F +/- 2°F) for 168 hours (Seven days).

   Test Method: Number 6

Chemical Product Category 10

Corrosion Inhibited
Liquid Sodium Chloride Plus Calcium Chloride Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 15% sodium chloride plus no less than 2% calcium chloride.

   Test Method: Number 1 (Adapted to measure Sodium by emission spectroscopy)
   Number 23

2. Weight per gallon will be established according to the specific gravity and percentage of sodium chloride and calcium chloride contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. Product will contain the corrosion control inhibitor in quantities not less than those indicated by the bidder. The finished deicing product, including corrosion inhibitors, must be completely accomplished at the original manufacturing plant location. Post adding of corrosion inhibitors or any other ingredients and splash mixing is unacceptable after the product has left the original manufacturing plant.

   Test Method: Number 3

4. The pH must be 6.0 - 9.0

   Test Method: Number 4

5. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at -17.8°C +/- 1°C (0°F +/- 2°F) for 168 hours (Seven days).

   Test Method: Number 6

Chemical Product Category 11

Corrosion Inhibited
Liquid Chloride Blended Brines Specifications

In addition to the General Specifications the following requirements shall also apply:

1. Product must contain no less than 25% concentration of the total accumulation of chloride based salts in percent including Magnesium Chloride, Calcium Chloride, Sodium Chloride and Potassium Chloride. Any one individual chloride based salt shall exist in a concentration above 2% to be added to the total accumulated concentration.

   Test Method: Number 1 (Adapted to measure Sodium and Potassium by emission spectroscopy.)
   Number 23

2. Weight per gallon will be established according to the specific gravity and total percentage of chloride blended brines contained in the product bid as indicated by the bidder.

   Test Method: Number 2

3. Product will contain the corrosion control inhibitor in quantities not less than those indicated by the bidder. The finished deicing product, including corrosion inhibitors, must be completely accomplished at the original manufacturing plant location. <u>Post adding of corrosion inhibitors or any other ingredients and splash mixing is unacceptable after the product has left the original manufacturing plant.</u>

   Test Method: Number 3

4. The pH must be 6.0 - 9.0

   Test Method: Number 4

5. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at <u>-17.8°C +/- 1°C (0°F +/- 2°F)</u> for 168 hours (Seven days).

   Test Method: Number 6

PNS EXPERIMENTAL CATEGORY

The PNS Experimental Category is designed for potential products that do not fit the current chemical profiles of the already existing defined PNS categories.

The submitted experimental products shall meet the specified limits of the General Specifications including corrosion inhibition. The experimental products shall be analyzed for the informational requirements also listed in the General Specifications.

Products submitted for acceptance testing within the Experimental Category shall remain in this category until other similar products warrant a new category to be developed at the discretion of the PNS. The manufacturer shall submit all test results as required along with the following information:

Define the active ingredient that can be analytically measured.

Define the concentration of the active constituent at which the product will be manufactured.

Test protocols for analyzing the primary constituent.

For liquid products the manufacturer shall designate the appropriate temperature at which the Percent Total Settleable Solids and Percent Passing the No. 10 Sieve test shall be accomplished.

Once the testing information is completed the manufacturer shall then follow the protocols for submitting samples and testing information to the PNS for Quality Assurance Testing. Upon request of the PNS the manufacturer shall supply all additional testing information that may be deemed necessary to complete the review of the product before acceptance to a provisional standing is provided. Provisional standing will be imposed on products that have satisfactorily completed the standards of the PNS. Provisional standing will be issued for the products for a period not to exceed 12 months so that field testing and evaluations can be completed. Provided that the field testing and evaluations are determined to be successful the product will then be classified as a Qualified Product in the Experimental Category.

Field testing of the products for this category shall be conducted by the PNS members or by agencies within the Associations' domain. If other than a PNS member is conducting the testing the manufacture shall be responsible for collecting the field data and submitting it to the PNS for review. Field Data from Taper logs will be reviewed for the products ability to perform. Additionally, the names and telephone numbers of the individuals conducting the field testing and providing the taper logs shall be submitted so that the PNS can not only review questions of performance but also handling, storage, application information and any other information that the PNS feels is relevant regarding a product and its use.

INHIBITOR PRODUCT CATEGORY A-1

CORROSION INHIBITOR FOR SODIUM CHLORIDE (SALT) BRINE

This specification is for a liquid corrosion inhibitor for field addition to concentrated sodium chloride (salt) brine.

The finished corrosion inhibited sodium chloride shall have a minimum sodium chloride concentration of no less than 21% and shall have a Corrosion Percent Effectiveness Rating of 30% or less as tested by PNS specifications.

This liquid corrosion inhibitor when added to concentrated sodium chloride brine will provide a finished product that is compliant to all the General Provisions of the PNS Specifications.

The finished product shall provide eutectic temperature points equal to or lower than that of a standard uninhibited liquid sodium chloride brine of 23.3% concentration. The manufacture shall provide a eutectic temperature graph and table showing both eutectic curves of the finished product and the standard uninhibited liquid sodium chloride solution of 23.3% concentration for direct comparison. The graph shall be constructed according the specifications in Section II Sample Submittals.

For testing purposes, the inhibitor product shall be added to reagent grade sodium chloride brine prepared from distilled water meeting ASTM D 1193 Type II. The salt brine concentration will be prepared in a weight to weight ratio with water. The inhibitor concentration will be added as a volume to volume measurement to the brine solution. The sodium chloride brine and inhibitor concentrations will be prepared according to the inhibitor manufacturer's specifications and guidelines.

The inhibitor shall be capable of being homogenously mixed with the 23% to 24% concentration of sodium chloride brine and resulting in a finished product that does not separate or settle out.

The corrosion inhibitor product bid shall be flowable and have the capability to be mixed fully into the concentrated sodium chloride brine solution at a minimum temperature of 15° F.

Temperature Storage Class of Inhibitor: The corrosion inhibitor must be capable of being stored at a minimum temperature Class as delivered until time of use with no separation or settling.

Class 1: 10° F
Class 2: 0° F

This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at the designated Temperature Storage Class (+/- 2°F) for 168 hours (Seven days).

Test Method: Number 6

INHIBITOR PRODUCT CATEGORY A-2

CORROSION INHIBITOR FOR SODIUM CHLORIDE PLUS CALCIUM CHLORIDE BRINE

This specification is for a field added liquid corrosion inhibitor to produce corrosion inhibited sodium chloride/calcium chloride brine.

The finished corrosion inhibited product shall have a minimum concentration of 15% sodium chloride and a minimum concentration of 2% calcium chloride. The product shall have a minimum of 10% inhibitor added to the product. The finished product shall have a Corrosion Percent Effectiveness Rating of 30% or less as tested by PNS specifications.

The finished product shall provide eutectic temperature points equal to or lower than that of a standard uninhibited liquid sodium chloride brine of 23.3% concentration. The manufacture shall provide a eutectic temperature graph and table showing both eutectic curves of the finished product and the standard uninhibited liquid sodium chloride solution of 23.3% concentration for direct comparison. The graph shall be constructed according the specifications in Section II Sample Submittals.

The process by which this is achieved is classified into the following Types:

Type I – The corrosion inhibitor contains sufficient calcium chloride that additional calcium chloride is not required to be added to the salt brine.
Type II – The corrosion inhibitor, salt brine, and calcium chloride are added separately.

For testing purposes of Type I inhibitors, the inhibitor product shall be added to the concentrated liquid salt brine prepared from reagent grade sodium chloride and distilled water meeting ASTM D 1193 Type II. The salt brine concentration will be prepared in a weight to weight ratio with distilled water. The inhibitor concentration will be added as a volume to volume measurement to the brine solution. The sodium chloride brine and inhibitor concentrations will be prepared according to the inhibitor manufacturer's specifications and guidelines.

For Testing purposes of Type II inhibitors, the inhibitor product shall be added to a mixture of concentrated salt brines prepared from reagent grade sodium chloride and calcium chloride, and distilled water meeting ASTM D 1193 Type II. The salt brine concentrations will be prepared in a weight to weight ratio with distilled water. The inhibitor concentration will be added as a volume to volume measurement to the brine solution. The brine and inhibitor concentrations will be prepared according to the inhibitor manufacturer's specifications and guidelines.

The inhibitor shall be capable of being homogenously mixed with the 23% to 24% concentration of sodium chloride brine and resulting in a finished product that does not separate or settle out.

The corrosion inhibitor product bid shall be flowable and have the capability to be mixed fully into the concentrated brine solution at a minimum temperature of 15° F.

Storage Class of Inhibitor: The corrosion inhibitor must be capable of being stored at a minimum temperature Class as delivered until time of use with no separation or settling.

Class 1: 10° F
Class 2: 0° F

This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at the designated Temperature Storage Class (+/- 2°F) for 168 hours (Seven days).

Test Method: Number 6

INHIBITOR PRODUCT CATEGORY A-3

CORROSION INHIBITOR FOR SODIUM CHLORIDE (SALT) BRINE

This specification is for a liquid corrosion inhibitor for field addition to concentrated sodium chloride (salt) brine.

The finished corrosion inhibited sodium chloride shall have a minimum sodium chloride concentration of no less than 15% and have a minimum corrosion inhibitor concentration of no less than 15%. The finished product shall have a Corrosion Percent Effectiveness Rating of 30% or less as tested by PNS specifications.

The finished product shall provide eutectic temperature points equal to or lower than that of a standard uninhibited liquid sodium chloride brine of 23.3% concentration. The manufacture shall provide a eutectic temperature graph and table showing both eutectic curves of the finished product and the standard uninhibited liquid sodium chloride solution of 23.3% concentration for direct comparison. The graph shall be constructed according the specifications in Section II Sample Submittals.

This liquid corrosion inhibitor when added to concentrated sodium chloride brine will provide a finished product that is compliant to all the General Provisions of the PNS Specifications.

For testing purposes, the inhibitor product shall be added to a salt brine prepared from reagent grade sodium chloride and distilled water meeting ASTM D 1193 Type II. The salt brine concentration will be prepared in a weight to weight ratio with water. The inhibitor concentration will be added as a volume to volume measurement to the brine solution. The sodium chloride brine and inhibitor concentrations will be prepared according to the inhibitor manufacturer's specifications and guidelines.

The inhibitor shall be capable of being homogenously mixed with the 23% to 24% concentration of sodium chloride brine and resulting in a finished product that does not separate or settle out.

The corrosion inhibitor product bid shall be flowable and have the capability to be mixed fully into the concentrated sodium chloride brine solution at a minimum temperature of 15° F.

Storage Class of Inhibitor: The corrosion inhibitor must be capable of being stored at a minimum temperature Class as delivered until time of use with no separation or settling.

Class 1: 10° F
Class 2: 0° F

. This chemical product shall not contain greater than 1.0% (V/V) Total Settleable Solids and shall have Ninety-nine percent (99.0%) of the Solids Passing through a Number 10 sieve after being stored at the designated Temperature Storage Class (+/- 2°F) for 168 hours (Seven days).

Test Method: Number 6

VI. TEST METHODS

1. Percent Concentration of Active Ingredient In The Liquid

Test Method: Atomic Absorption or Inductively Coupled Plasma Spectrophotometry as described in "Standard Methods for the Examination of Water and Waste Water", APHA-AWWA-WPCF is acceptable. Test Method "A" in Appendix "A" is used to determine percent concentration of Calcium Chloride or Magnesium Chloride by Atomic Absorption. The operator should be aware that the high solids content of the samples can present special considerations when conducting the analysis.

2. Weight Per Gallon

Test Method: Specific Gravity by ASTM D 1429 Test Method A - Pycnometer at 20° C +/- 1° C.

3. Corrosion Control Inhibitor Presence and Concentration

Test Method: The Materials Laboratory may use the test procedures provided by the bidder or manufacture for testing quantitative concentrations of additives. These same tests can then be used to verify that materials being delivered are the same as those previously tested and approved in the bid process.

4. pH

Test Method: ASTM D 1293 except a dilution shall be made of 1 part chemical product to 4 parts distilled water before attempting a reading.

5. Corrosion Rate

Test Method: NACE Standard TM0169-95 (1995 Revision) as modified by PNS. This procedure is listed as Test Method "B" in Appendix A.

6. Percent Total Settleable Solids and Percent Solids Passing a 10 Sieve

Test Method: This procedure is listed as Test Method "C" in Appendix A.

7. Total Phosphorus

Test Method: Total Phosphorous as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

8. Total Cyanide

Test Method: Total Cyanide as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

9. Total Arsenic, Barium, Cadmium, Chromium, Copper, Lead, Selenium and Zinc.

Test Method: Atomic Absorption Spectrophotometry or Plasma Emission Spectroscopy as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

10. Total Mercury

Test Method: Cold Vapor Atomic Absorption Spectrophotometry as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

11. Milliequivalents OR "meq"

Test Method: This is a measure of the amount of unreacted base in the product. "meq" means milliequivalents or the milligrams of acetic acid to neutralize 1 gram of unreacted base.

Method for measuring unreacted base is a standard acid/base titration procedure. A fixed volume of acid (30 ml of 0.1 N HCl) is added to 1 gram sample of CMA. The excess acid is titrated with a standard base (0.1 N NaOH) to phenolphthalein endpoint, pH of 8.6.

12. Moisture Content Of Solid Chemical Products.

Test Method: According to ASTM E 534

13. Gradation

Test Method: Gradation shall be ran according to ASTM D 632. The sample size shall be a minimum of 300 grams and be hand shaken through each sieve until the sample has been adequately processed. Caution: Care should be used when running the gradation test, as the salt is very soft and can be resized by over shaking. Salts that contain sticky organic matter inhibitors may require additional attention with a rubber policeman to insure that the sample passes the screens correctly as the sticky inhibitors will tend to clump up smaller particles of salt and prohibit them from being analyzed correctly.

14. Visual Inspection and Field Observations.

Test Method: Visual inspection and field observations to assure that the material remains clean and free of extraneous matter, free from hard caking, does not segregate, and remains suitable for the intended purpose and as otherwise outlined in Section IV. NOTE: Purchaser may use any laboratory test method necessary to verify conclusions from visual inspections.

15. Toxicity Test

Test Method: According to "Short-Term Methods for Estimating the Chronic Toxicity of Effluent and Receiving Waters to Freshwater Organisms", Third Edition, EPA-600/4-91/002.

16. Ammonia - Nitrogen

Test Method: Ammonia as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

17. Total Kjeldalh Nitrogen

Test Method: Total Kjeldalh Nitrogen as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

18. Nitrate and Nitrite as Nitrogen

Test Method: Nitrate and Nitrite as Nitrogen as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

19. Biological Oxygen Demand

Test Method: Biological Oxygen Demand as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

20. Chemical Oxygen Demand

Test Method: Chemical Oxygen Demand as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

21. Frictional Analysis

Test Method: Frictional Analysis shall be conducted on products that have been applied at the prescribe application rate to a pavement surface within a sealed and controlled humidity chamber. The frictional coefficient shall be measured on pavement surface as the humidity in the chamber is lowered and raised over the course of time. The data shall show a plot of the humidity curve and a plot of the coefficient of friction curve over time. The device that measures the friction coefficient shall be calibrated and certified prior to use on the sample analysis.

22. Insoluble Material

Test Method: ASTM E534 "Standard Test Methods for Chemical Analysis of Sodium Chloride". The method shall be modified by dissolving 100 grams of the sodium chloride sample into the prescribed volume and filtering the entire solution through a Whatman No. 541(or equal), 125 mm diameter filter paper seated in a Buchner Funnel.

23. Chloride

Test Method: Chloride as described in "Standard Methods for the examination of Water and Waste Water", APHA-AWWA-WPCF.

VII. PRODUCT REJECTION AND PRICE ADJUSTMENTS

ATTENTION: PLEASE REFER TO EACH INDIVIDUAL AGENCIES SPECIFICATIONS FOR PRODUCT REJECTIONS AND PRICE ADJUSTMENTS.

VIII. BID EVALUATION PROCESS

A. BID PREFERENCES FOR HIGHER CONCENTRATIONS
(Approved Liquid Chemical Products)

STEP 1: Best buy (FOB delivery destination) based on percentage of active chemical in the product will be determined by the following formula**. Bidder Quoted Concentrations (BQC) and price per ton will be used for calculations.** Delivered Price/Concentration Percentage equals the best buy factor for this step of the process. (The bidders quoted concentration will be used in the calculation.)

Example:

a. $60.00/27% = 222.22 best buy factor
b. $65.00/30% = 216.67 best buy factor

Example "b" at the higher purchase price per ton, with the higher concentration, and with the lower best buy factor would be selected if this were the final step.

B. BID PREFERENCES FOR SUPERIOR CORROSION INHIBITION
(Approved Liquid and Solid Chemical Products)

STEP 2: Bid preferences based on the corrosion inhibiting ability of a product as demonstrated by the PNS's laboratories and verified by field applications will be applied from the values as shown in the following table**.** The values shown in the table under "Value Added" are used to reduce the calculated best buy factor (see above) to arrive at the final calculation/determination of best buy.

PERCENT CORROSION EFFECTIVENESS RANGES	VALUE ADDED
25.0 to 30.0	0.00
20.0 to 24.9	40.00
15.0 to 19.9	60.00
10.0 to 14.9	80.00
5.0 to 09.9	100.00
4.9 and less	150.00

Example:

As noted above in step 1, based on concentration calculations, product "b" resulted in the lowest best buy factor. When corrosion inhibiting values are considered, the calculations will be as follows. Product "a" has a corrosion value of 15.5%, which equates to 60.00 added value points while product "b" displayed a corrosion value of 27.0%, which results in no added value points. See the following:

a. $60.00/27% = 222.22 -60.00 = 162.00 our final best buy factor.

b. $65.00/30% = 216.67- 00.00 = 216.67 our final best buy factor.

Example "a" with the lower concentration but with higher corrosion inhibiting value would be determined to be the best buy in the final step.

Acceptance of bids will be based on approved PNS laboratory results. Final determination of the liquid chemicals products will be based on the "final best buy factor" calculated from the combination of the lowest cost per percent concentration of liquid chemical and credit for corrosion inhibiting ability as specified in Steps 1 & 2. On solid chemical products, only the value added for corrosion inhibiting performance will be used in the "final best buy factor" determination process as specified in Step 2. Bids will be awarded for the lowest "final best buy factor" for each category and to each designated location or zone.

IX. QUALIFIED PRODUCTS LIST

Purchased products that appear on the Qualified Products List may be tested for compliance to the material that was originally submitted for qualification. The agency has the right to conduct this testing at its own will. The most current Qualified Products List can be viewed at the PNS web site location of http://www.wsdot.wa.gov/partners/pns/ or by contacting one of the PNS members.

X. CHEMICAL PRODUCT SUBMISSION FOR THE QUALIFIED PRODUCTS LIST

The PNS member who is conducting the qualification testing has the right to test for verification or to accept the product as approved. Bidders of samples to be tested for acceptance to the Qualified Product List shall complete all the information and submit all the required documentation as specified in these specifications. Two One-gallon samples of the bid product shall accompany the required information for qualification testing.

XI. PRODUCT SAMPLE CHECKLIST

All samples that are submitted must be accompanied with the Product Sample Checklist if they are to be considered for evaluation to the Qualified Product List. Fill in blanks with yes, no, or what is appropriate. If something does not apply, use N/A. Do not leave blanks. Blanks will be considered missed information and may be cause for rejection. Type or print clearly in ink. All documents must be clear and legible. If unreadable, it may be rejected.

Bidder's response to the following items will be considered representative of their product. During qualification testing of the submitted sample the liquid products cannot deviate from the percent concentration by more than minus one full percentage of the bidder quoted concentration as indicated below. If the submitted sample exceeds this deviation tolerance, that product will be disqualified. **During a bid opportunity the submitted Percent Concentration and the Percent Effectiveness will be compared to the approved product test results for verification. If different, the qualification results that appear on the PNS Qualified Products List will be used to determine the "final best buy factor".)** At no time will any sample be allowed to be below the minimum concentration requirement for that product as stated in these specifications.

PRODUCT SAMPLE CHECKLIST

Bidder Information

1. Name of bidding company? ____
2. Mailing Address:____
3. Email Address:____
4. Phone number with area code: ____
5. Fax Number with area code: ____
6. Name of company contact: ____

Chemical Product Information (Categories 1-11 or Experimental)

1. Which chemical product category is your chemical to be sold under? _________________
2. What is the name of the product? _____________________________
3. The product is manufactured by ____
4. If the product is a liquid what is the percent concentration of the product? _________ %.**
   (**This is the Bidder Quoted Concentration NO ranges please. If a range is used, the lowest bidder specified concentration will be used for cost analysis.)**
5. Corrosion inhibited products have a Percent Effectiveness determined to measure the products corrosion rate on steel. What is the Percent Effectiveness of the Product? ________%

Inhibitor Product Information (Inhibitor Categories A1-A3)

1. Which inhibitor product category is your chemical to be sold under? _________________
2. What is the name of the product? ____
3. The product is manufactured by? ____
4. What is the finished concentration(s) of the brine(s)? ______________________________
5. What is the percent volume of the inhibitor to be added to the brine(s)? _______________
6. What is the corrosion Percent Effectiveness of the finished product? _________________
7. What temperature class is the product (1 or 2)? _______________________________________
8. If the product is submitted for category A2, what Type is it (I or II)? _______________________

Information to be included with all submittals.

1. Product Data Sheet: __________
2. Material Safety Data Sheets (MSDS) for the product and the corrosion inhibitor: ________
3. Specific gravity information for liquid products as required: ______________________
4. Eutectic Temperature chart and graphs:_________________________
5. pH data (liquid products only): __________________________________
6. Does your product contain an organic matter based corrosion inhibitor? ________________
7. If yes, complete and submit the required information on the inhibitor as specified within these specifications.

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8. Waiver of pH requirements being requested? Yes ______________ No _____________

9. Percentage of organic matter present in your material? __________________________

10. Analytical results of all specified and informational chemical constituents as specified in the General Specifications, and for the specific category for which application is being made.______________

11. Toxicity Report ____________

12. Frictional Analysis Report ____________

13. Corrosion test data for corrosion inhibited products____________

14. Proprietary information regarding the corrosion inhibitor shall be included in a separate sealed envelope and marked in large bold lettering "Confidential Information". __________

15. Analytical testing procedures for verifying corrosion inhibitor concentration. ___________

16. Two each one gallon containers samples of the product included with submittal. _________

Experimental Products

1. In addition the information contained above the following information is required.

2. Identify the primary active ingredient that the product can be measured for ______________

3. Test protocols for testing the main ingredient ______________________

4. For liquid products, what is the lowest temperature that the material can be stored to while meeting the requirements of the Settleable Solids and Percent Passing the No. 10 sieve? _________

Have you completely read the PNS specifications and included all the required information into the submittal package? Yes _____________ No _________________

Signature of the Individual making the submission __________________________________

Date of Submission _______________________

Please send all information to the following address:

Attention: Ron Wright
Idaho Transportation Department
Materials Section
P.O. Box 7129
Boise, Idaho 83707-1129

Please ship all samples to the following address:

Attention: Ron Wright
Idaho Transportation Department
Materials Section
3311 W. State Street
Boise, Idaho 83703-5879

XII. BID AND SAMPLE DELIVERY

All bids and samples shall be delivered by the time and date of the bid opening. Bids and samples that are received late will be rejected and not tested. Mark all samples submitted to the Laboratory in large black lettering as "**BID SAMPLES-TIME CRITICAL**".

XIII. BID SCHEDULE

The following quantities of chemical products are projected from use for the terms of this contract. These quantities are estimates to be used for bidding purposes only. They are not guaranteed deliverable quantities as the winter weather can and does change and quantities may be less or more than what is being represented. Bidders can bid their approved products but are limited to two new chemical product submissions per category. **Bids will be awarded for the lowest "final best buy factor" for each category (if applicable) and to each designated Area. All prices are to be bid per ton and based on BULK DELIVERY, FOB point of delivery. If your are not entering a bid for an Area of the selected category enter a "No Bid" for that line item.**

LIQUID CHEMICAL PRODUCTS

The liquid portion of this contract will be bid based on the following locations within an Area. These locations are the sites of delivery. The unit price bid for each Area will be the price of delivery to all location within the Area and will be used in the analysis for the "Final Best Buy Factor". **The bid will be award based on the lowest "Final Best Buy Factor" of each category per Area.**

Identify the Category for which you are bidding and provide the product name, the name of your company and the Vendor Quoted Concentration of the Product.

Category ___________________

Product Name____

Bidders Name____

Vendor Quoted Concentration of Product_______________________

ATTACHED AGENCY BID LIST FOR AREAS, LOCATIONS AND QUANTITES

SOLID CHEMICAL PRODUCTS

The solid portion of this contract will be bid based on the following locations within an Area. These locations are the sites of delivery. The unit price bid for each Area will be the price of delivery to all location within the Area and will be used in the analysis for the "Final Best Buy Factor". **The bid will be award based on the lowest "Final Best Buy Factor" of each category per Area (if applicable).**

Identify the Category for which you are bidding and provide the product name and the name of your company.

Category ______________

Product Name____

Bidders Name____

DOES YOUR PRODUCT CONTAIN AND ANTICAKING AGENT? (Circle One) YES NO

IF YOUR PRODUCT DOES CONTAIN AN ANTICAKING AGENT PLEASE PROVIDE THE FOLLOWING INFORMATION:

AMOUNT OF ANTICAKING AGENT ADDED PER TON OF PRODUCT: __________

WHAT IS THE NAME OF THE ANTICAKING AGENT ARE YOU ADDING:______________

ATTACHED AGENCY BID LIST FOR AREAS, LOCATIONS AND QUANTITES

INDEX

APPENDIX I

Concrete Scaling Committee
Montana Department of Transportation

MONTANA DEPARTMENT OF TRANSPORTATION
Helena, Montana 59620-1001

MEMORANDUM

To: Concrete Scaling Committee

From: Susan C. Sillick
Manager, Research Program

Date: February 8, 2002

Subject: Meeting Minutes, January 28, 2002

A committee met on January 28, 2002 to discuss the concrete scaling issue. Attendees were Jim Walther/Engineering Division, Kent Barnes/Materials Bureau, Nigel Mends/Bridge Bureau, Mike Lynch/Materials Bureau, Mike Bousliman/Maintenance Division, Dan Williams/Maintenance Division, Craig Abernathy/Research Section, and Sue Sillick/Research Section. The purpose of this meeting was to take a step back from the on-going effort to ensure involvement of all appropriate MDT staff, a clear definition of the problem, and a survey of the literature. In taking this step back, the committee can reevaluate the need for research so that whatever is done, is done the right way the first time.

The committee first discussed the problem. This problem is limited to concrete scaling, a surface defect characterized by flaking, peeling, or pitting of the concrete surface. For the most part this has only been seen in residential concrete. The extent of concrete scaling in residential areas is unknown; however, it seems to have increased over the past few years.

The committee then discussed the literature. It is clear concrete must have sufficient strength, and proper air entrainment and placement to prevent concrete scaling. These factors can be achieved through proper concrete mix design (including, but not limited to appropriate cement content, aggregate gradation, and addition of admixtures), appropriate air entrainment, proper placement, low water to cement ratio, and sufficient curing. Deicing chemicals and inadequate drainage can exacerbate the scaling of concrete, especially concrete without sufficient strength or air entrainment. Sealing the concrete can help to prevent concrete scaling. Many good resources in addition to the published literature are available on this topic, some containing more specific guidelines - see http://www.beaverconcrete.com/corner2.html, http://www.prmconcrete.com/scaling.htm, and http://www.lafargecorp.com/ttt_sur.htm. The Idaho Department of Transportation (ITD) also supports this opinion. ITD sampled and tested cores of scaled concrete. These cores all exhibited low air entrainment.

The committee feels that scaling is occurring on residential concrete rather than roads built and maintained by MDT because the Department has strict standards for design and construction. In addition, the committee feels that this phenomenon is not occurring all of a sudden, rather, it appears to be a cumulative effect in a couple of different ways. First, it should be expected to take homeowners a certain period of time and discussion with other homeowners to realize that the concrete scaling they are seeing is not an isolated event, but an event that others are also seeing. Second, MDT and homeowners have increased use of deicing chemicals over the last five years or so. As mentioned above, deicing chemicals can exacerbate the scaling of poorly produced or improperly placed concrete. Before deicing chemicals reach residential concrete, mixing with snow, mud, etc has diluted them. Over time, this continual application of these dilute chemicals may enhance scaling. Finally, older concrete does not seem to be exhibiting concrete scaling. The answer seems to be that before the industry knew how to engineer concrete, it contained an unusually high content of cement. Also, the older concrete has had additional time for the cement to hydrate and the concrete to gain strength. A high cement content in concrete can overcome many flaws. Finally, concrete placed many years ago that was not good has since been removed.

It is the opinion of this committee that there are too many causal factors and not enough documentation of concrete design and construction in residential areas, as well as application of materials, such as deicing chemical (both residual MDT chemicals and personal application) to determine why the concrete is scaling. In addition, there are many more causal factors such that what causes scaling in one driveway may not be the same causal factor for another driveway. It is clear that concrete with sufficient strength and proper air entrainment can prevent concrete scaling.

MDT moved to the use of deicers due to air quality and safety issues. Use of deicers is not a panacea. Winter maintenance is a balance and safety has always been MDT's utmost concern. The issue is to maximize safety and to minimize the detrimental effects of MDT's winter maintenance practices, while not decreasing safety. Given this, the Maintenance Division needs to continually evaluate application rates, new potential deicing chemicals, and other potential practices through literature, field trials, etc to minimize the detrimental effects of their use.

This committee recommends a number of actions.

- A public relations campaign
  - MDT needs to inform the public of its deicing strategy and needs to make it clear that the safest roads come at a cost.
  - MCA should take a proactive approach to educate residential concrete contractors and the public with regards to designing and constructing concrete with the proper strength and air entrainment for the intended use.
- MDT should participate in the South Dakota Department of Transportation's (SDDOT) pooled-fund study investigating the effects of deicing chemicals on concrete.
- MDT Maintenance needs to continually evaluate best management practices (BMP's) on application rates, new potential deicing chemicals, and other potential practices through literature, field trials, etc., to maximize the beneficial aspect of these products as well to minimize the detrimental effects of their use.

APPENDIX J

TxDOT Designation TEX-624-J
Test Procedure for
Corrosion Test of De-Icers and Anti-Icers

with
Laboratory Test Notes

Test Procedure for

CORROSION TEST OF DE-ICERS AND ANTI-ICERS

TxDOT Designation: Tex-624-J

Effective Date: January 2001

1. SCOPE

1.1 Use this method to determine the percent corrosion of de-icers and anti-icers on steel washers as compared to corrosion using sodium chloride.

1.2 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 *Ungalvanized washers,* in conformance with ASTM F 436, hardened to RC 38-45.

2.2 *Erlenmeyer flask,* 500 mL (16.9 fl. oz.)

2.3 *Corrosion test apparatus*, to automatically lower and raise washers into solutions for the specified amount of time.

2.4 *Concentrated hydrochloric acid.*

2.5 *Deionized water*.

2.6 *Sodium chloride*, reagent grade.

2.7 *Stannous chloride.*

2.8 *Antimony trioxide.*

2.9 *Cloth,* to clean washers.

2.10 *Trichlorethylene.*

2.11 *Analytical balance,* Class B in accordance with Tex-901-K.

3. SOLUTION

3.1 *De-icer or anti-icer,* 3% solution.

4. PREPARATIONS

4.1 *Preparing Washers:*

4.1.1 All washers used should be from the same batch to assure accuracy in test results. Use 3 washers for each de-icer/anti-icer solution (to include NaCl) and for the deionized water control tests.

4.1.2 Wash washers with concentrated hydrochloric acid to remove any type of residue, and rinse with deionized water.

4.1.3 Using a micrometer, measure the dimensions of each washer to the nearest 0.01 mm (0.0004 in.), and calculate the surface area as described under Section 6.

4.1.4 Rinse the washers with trichloroethylene.

4.1.5 Air-dry the washers.

4.1.6 Weigh the washers using an analytical balance to the nearest 0.001 g.

4.2 *3% Solutions:*

4.2.1 In an Erlenmeyer flask:

- for liquid de-icers/anti-icers, mix 3 parts de-icer/anti-icer to 97 parts deionized water, by volume.
- for solid de-icers/anti-icers, prepare a 3% solution, by weight.

4.2.2 Prepare a 3% NaCl solution (by weight).

4.2.3 Thoroughly mix solutions to ensure solubility.

4.3 *Cleaning Solution:*

4.3.1 Add 50 g stannous chloride and 20 g antimony trioxide to 4 L (1 gal.) of concentrated hydrochloric acid (HCl).

4.3.2 Mix the solutions thoroughly.

Note 1—Add the salts to the HCl to stop the reaction of the HCl with the steel once removing the rust or corrosion.

5. PROCEDURES

5.1 *Corrosion Test:*

5.1.1 Pour 300 mL (9 fl. oz.) of each solution (de-icer/anti-icer, NaCl, and deionized water) into separate 500-mL (16.9-fl. oz.) Erlenmeyer flasks.

5.1.2 Label each flask appropriately.

5.1.3 Place 3 washers in each flask, and cover flasks.

5.1.4 Set up the corrosion test apparatus to alternately lower the washers in the solution for 10 minutes and raise them to air dry for 50 minutes. Run for 72 hours.

5.1.5 Immediately remove washers from the solutions after the 72-hour cycle.

5.2 *Cleaning Washers:*

5.2.1 Place washers into a beaker containing the cleaning solution.

5.2.2 After 15 minutes, remove the washers, rinse them with deionized water, and wipe them with a cloth to clean off any deposit.

5.2.3 Return washers to the cleaning solution and repeat Sections 5.2.1 and 5.2.2.

5.2.4 Rinse with trichlorethylene, air dry, and weigh to the nearest 0.001 g.

---

6. CALCULATIONS

6.1.1 Calculate weight loss:

$$W(mg) = (I - F)1000\frac{mg}{g}$$

Where:
W = test specimen weight lost
I = test specimen initial weight
F = test specimen final weight.

6.2 Calculate the surface area of the washers:

$$A = \frac{3.1416(D^2 - d^2)}{2} 3.1416(t)(D) + 3.14(t)(d)$$

Where:
D = outside diameter, mm (in.)
d = inside diameter, mm (in.)
t = thickness, mm (in.)

6.2.1 Calculate corrosion rate of each washer:

$$CR(mpy) = \frac{KW}{ATD}$$

Where:
CR = corrosion rate (mils per year [mpy])
K = constant = 3450 for weight lost, mg
W = weight lost, mg
A = specimen area, mm^2 ($in.^2$)
T = time, hr.
D = specimen density, 7.86 mg/mm^3.

7. ARCHIVED VERSIONS

7.1 Archived versions are available.

Tex-624-J Laboratory Notes.

These are additional laboratory notes that were followed in the procedure of the tests to increase the repeatability between tests:

4.1.2 The washers can be placed in the hydrochloric acid in batches. For my tests I used 24 washers and split between two 250mL of HCL. The easiest way to get the washers out of the hydrochloric acid is to pour the acid into another container using a glass funnel. The glass funnel will catch the washers. Be careful not to break the funnel.

4.1.5 Washers were taken out of the ethanol and hand dried with paper towels. The washers were then transferred to a clean and dry paper towel and were air dried for 10 minutes. 5 minutes per side.

4.2.1-4.2.3 Solid material was split sampled in order to get a mix of material. Solid material was mixed in 500ml solution (15g solid) and liquids were mixed in 300mL solutions. Immediately after mixing (using the magnetic stirrer) the chemical excess was dumped allowing for 300mL solution (as called for in the procedure).

All chemicals were then allowed to sit for at least 12 hours before the start of the test to ensure complete solubility.

4.2.1-4.2.3 Meltdown 20 was a non-homogeneous mixture. After split sampling a 1000mL solution (30g of meltdown 20) was mixed. After mixing the solution for 10 minutes it was allowed to sit for at least 12 hours. After the minimum 12 hours a second 10 minute mixing took place using the magnetic stirrer. Immediately afterwards, 300ml of the solution was placed in the Erlenmeyer flask for testing.

4.2.3 All chemicals were stirred using a magnetic stirrer for 10 minutes. The magnetic bar was dipped in distilled water between batches to clean the bar and dried on a paper towel.

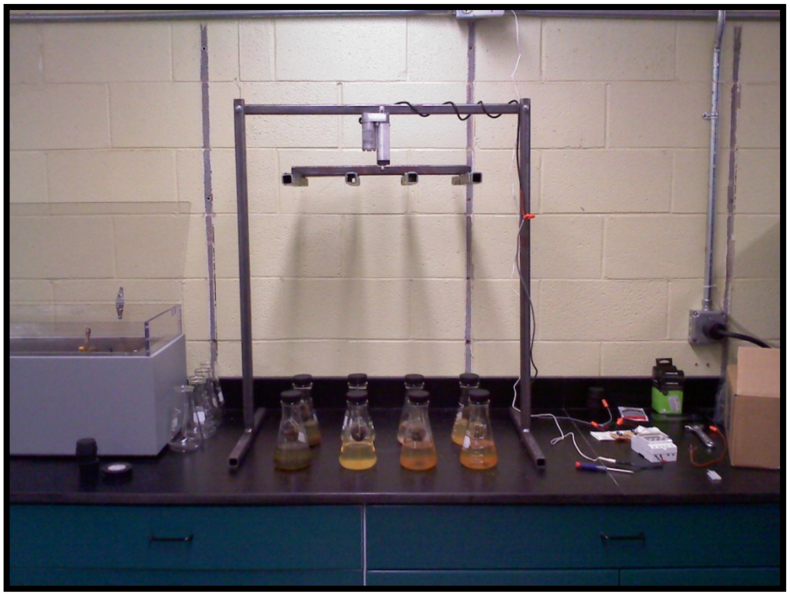
5.3.2 The Corrosion Constant K has the unit of([grams*hours*mils]/[mg*cm*yr]). See below:

$$K = \frac{g}{1000mg} * \frac{10mm}{cm} * \frac{(365 * 24)hr}{yr} = \frac{87.6\ g * hr * mm}{mg * cm * yr}$$

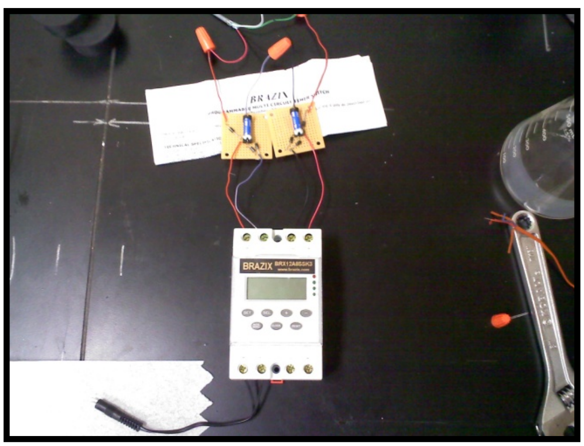
$$K = \frac{87.6\ g * hr * mm}{mg * cm * yr} * \frac{1in}{25.4mm} * \frac{1000mils}{in} = \frac{3448.8\ g * hr * mils}{mg * cm * yr}$$

$$K = \frac{3448.8\ g * hr * mils}{mg * cm * yr}$$

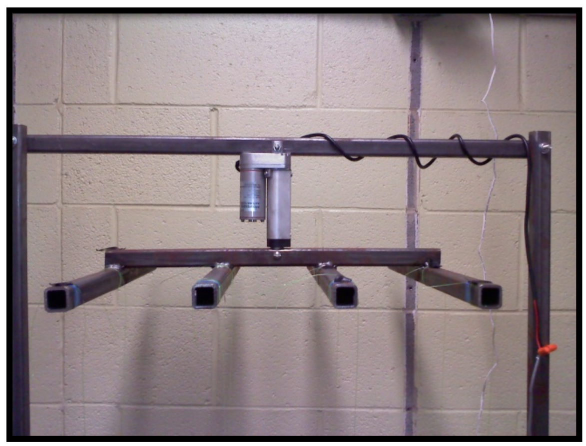
The following are pictures from the tests. The testing apparatus can be seen in the following pictures:



Testing Apparatus

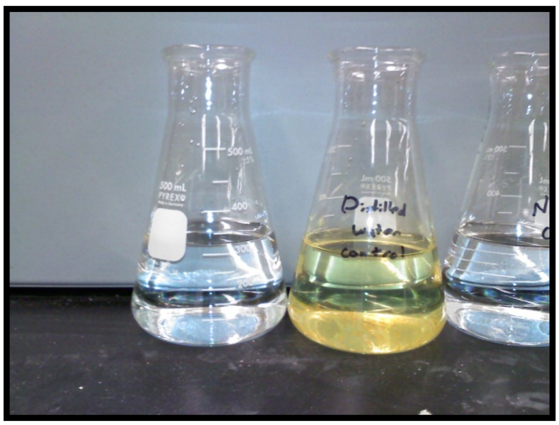


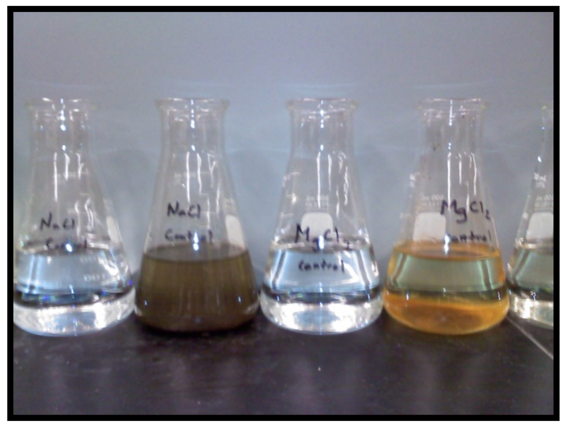
Controller with wiring for DC Linear Actuator

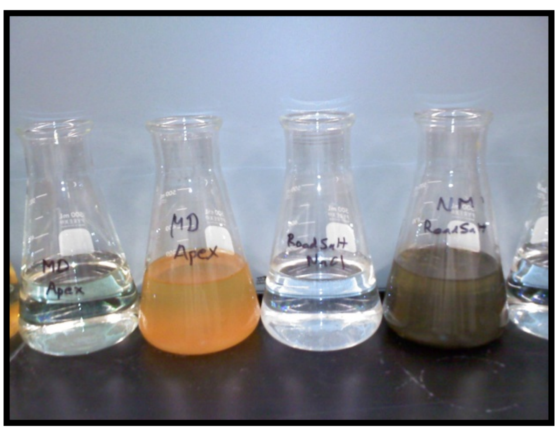


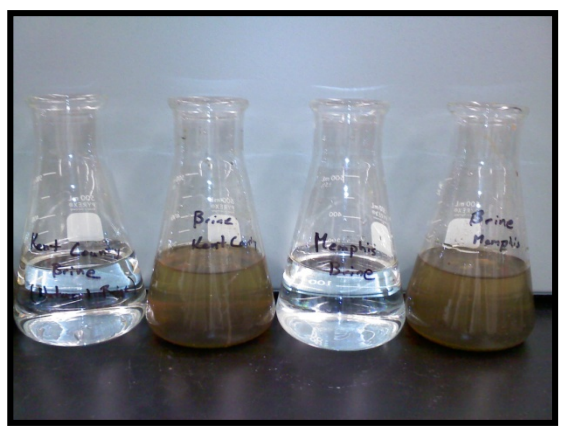
Linear Actuator

The following are pictures of the chemicals before and after the completion of the Tex-624-J test:









Documentation and pictures for the materials needed for the Tex-624-J test:

Materials needed for test	**Description:**
	Bought from Fisher Scientific
Product Name:	Catalog Number
Hydrochloric Acid, Certified ACS Plus	A144212
Sodium Chloride Certified ACS	S271-1
Antimony Trioxide Certified ACS	A860100
Stannous Chloride ACS	T142100
Denatured Ethanol	S73985A
	Bought from Ad-Tek, Inc. Advanced Calibration Technologies phone: 800-259-5058
Steel Coupons	½ inch flat steel washers Hardener Round Washer Domestic ASTM F436, Type 1. Hardened to RC 38-45, Non galvanized Code Number: CouponTSI#

Documentation for chemicals used in Tex-624-J Test:

	Chemicals	DHT#	Shipment Date	Invoice# / Ticket #	Date Received from TxDOT/other	Location
(1)	MD 20	165614	1/26/2012	16345-02	8/20/2012	Lubbock Southeast Maintenance
(2)	MD Apex	157072	1/26/2012	6493-002	8/20/2012	Lubbock Southeast Maintenance
(3)	RoadSalt	139821	3/1/2012	843886	8/6/2012	Memphis Maintenance
(4)	Brine	166775	3/1/2012	843884	8/6/2012	Memphis Maintenance
(5)	Natural Brine	N/A	N/A	N/A	8/2/2012	Kent County, Texas
	Sodium Chloride Certified ACS	N/A	N/A	N/A	N/A	Fisher Scientific Catalog Number: S271-1
	Magnesium Chloride Hexahydrate Certified ACS	N/A	N/A	N/A	N/A	Fisher Scientific Catalog Number: 7791-18-6

APPENDIX K

RAW DATA
TxDOT Designation TEX-624-J
Test Procedure for
Corrosion Test of De-Icers and Anti-Icers

Tex 624-J											
Date:	1/18/2013	1/21/2013									
Product Name	Sample	Washer Number	Initial Weight (g)	Final Weight (g)	**Change (g)**	Inner Diameter (in)	Outer Diameter (in)	Thickness (in)	**Surf. Area (in^2)**	**Corrosion (mils/yr)**	**PNS % Corrosion**
NaCl	1	1	15.5443	15.4476	**0.0967**	0.6130	1.3730	0.1000	**2.9948**		
	2	2	15.4898	15.3902	**0.0996**	0.6115	1.3765	0.1010	**3.0197**		
	3	3	15.5597	15.4521	**0.1076**	0.5600	1.3720	0.1010	**3.0773**		
	Avg				**0.1013**				**3.0306**	**31.585**	**----**
H20	1	4	15.5154	15.5041	**0.0113**	0.5675	1.3770	0.0990	**3.0773**		
	2	5	15.5221	15.5025	**0.0196**	0.5605	1.3775	0.1005	**3.0990**		
	3	6	15.4828	15.4627	**0.0201**	0.5610	1.3780	0.1010	**3.1036**		
	Avg				**0.0170**				**3.0933**	**5.193**	**---**
	1	7	15.3873	15.3337	**0.0536**	0.5655	1.3740	0.0990	**3.0664**		
	2	8	15.3950	15.3394	**0.0556**	0.5565	1.3740	0.1000	**3.0855**		
MD 20	3	9	15.5806	15.5316	**0.0490**	0.5565	1.3760	0.1015	**3.1039**		
(1)	Avg				**0.0527**				**3.0852**	**16.151**	**41.52**
	1	10	15.5178	15.4578	**0.0600**	0.5650	1.3735	0.1010	**3.0770**		
	2	11	15.5341	15.4670	**0.0671**	0.6000	1.3770	0.1000	**3.0340**		
MD Apex	3	12	15.2019	15.1360	**0.0659**	0.5465	1.3750	0.0985	**3.0953**		
(2)	Avg				**0.0643**				**3.0688**	**19.809**	**55.38**
	1	13	15.4925	15.4032	**0.0893**	0.5925	1.3720	0.0100	**2.4671**		
	2	14	15.4343	15.3333	**0.1010**	0.5665	1.3725	0.0995	**3.0610**		
RoadSalt	3	15	15.2361	15.1329	**0.1032**	0.6205	1.3735	0.0980	**2.9724**		
(3)	Avg				**0.0978**				**2.8335**	**32.626**	**103.94**
	1	16	15.5034	15.3826	**0.1208**	0.5680	1.3745	0.0995	**3.0681**		
	2	17	15.4213	15.2976	**0.1237**	0.5895	1.3710	0.1000	**3.0226**		
Magnesium Chloride	3	18	15.5483	15.4328	**0.1155**	0.5960	1.3750	0.1025	**3.0465**		
	Avg				**0.1200**				**3.0457**	**37.230**	**121.39**
	1	19	15.5572	15.4612	**0.0960**	0.5665	1.3765	0.1000	**3.0826**		
Memphis	2	20	15.4367	15.3380	**0.0987**	0.5870	1.3735	0.0995	**3.0349**		
Brine	3	21	15.3741	15.2791	**0.0950**	0.6205	1.3760	0.0990	**2.9903**		
(4)	Avg				**0.0966**				**3.0359**	**30.056**	**94.21**
	1	22	15.2762	15.1808	**0.0954**	0.5655	1.3740	0.0990	**3.0664**		
Natural Brine 1	2	23	15.5452	15.4469	**0.0983**	0.5750	1.3750	0.1010	**3.0692**		
(5)	3	24	15.1920	15.1020	**0.0900**	0.5650	1.3740	0.0980	**3.0610**		
	Avg				**0.0946**				**3.0655**	**29.150**	**90.77**

Tex 624-J											
Date:	2/15/2013	2/18/2013									
Product Name	Sample	Washer Number	Initial Weight (g)	Final Weight (g)	**Change (g)**	Inner Diameter (in)	Outer Diameter (in)	Thickness (in)	**Surf. Area (in^2)**	**Corrosion (mils/yr)**	**PNS % Corrosion**
NaCl	1	25	15.5539	15.4666	**0.0873**	0.5700	1.3750	0.1000	**3.0705**		
	2	26	15.1982	15.1135	**0.0847**	0.5695	1.3760	0.0995	**3.0728**		
	3	27	15.2314	15.1462	**0.0852**	0.5680	1.3730	0.0990	**3.0581**		
	Avg				**0.0857**				**3.0671**	**26.413**	**----**
H20	1	28	15.4421	15.4307	**0.0114**	0.5700	1.3750	0.1010	**3.0766**		
	2	29	15.4844	15.4734	**0.0110**	0.5515	1.3780	0.1010	**3.1172**		
	3	30	15.4513	15.4392	**0.0121**	0.5720	1.3735	0.1015	**3.0697**		
	Avg				**0.0115**				**3.0879**	**3.519**	**---**
	1	31	15.4404	15.4280	**0.0124**	0.5465	1.3750	0.1010	**3.1103**		
	2	32	15.4446	15.4338	**0.0108**	0.5650	1.3780	0.1010	**3.0978**		
MD 20 *	3	33	15.4579	15.4473	**0.0106**	0.5705	1.3750	0.1000	**3.0697**		
(1)	Avg				**0.0113**				**3.0926**	**3.442**	**-0.34**
	1	34	15.4866	15.4367	**0.0499**	0.5730	1.3740	0.1015	**3.0706**		
	2	35	15.4689	15.4131	**0.0558**	0.5720	1.3740	0.1015	**3.0721**		
MD Apex	3	36	15.2123	15.1550	**0.0573**	0.5680	1.3760	0.0995	**3.0750**		
(2)	Avg				**0.0543**				**3.0725**	**16.710**	**57.62**
	1	37	15.4821	15.3956	**0.0865**	0.5415	1.3785	0.1020	**3.1396**		
	2	38	15.5433	15.4676	**0.0757**	0.5705	1.3785	0.1020	**3.0982**		
RoadSalt	3	39	15.5364	15.4549	**0.0815**	0.5680	1.3775	0.1025	**3.1003**		
(3)	Avg				**0.0812**				**3.1127**	**24.660**	**92.34**
	1	40	15.4697	15.3539	**0.1158**	0.5715	1.3740	0.1010	**3.0697**		
	2	41	15.5098	15.3960	**0.1138**	0.5715	1.3750	0.1025	**3.0835**		
Magnesium Chloride	3	42	15.4741	15.3593	**0.1148**	0.5665	1.3785	0.1010	**3.0980**		
	Avg				**0.1148**				**3.0838**	**35.177**	**138.28**
	1	43	15.5180	15.4273	**0.0907**	0.5475	1.3760	0.1035	**3.1287**		
Memphis	2	44	15.4603	15.3767	**0.0836**	0.5735	1.3770	0.1020	**3.0868**		
Brine	3	45	15.4962	15.4085	**0.0877**	0.5700	1.3760	0.0990	**3.0690**		
(4)	Avg				**0.0873**				**3.0948**	**26.665**	**101.10**
	1	46	15.2170	15.1325	**0.0845**	0.5725	1.3765	0.1000	**3.0737**		
Natural Brine 1	2	47	15.5091	15.4167	**0.0924**	0.5675	1.3790	0.1020	**3.1049**		
(5)	3	48	15.4693	15.3832	**0.0861**	0.5730	1.3780	0.1010	**3.0861**		
	Avg				**0.0877**				**3.0883**	**26.824**	**101.79**

*Note: The Meltdown 20 product is not a homogenous material. After a higher than expected corrosion rate from the 1/18/2013 to 1/21/2013 Tex-624-J test, the split sampling for Meltdown 20 was completed with the omission of large diameter particles, with the larger diameter particles consisting mostly of salt. This inevitably changed the ratio of sodium chloride to corrosion inhibitor. Split sampling should have a mix of particle sizes, roughly at the same ratio of the overall batch. Therefore, Meltdown 20 results from this test were omitted in the analysis of the results.

Tex 624-J											
Date:	2/19/2013	2/22/2013									
Product Name	Sample	Washer Number	Initial Weight (g)	Final Weight (g)	**Change (g)**	Inner Diameter (in)	Outer Diameter (in)	Thickness (in)	**Surf. Area (in^2)**	**Corrosion (mils/yr)**	**PNS % Corrosion**
NaCl	1	49	15.5663	15.4854	**0.0809**	0.5695	1.3740	0.1045	**3.0941**		
	2	50	15.4713	15.3831	**0.0882**	0.5715	1.3755	0.1055	**3.1042**		
	3	51	15.5189	15.4335	**0.0854**	0.5705	1.3770	0.1065	**3.1188**		
	Avg				**0.0848**				**3.1057**	**25.811**	**----**
H20	1	52	15.4090	15.3952	**0.0138**	0.5675	1.3740	0.1035	**3.0909**		
	2	53	15.5204	15.5061	**0.0143**	0.5705	1.3750	0.1060	**3.1064**		
	3	54	15.4293	15.4150	**0.0143**	0.5690	1.3710	0.1030	**3.0717**		
	Avg				**0.0141**				**3.0897**	**4.322**	**---**
	1	55	15.5009	15.4512	**0.0497**	0.5715	1.3730	0.1035	**3.0804**		
	2	56	15.4118	15.3640	**0.0478**	0.5675	1.3730	0.1030	**3.0832**		
MD 20	3	57	15.4741	15.4239	**0.0502**	0.5625	1.3730	0.1050	**3.1026**		
(1)	Avg				**0.0492**				**3.0887**	**15.062**	**49.98**
	1	58	15.4319	15.3829	**0.0490**	0.5725	1.3745	0.1025	**3.0797**		
	2	59	15.5190	15.4666	**0.0524**	0.5695	1.3760	0.1055	**3.1095**		
MD Apex	3	60	15.2330	15.1813	**0.0517**	0.5690	1.3730	0.1025	**3.0779**		
(2)	Avg				**0.0510**				**3.0891**	**15.611**	**52.53**
	1	61	15.4519	15.3664	**0.0855**	0.5715	1.3740	0.1030	**3.0820**		
	2	62	15.4859	15.3972	**0.0887**	0.5715	1.3760	0.1050	**3.1035**		
RoadSalt	3	63	15.2297	15.1476	**0.0821**	0.5695	1.3765	0.1030	**3.0965**		
(3)	Avg				**0.0854**				**3.0940**	**26.092**	**101.31**
	1	64	15.5329	15.4202	**0.1127**	0.5710	1.3725	0.1035	**3.0788**		
	2	65	15.5650	15.4476	**0.1174**	0.5700	1.3780	0.1040	**3.1089**		
Magnesium Chloride	3	66	15.4778	15.3627	**0.1151**	0.5700	1.3765	0.1040	**3.1019**		
	Avg				**0.1151**				**3.0965**	**35.113**	**143.29**
	1	67	15.4794	15.3880	**0.0914**	0.5705	1.3735	0.1040	**3.0872**		
Memphis	2	68	15.4761	15.3912	**0.0849**	0.5710	1.3730	0.1035	**3.0811**		
Brine	3	69	15.5459	15.4531	**0.0928**	0.5720	1.3735	0.1055	**3.0942**		
(4)	Avg				**0.0897**				**3.0875**	**27.452**	**107.64**
	1	70	15.4975	15.4077	**0.0898**	0.5685	1.3730	0.1055	**3.0970**		
Natural Brine 1	2	71	15.1852	15.0944	**0.0908**	0.5690	1.3765	0.1030	**3.0972**		
(5)	3	72	15.5017	15.4134	**0.0883**	0.5675	1.3745	0.1055	**3.1054**		
	Avg				**0.0896**				**3.0999**	**27.323**	**107.03**

Tex 624-J											
Date:	5/7/2013	5/10/2013		Temp	71 F						
Product	Sample	Washer	Initial Weight	Final Weight	**Change**	Inner Diameter	Outer Diameter	Thickness	**Surf. Area**	**Corrosion**	**PNS % Corrosion**
Name		Number	(g)	(g)	**(g)**	(in)	(in)	(in)	**(in^2)**	**(mils/yr)**	
NaCl	1	76	15.4212	15.3291	**0.0921**	0.5771	1.3755	0.1035	**3.0838**		
	2	77	15.4284	15.3352	**0.0932**	0.5715	1.3795	0.1035	**3.1106**		
	3	78	15.5190	15.4153	**0.1037**	0.5685	1.3750	0.1035	**3.0941**		
	Avg				**0.0963**				**3.0961**	**29.400**	----
H20	1	73	15.5531	15.5356	**0.0175**	0.5730	1.3785	0.1030	**3.1007**		
	2	74	15.2762	15.2549	**0.0213**	0.5705	1.3765	0.1020	**3.0889**		
	3	75	15.5163	15.4922	**0.0241**	0.5640	1.3765	0.1050	**3.1167**		
	Avg				**0.0210**				**3.1021**	**6.387**	---
	1	79	15.5147	15.4776	**0.0371**	0.5675	1.3750	0.1035	**3.0955**		
	2	80	15.4902	15.4559	**0.0343**	0.5665	1.3765	0.1040	**3.1070**		
MD 20	3	81	15.4471	15.4153	**0.0318**	0.5685	1.3785	0.1065	**3.1287**		
(1)	Avg				**0.0344**				**3.1104**	**10.451**	**17.66**
	1	82	15.5540	15.5039	**0.0501**	0.5660	1.3795	0.1055	**3.1309**		
	2	83	15.5327	15.4811	**0.0516**	0.5700	1.3780	0.1065	**3.1242**		
MD 20	3	84	15.5226	15.4678	**0.0548**	0.5690	1.3755	0.1055	**3.1079**		
(1)	Avg				**0.0522**				**3.1210**	**15.794**	**40.88**

APPENDIX L

LAB NOTES CHLORIDE DIFFUSION

AASHTO T-259-02
Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration

Concrete Mix Design

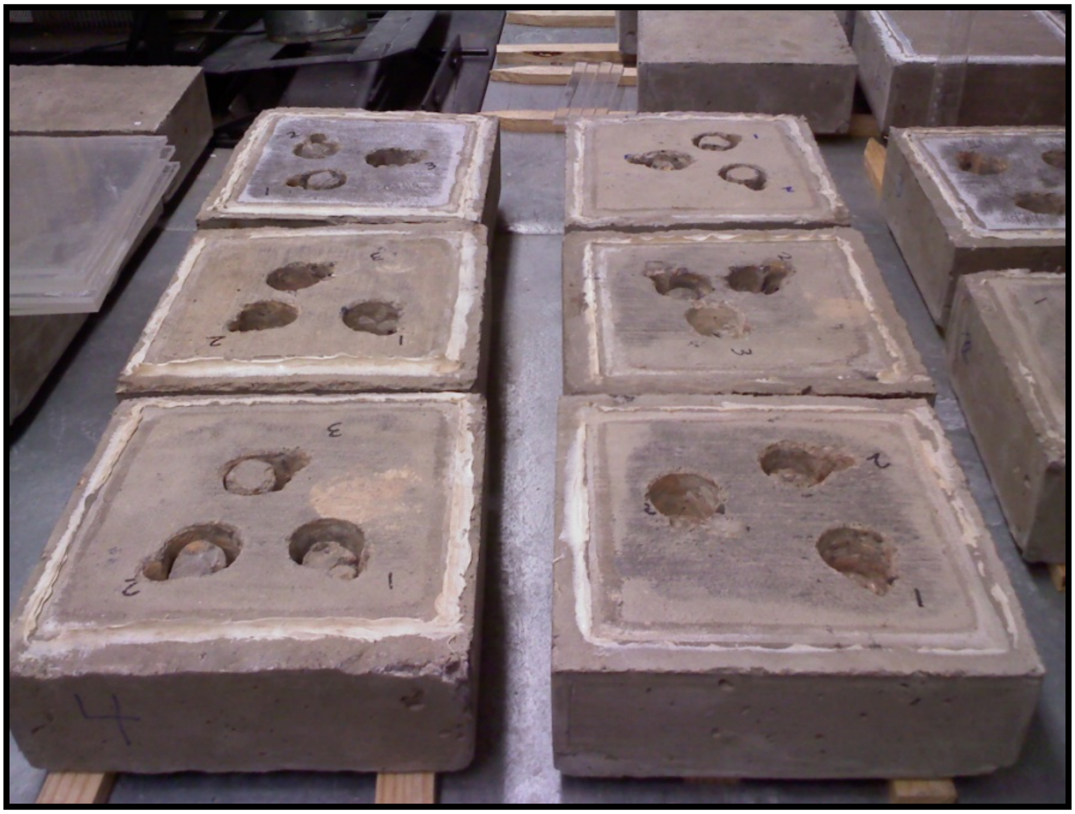
	Last Updated: Monday March 12, 2012
Name: 215 Class S yd	
Description: TxDOT Class S HPC	
Mix Yield: 25.771 cf	W/C Ratio: 0.42
Ingredient	**Amount**
1" Crockett	1800 lb
Intermediate	245 lb
Sand	990 lb
Cement	397 lb
Fly ash (Class C)	212 lb
Water	255 lb
BASF MBAE-90	6 oz
BASF Polyhead 1720	54 oz

Crockett County Mining Plant #2
Material:
1" Crockett
Intermediate

R.E. Janes Gravel Co.
Woods
Material:
Sand

Sample blocks during ponding

Gilson Model HM-343 Sample Drilling Assembly



Sample blocks after coring.

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4. Title and Subtitle Snow and Ice Control Materials for Texas Roads: VOLUME 2, Field Trials and Laboratory Study		5. Report Date March 2017 6. Performing Organization Code
7. Author(s) Andrew Jackson, Ken Rainwater, William Lawson, Sanjaya Senadheera, Daan Liang, James Surles, Audra Morse, Weile Yan		8. Performing Organization Report No. 0-6793-1 – Vol. 2
9. Performing Organization Name and Address Texas Tech University Center for Multidisciplinary Research in Transportation Box 41023 Lubbock, TX 79409		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-6793
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report January 2012 – August 2015 14. Sponsoring Agency Code
15. Supplementary Notes: Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.		

16. Abstract

This report provides findings from a four-year research study of snow and ice control materials for winter weather roadway maintenance applications in Texas. The report is presented in two volumes. Volume 1 is a literature review and best practices review of snow and ice control materials both nationally and statewide, addressing material application and effectiveness, the availability and usability of Texas brines, durability impacts (corrosion) on infrastructure, environmental impacts and regulations, and a detailed cost analysis of TxDOT's current usage of snow and ice control materials. Volume 2 presents findings from side-by-side comparison of selected snow and ice control chemicals through field trials and laboratory testing. Key findings are (1) the effectiveness of TxDOT's maintenance response to winter weather is a direct function of TxDOT having a clearly-articulated strategy for responding to winter weather, both for typical climate and extreme winter storm events for all regions of the state; (2) geologic brines for snow and ice control include natural brine, manufactured brine, and produced brine related to oilfield operations, and all three must be tested and approved to be considered for widespread use; (3) TxDOT's current snow and ice control chemicals include granular road salt, salt brine, MeltDown 20®, and MeltDown Apex™, all of which are chlorides, and, notwithstanding TxDOT's comparatively low application rates and application frequencies, may potentially cause long-term infrastructure durability impacts; (4) environmental regulations and literature suggest minimal added risk to the environment associated with TxDOT's current usage of snow and ice control chemicals; (5) under typical Texas winter weather and road conditions, at manufacturer's recommended application rates, granular road salt performed comparably to or better than MeltDown 20® at lower cost per lane mile and similarly, salt brine performed comparably to MeltDown Apex™ with the added benefit that salt brine does not create a slick pavement surface for anti-icing when applied at temperatures above freezing; and (6) cost savings associated with TxDOT's snow and ice operations can be achieved through standardized selection of materials, improved operational efficiency, better risk management practices, and use of performance-based models for snow and ice control.

17. Key Words: Snow and Ice, Winter Roadway Maintenance, Road Salt, Brine, MeltDown 20, MeltDown Apex, Abrasives, Durability, Corrosion, Environmental Impact, Field Trials, Cost Analysis, Side-by-Side Comparison		18. Distribution Statement No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161, www.ntis.gov	
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Snow and Ice Control Materials for Texas Roads
VOLUME 2: Field Trials and Laboratory Study

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Project Number 0-6793

Project Report 0-6793-1- Vol. 2

performed in cooperation with

Texas Department of Transportation

and

Federal Highway Administration

Center for Multidisciplinary Research in Transportation

Department of Civil, Environmental and Construction Engineering

Texas Tech University

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CHAPTER 1
INTRODUCTION

1.1 The Research Problem

1.1.1 Purpose

This document, Volume 2 of the research report, presents findings from field trials and laboratory testing conducted as part of a four-year research study on snow and ice control materials for winter weather roadway maintenance applications in Texas. The purpose of this research was to provide Texas Department of Transportation (TxDOT) roadway maintenance professionals with the information they need to know in order to evaluate, select, procure, apply, and otherwise implement snow and ice control materials and achieve satisfactory results in their respective areas of Texas.

1.1.2 Scope

The focus of this project was on common snow and ice materials used by TxDOT in its maintenance operations, as well as on alternative products such as natural brines. The research considered all major aspects of snow and ice control materials including effectiveness, availability, impact on infrastructure durability (corrosion), environmental concerns and regulations, and cost.

1.2 TxDOT-sponsored Winter Weather Research

1.2.1 Prior Research

TxDOT has recognized the need to promote effective winter weather roadway maintenance in all areas of the state. In early 2011, TxDOT sponsored two major winter weather research studies:

- Project 0-6669, Best Practices for Emergency Operations
- Project 5-9044, Winter Weather Management and Operations Training Curriculum Development and Instruction

Project 0-6669 focused on identifying actionable practices relative to winter weather operations (Perkins, et al. 2012). The research objective was to develop a winter weather operations manual that could be used by TxDOT districts vulnerable to weather related emergencies.

Project 5-9044 consisted of two curriculum development and training programs (Lawson, et al. 2012). The first program created a 6-hour training course on management of winter weather events, and then delivered this management training to 845 TxDOT maintenance professionals statewide. The second program created a 12-hour training course on winter weather operations, and then delivered train-the-trainer events to TxDOT training vendors who, in turn, offer the operations training to TxDOT maintenance personnel on a recurring basis.

1.2.2 TxDOT Project 0-6793

In January 2012, TxDOT sponsored 0-6793, “Snow and Ice Chemicals for Texas Roads,” which is the research described in this report. This study was initially scheduled to be completed in 20 months but was subsequently modified to include two additional years of field and laboratory data collection. The work plan included seven functional tasks.

1.2.2.1 Task 1. Characterize the application and effectiveness of snow and ice control chemicals. The objective of Task 1 was to identify and classify the types of snow and ice control chemicals which can be used for Texas roads and winter weather conditions. This included the effectiveness, as a function of application, of the major snow and ice chemicals currently used by TxDOT (e.g. NaCl, $MgCl_2$, and $MgCl_2$ with additives) as well as natural brines. This task also included limited evaluation of abrasives to provide a basis for comparison.

1.2.2.2 Task 2. Determine the availability, storage requirements and transport issues related to natural brines. Task 2 characterized natural brines as a potential snow and ice control chemical for Texas roads. This required evaluation of the availability of natural brine suppliers or potential suppliers for the state of Texas, review of storage requirements for these products, and consideration of transport issues including mode of transport, time of transport, and cost. Durability concerns associated with corrosion, and environmental concerns and regulatory issues associated with the use of these brines were also addressed.

1.2.2.3 Task 3. Evaluation of infrastructure durability impacts due to anti-icing and de-icing operations. The primary objective of Task 3 was to evaluate possible adverse impacts to the durability of highway infrastructure caused by de-icing and anti-icing operations on Texas roads. These durability concerns include corrosion of steel reinforcement and scaling of surfaces of concrete structures, and also corrosion of infrastructure exposed to these chemicals such as steel bridge girders, expansion joints and supports, and also snow and ice control equipment.

1.2.2.4 Task 4. Evaluate the environmental impact and regulations with relation to the current and future use of salts and brines to control snow and ice on Texas roads. Task 4 consisted of a comprehensive review of the relative environmental impacts of anti-icing and de-icing salts including natural brines. Research also evaluated the current state and future direction of environmental regulations covering the use of these salts and brines in Texas. In addition, this task evaluated environmental impacts associated with selected, commonly-used abrasives.

1.2.2.5 Task 5. Field trial to compare effectiveness of snow and ice control chemicals. The objective of Task 5 was to obtain a comparative “side-by-side” determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions. Task 5 is the part of project 0-6793 that was expanded and extended two additional years. Subtasks included:

Winter 2012-13 (original contract)

- Identify and Establish Field Research Site
- Storm Monitoring and Data Collection
- Data Analysis and Reporting

The Winter 2012-13 season was very mild and produced no candidate storms at the field research site. Thus no data were collected and the study was extended two more years for the purpose and intention of obtaining field data.

Winter 2013-14 (Modification 2)

- Subtask 5.1 Identify and Establish Field Research Site
- Subtask 5.2 Storm Monitoring and Data Collection
- Subtask 5.3 Data Analysis and Reporting

Winter 2014-15 (Modification 3)

- Subtask 5.4 Laboratory Test Program to Evaluate Snow and Ice Control Chemicals
- Subtask 5.5 Update Field Research Site for Winter 2014-15
- Subtask 5.6 Winter 2014-15 Storm Monitoring and Data Collection
- Subtask 5.7 Data Analysis and Reporting

The field and laboratory work performed for Task 5 represented a major research effort for this project. This volume, Volume 2, of the 0-6793 report presents the findings from Task 5.

1.2.2.6 Task 6. Perform a comprehensive cost analysis of the use of snow and ice control materials. Task 6 consisted of an analysis of the life-cycle costs of selected snow and ice control materials used in Texas. This analysis considered both the short-term cost factors (e.g., purchase, processing, storage, transport, and application) and long-term factors (e.g., potential damage to equipment and roadways) of these materials.

1.2.2.6 Task 7. Production of deliverables. The objective of Task 7 was to produce the deliverables associated with the project including the research report and products.

Project 0-6793 considered all major aspects of TxDOT's typical snow and ice control materials including their effectiveness, availability, impact on infrastructure durability (corrosion), environmental concerns and regulations, field performance, and cost. Research

Tasks 1 through 4, and Task 6, were performed in 2012-2013 in accordance with the initial project agreement, and findings from these tasks are reported in Volume 1 of the research report. Research Task 5 spanned 2012-2015 as per the modified project agreement, and findings from Task 5 are reported in Volume 2 of the research report. Collectively, this work serves to quantify and qualify the relative merits of common snow and ice materials used in TxDOT's maintenance operations.

1.3 Organization of the Research Report

As has been noted, the 0-6793 research is reported in two volumes, each with its own appendixes.

The companion volume, VOLUME 1, is essentially a literature and best practices review. Organized into six chapters, VOLUME 1 reports findings from research Tasks 1 through 4 and from research Task 6. Except for the introduction, each chapter in VOLUME 1 directly addresses a particular research task. Chapter 1 provides a statement of the research problem and an overall introduction to research project 0-6793. Chapter 2 summarizes a comprehensive review of technical literature on snow and ice control materials used in the United States including the effectiveness of these materials in relation to type of application (Task 1). Chapter 3 discusses the availability and potential usability of brines for snow and ice control including natural brines, manufactured brines, and oilfield brines (Task 2). Chapter 4 discusses the durability impacts of snow and ice chemicals on infrastructure, both based on review of the literature and on a limited experimental program (Task 3). Chapter 5 summarizes the known environmental impacts and regulations associated with application of snow and ice chemicals, nationally and in Texas (Task 4). Finally, Chapter 6 provides a detailed cost analysis of TxDOT's current usage of snow and ice chemicals (Task 6). The research summarized in VOLUME 1 was performed in 2012-13 and the report reflects findings for that time period.

This volume, VOLUME 2, focuses on field trials and laboratory testing. VOLUME 2 is organized into eight chapters and reports findings from research Task 5 and the overall project summary and conclusions. Chapter 1 of VOLUME 2 provides a statement of the research problem and an overall introduction to Task 5 for project 0-6793. Chapter 2 describes the field research test site near Canyon, Texas. Chapter 3 presents the research method for Task 5 including storm response, field data collection, data presentation, and analyses. Chapter 4 of VOLUME 2 summarizes all field data obtained for the three winter seasons and identifies the subset of data judged of sufficient quality and reliability to be usable for subsequent analysis. Chapter 5 presents anti-icing results from the field test site, focusing on selected liquid snow and ice control chemicals. Chapter 6 presents de-icing results from the field test site, focusing on granular products. Chapter 7 summarizes results from laboratory testing performed for the study.

Chapter 8 summarizes overall findings from the research project including conclusions, limitations, and recommendations for further study.

1.4 Introduction to Task 5

The objective of Task 5 was to obtain a comparative “side-by-side” determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions and using both anti-icing and de-icing strategies. While it was recognized that field trials that explore *all* key variables associated with snow and ice control would be of interest, practically it was necessary to limit the field trials to a manageable number of variables.

The original (proposed) research program was to capture field data during four significant storm events during Winter 2012/13: two snow storms and two ice storms. The snow storm evaluations were to focus on clearing snow from an asphalt road surface and the ice storm evaluations were to focus on clearing ice from a concrete bridge deck. Test sections were established in advance to allow for head-to-head comparisons of four different chemical treatment scenarios for each storm, both for anti-icing and de-icing. Effectiveness would be assessed based on visual evaluation of the pavement surface (qualitative assessment) before and after chemical treatment and plowing. Where possible, pavement surface friction would also be measured.

The actual program for field trials was dynamically modified in response to the winter weather which presented at the field test site. After the first year with no candidate storms, the research test site was relocated north 100 miles to Canyon, to a location with only asphalt (seal coat surfaced) pavement. Field trials ultimately spanned three winters, not one, and the research only evaluated snow storms as no ice storms occurred at the field site over the course of the study. The original method for measuring surface friction was prohibited but an alternative field method was eventually implemented. A laboratory test program was added for the third year to explore the influence of certain variables which could not be addressed in the field trials.

This volume of the research report documents the field trials and laboratory test program which were performed under Task 5 of the research study, as modified.

CHAPTER 2
FIELD RESEARCH SITE

2.1 Introduction

2.1.1 Overview

The objective of research Task 5 was to obtain a comparative determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions. Achieving this objective required, among other things, establishing a field site to support winter maintenance operations and data collection focused on evaluation of actual performance of deicing and anti-icing products. Field research was selected for this study because laboratory testing often does not mimic actual field conditions such as varying temperatures, wind, traffic, plowing activity, and other roadway maintenance factors.

Field testing is desirable in terms of replicating actual winter roadway maintenance conditions, yet it can be difficult to accomplish because of ever changing conditions in the field environment where some variables are difficult to control or even to document. In this context, the field study was designed to measure or manipulate relevant variables to the extent practicable. This chapter summarizes work performed in identifying, selecting, and establishing the field research sites for the project.

2.1.2 Candidate Field Research Sites

Candidate field research test sites were identified based on several factors including but not limited to safety considerations associated with obtaining field measurements, climate considerations such as the likelihood of obtaining candidate winter storms, and field site considerations including site location and access, pavement surface type and condition, traffic and maintenance, and other factors. Ultimately the following sites were selected.

- Winter 2012-13: the candidate site selected for the project was the West Airport Runway at Reese Technology Center, Lubbock County, Texas. The researchers also identified a backup site, Oldham County Airport, located about 35 miles west of Amarillo near Vega, Texas.

- Winter 2013-14: the candidate site selected for the project was a 2.5-mile section of service road for southbound IH 27 between Cemetery Road and Hungate Road, located in Randall County, about 5 miles south of Canyon, Texas.

- Winter 2014-15: the field site from Winter 2013-14 was re-used, but with various modifications to accommodate an updated research design.

The following sections provide details about each field research site selected for the project. Emphasis is given to the Randall County site since that is where most of the field research operations were actually performed.

2.2 Winter 2012-13: West Airport Runway, Reese Technology Center

The primary site for field testing during Winter 2012-13 was established at the West Airport Runway, Reese Technology Center, Lubbock County, Texas (Figure 2.1). Located approximately 8 miles west of the Texas Tech University main campus and formerly Reese Air Force Base, this site provided a closed, typically-inactive section of airport runway to perform the field trials.

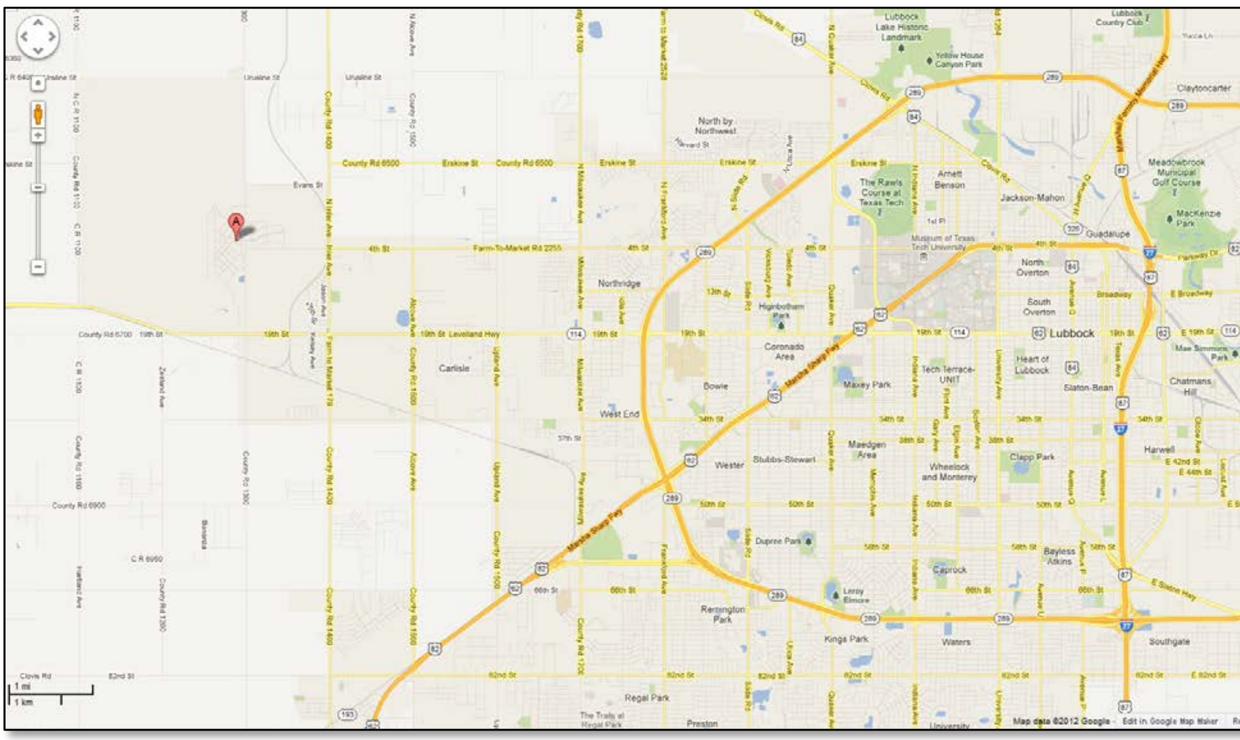


Figure 2.1 Reese Technology Center Vicinity Map (*source*: Google Maps)

The West Runway at Reese Technology Center (Figure 2.2) was particularly well-suited to achieving the research objective for two reasons:

- The Reese site is located close to Texas Tech University and thereby minimized both expense and travel risk associated with mobilization during winter weather.
- The West Runway provided both a concrete pavement surface and an asphalt pavement surface. This allowed testing to be done on two types of pavement surface during the same storm event.

Figure 2.2. West Runway, Reese Technology Center Aerial Photo (*source*: Google Maps)

The research plan was to capture field data during both snow and ice storm events at the Reese site. However, Winter 2012-13 was very mild for the Lubbock area and the Reese site experienced no candidate storms.

The research plan included a contingency for relocating to an alternative field site, Oldham County Airport, a general aviation airport located about 125 miles north of Lubbock, near Vega, Texas. Climate data showed this area was statistically more likely to experience significant snow storms than Lubbock. In January 2013, the project monitoring committee evaluated whether to relocate to Oldham County Airport, but considering the date, the significant resource input into the Reese Center location, and the superiority of Reese Center compared to the Oldham County Airport site, the decision was made to remain at Reese Center.

2.3 Winter 2013-14: Service Road, IH 27 Southbound, Randall County, Texas

2.3.1 Overview

Given the mild weather in Lubbock during Winter 2012-13, no field data were obtained under Task 5 of the research study. Therefore, TxDOT authorized Modification 2 on August 22, 2013, extending the project one year in order to obtain field data. Part of this modification included identifying and establishing a field test site suitable for field trials in the northern Texas Panhandle. To accomplish this task, the research team identified and evaluated alternative field sites that satisfied the project criteria including but not limited to:

a) The traveling public will not be impacted by field testing;

b) Research activities can be accomplished independently of TxDOT roadway maintenance operations;

c) Climate data suggest the location is likely to receive suitable snow and ice storms during Winter 2013-14;

d) The site has a suitable section of asphalt or seal coat-surfaced pavement on which to conduct the field trial;

e) The field site can be made secure and safe for the research team.

Within these guidelines, the research team selected a research site most suitable for the field trials.

2.3.2 Candidate Project Site Alternatives

In collaboration with TxDOT Lubbock and Amarillo maintenance leaders, the research team identified six sections of roadway in the northern Texas Panhandle which seemed to possess suitable characteristics for the Task 5 Field Trials, as shown in Figure 2.3. Upon review of aerial photography and other preliminary work, the research team delineated eight candidate test sites along these sections of road which appeared to satisfy the project requirements. The research team prepared a preliminary profile for each candidate site consisting of a basic description and detailed maps. This facilitated further evaluation through on-site observations which the research team conducted on September 12 and September 16, 2013. The purpose of the site observations was to systematically characterize key aspects of each site relative to the proposed field trials including road closure impacts and traffic control complexity, field enclosure location and suitability, and detailed information about the road segment and pavement condition.

This effort revealed that the most prominent factors influencing site selection were road closure impacts/ traffic control complexity, followed by field enclosure location/ suitability. Relative to road closure and traffic control, the objective was to identify sites where traffic control would be as simple as possible, a suitable detour could be easily provided, and impact to the travelling public would be minimal. Sites requiring more complex traffic control were eliminated on this basis.

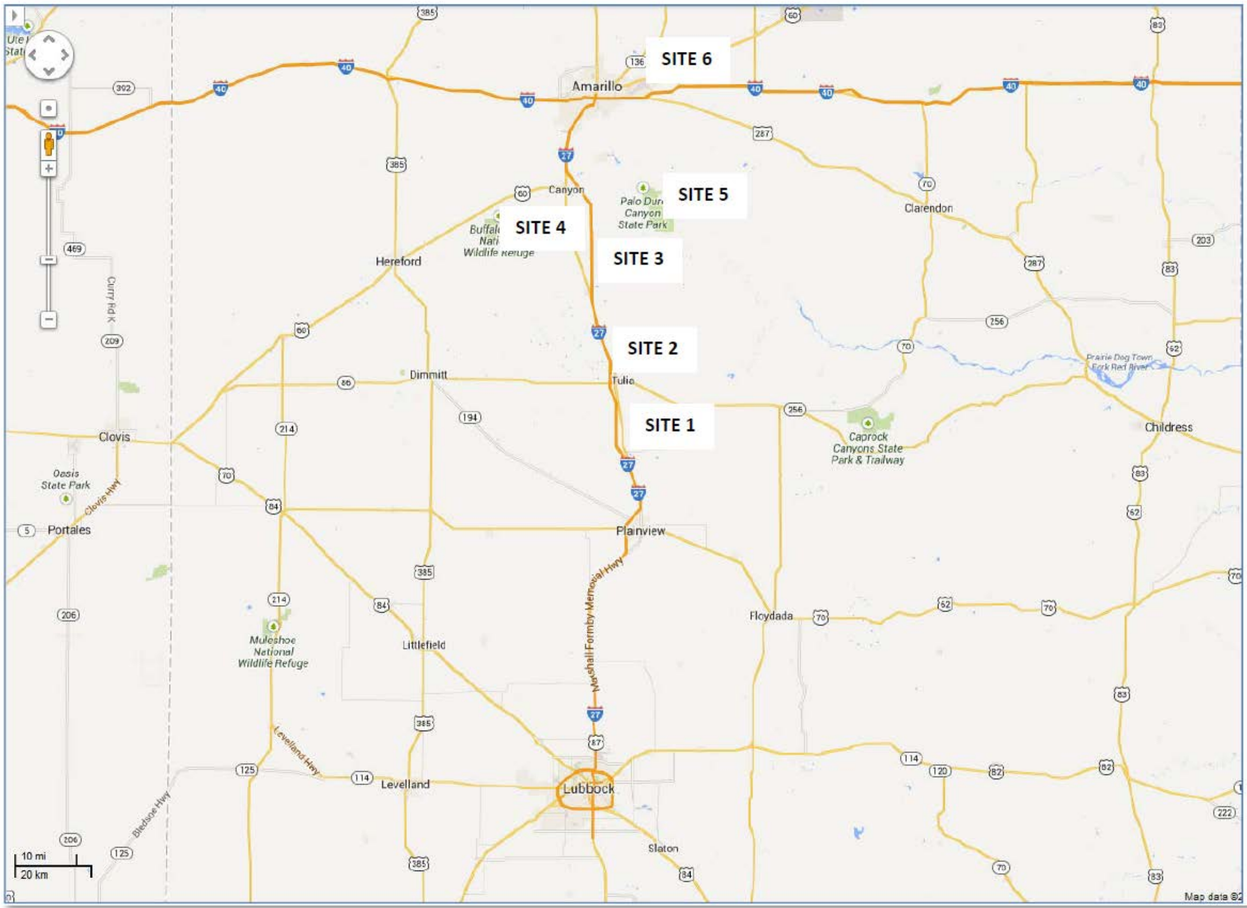


Figure 2.3. Candidate Roadway Sections for Snow & Ice Field Trials, Winter 2013-14

Relative to field enclosure location and suitability, some otherwise-suitable roadway segments simply did not have a good location to place a field enclosure from which to base our research operations. These sites were eliminated because they would have required operation from a poorly-drained, overly-narrow, or inadequately-protected area.

This systematic process culminated in identifying a short list of three candidate sites that were both suitable for the study from a research perspective and which also satisfied the full array of logistical requirements and constraints, chief among these being the safety of the traveling public, TxDOT maintenance personnel, and our research team.

Table 2.1 identifies the short-listed candidate sites and summarizes the pertinent characteristics of each site. This table reveals that while all three short-listed sites were suitable, each site had both strengths and limitations.

Table 2.1 Short-listed Sites for Snow & Ice Field Trials

Description	Site 1	Site 4a	Site 6
TxDOT District	Lubbock	Amarillo	Amarillo
County	Swisher	Randall	Carson
Annual snowfall (climate)	15 inches	18 inches	21 inches
Nearby town	Tulia (6 mi north)	Canyon (6 mi north)	Amarillo (15 mi west)
Road identification	US87 Southbound	IH27 SB Service Road	IH40 EB Service Road
Distance from Texas Tech	67 mi/1.0hr	101 mi/1.5hrs	136 mi/2.0hrs
Pavement surface	Seal coat	Seal coat	Seal coat
Pavement condition	Very good	Good	Fair
Pavement width	35ft total/12ft lanes	20ft total/10ft lanes	19' total/9' lanes
Test section length	1.0 mi	2.5 mi	1.0 mi
Usable lane miles	2.0 mi	5.0 mi	1.0 mi
Horizontal alignment	Straight	Straight	Gentle curve
Plowing difficulty	Very easy	Very easy	Easy
Traffic control complexity	Low	Simple	Very simple
Traffic impact	Moderate-Low	Very Low	Extremely low
Field enclosure site	Excellent	Good	Excellent

The research team submitted a memorandum to the Project Monitoring Committee (PMC) on September 18, 2013, documenting the short list of sites together with detailed maps, photographs, and other information, and requested guidance and approval for final site selection. The TxDOT Research and Technology Implementation Office (RTI) Project Manager convened a conference call of the full PMC on October 18, 2013, and RTI provided approval to proceed with execution of the project work plan at Site 4A on October 22, 2013.

2.3.3 The Field Research Site, Winter 2013-14

Located in Randall County, about 5 miles south of Canyon, TX (Figure 2.4), Field Test Site 4a is a 2.5 mile section of service road for southbound IH 27 between Cemetery Road and Hungate Road (Figure 2.5). This rural section of service road has very low traffic and with no homes along the road (Figure 2.6) and very limited land ownership impact (Figure 2.7).

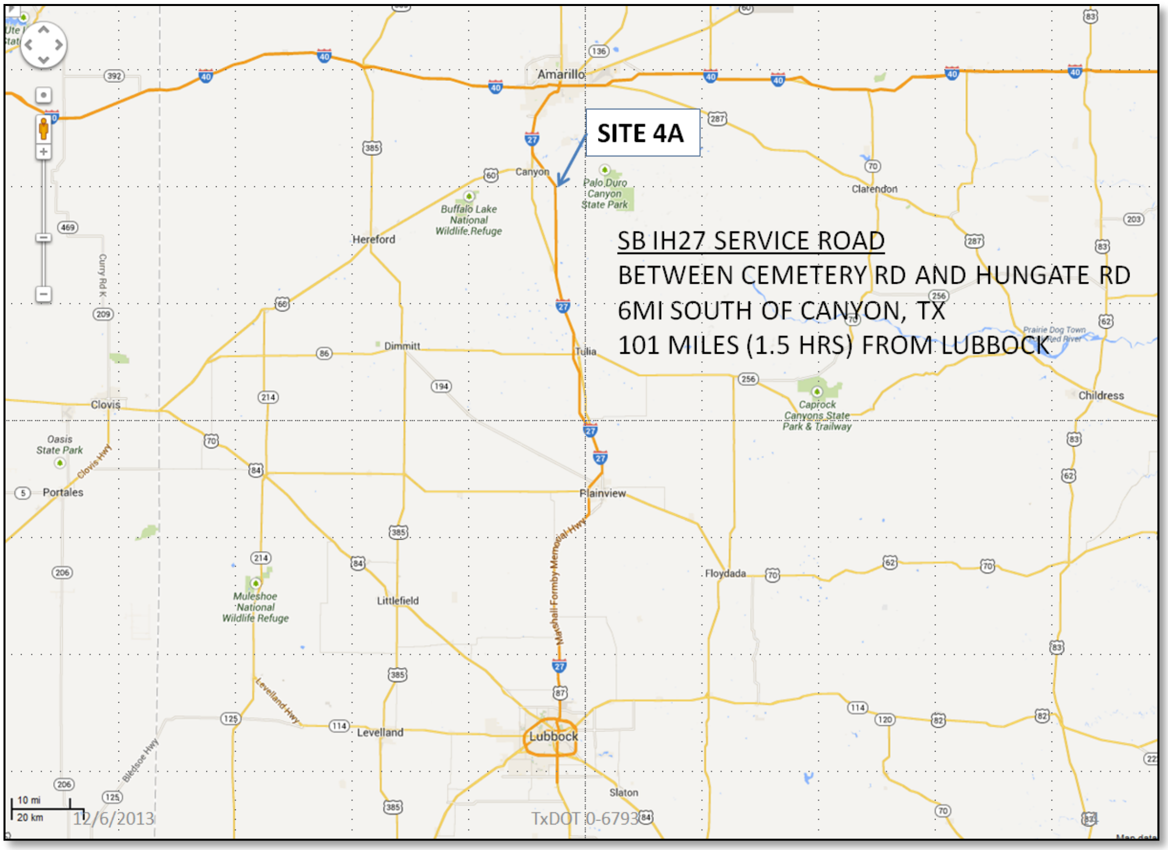


Figure 2.4. Site Location Map, Field Test Site 4a, Randall County, TX (*source*: Google maps)

As part of the field site vetting process, the research team met with Amarillo Director of Operations, Mike Taylor, P.E., and Randall County Roadway Maintenance Supervisor, Billy Hester, on November 1, 2013, to review and further refine site development plans for the field test layout at Site 4a. The research team also met with Lubbock Director of Maintenance, Ted Moore, P.E., Lubbock Maintenance Engineer, Jeremy Dearing, P.E., and Lubbock Maintenance Administrator, David Barrera, on November 21, 2013, to finalize site development planning.

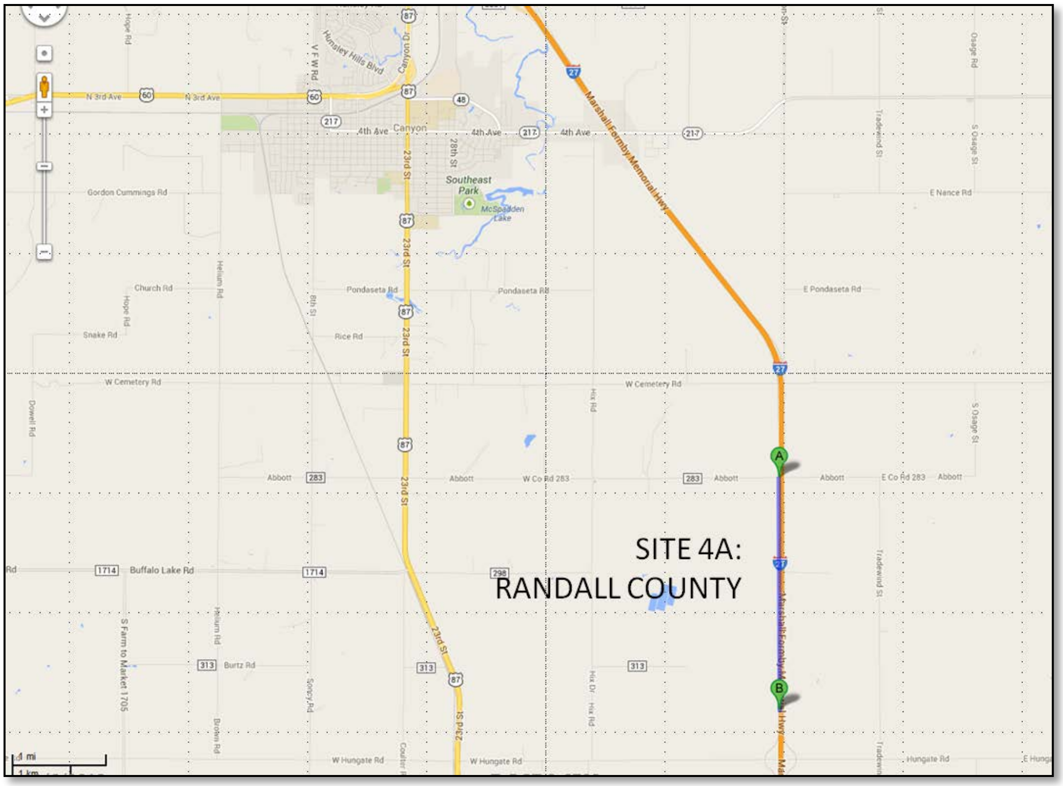


Figure 2.5. Site Vicinity Map, Field Test Site 4a, Randall County, TX (*source*: Google maps)

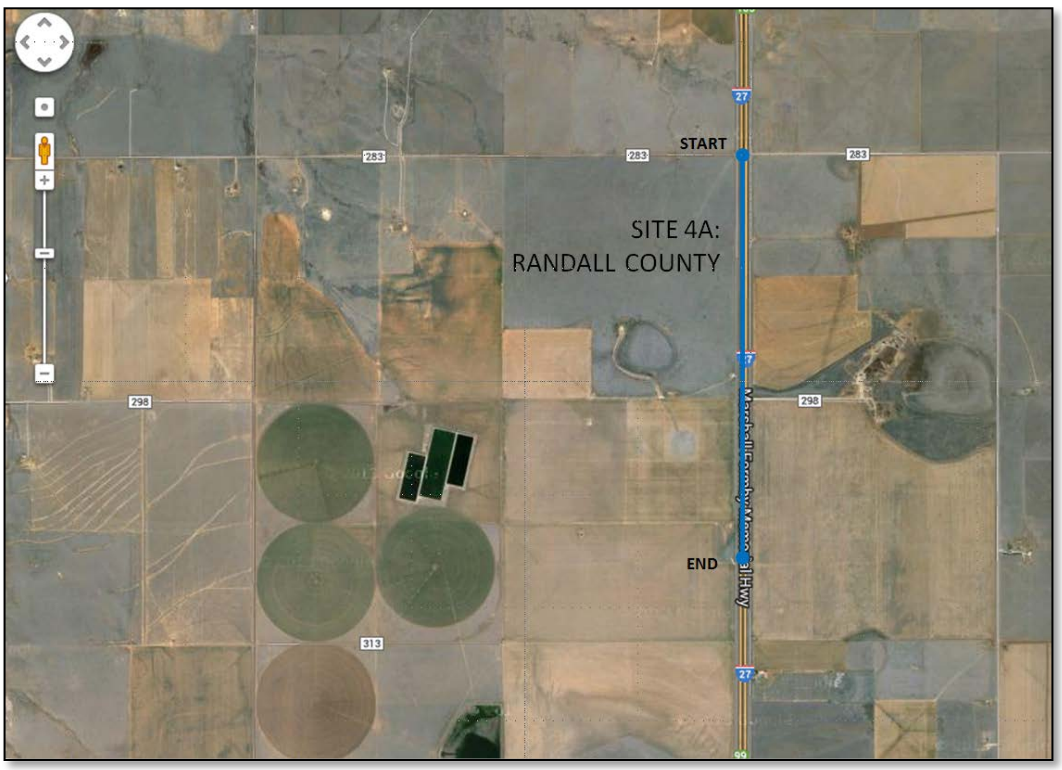


Figure 2.6. Surface Features, Field Test Site 4a, Randall County, TX (*source*: Google satellite images)

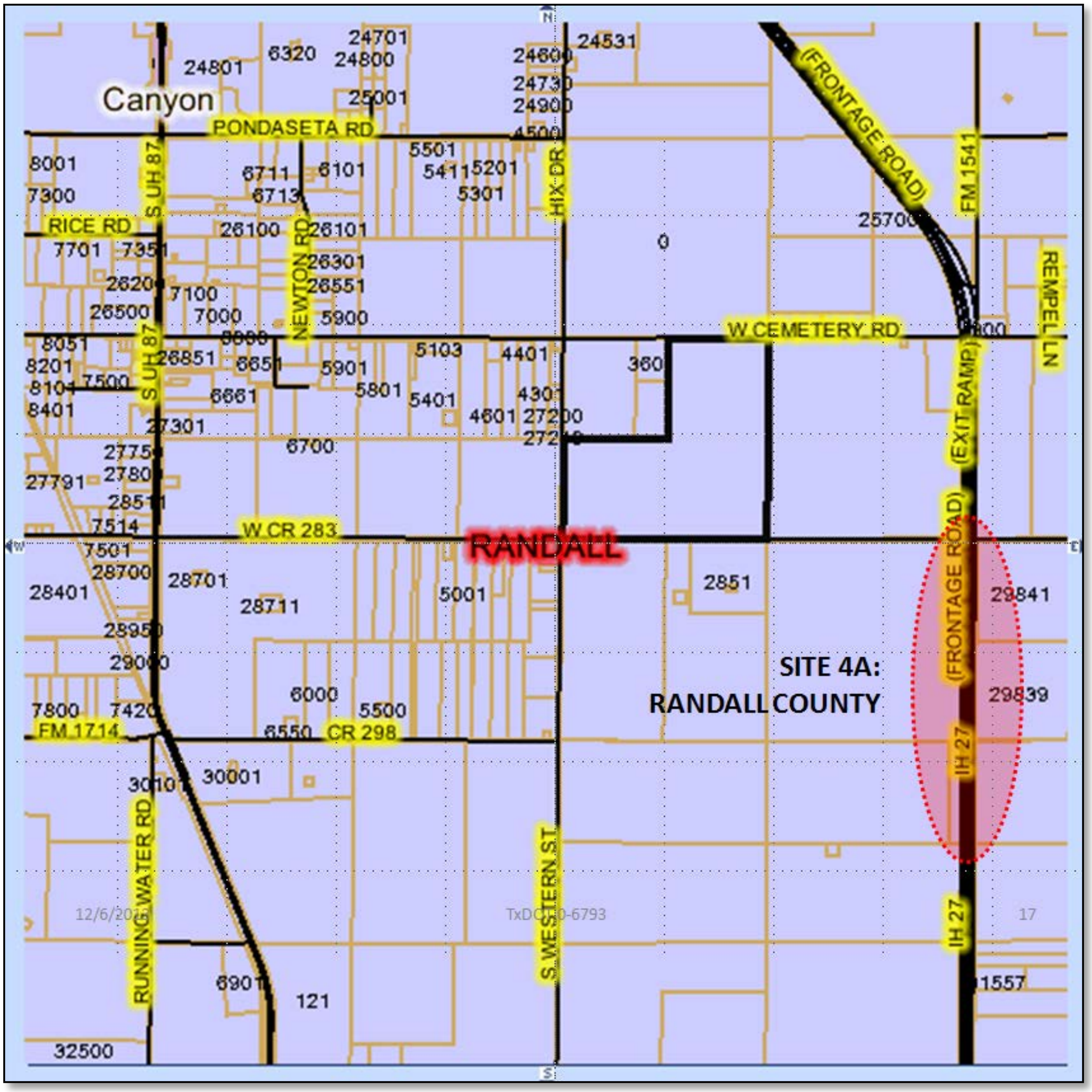


Figure 2.7. Neighboring Land Owners, Field Test Site 4a, Randall County, TX (*source*: Randall County Central Appraisal District)

As part of the site review process, the research team documented conditions of Site 4a through detailed notes and photographs. Figure 2.8 summarizes field observations and technical details of Site 4a. Figures 2.9 and 2.10 are selected images of the site taken during the site evaluation process. Figure 2.11 is a topographic map of the site.

SITE 4a (Randall County)	SB IH 27 Service Road		Date	9/12/2013	Observers	WDL, TW, ET
Test Site Data						
Test Bed Location	2-lane Service Road for I27 Southbound					
Start	CR 283 (Abbot Road), 1 mi south of Cemetery Road					
End	Exit at MP 100 (0.5 mi north of Hungate Road)					
Total Length	2.5 mi					
Available Lane Miles	5.0 mi					
Pavement Closure						
Start Detour	Close SB lane of service road at I27S entry ramp S of Cemetery Rd; Further close SB lane of service road at CR 283 (allow NB traffic)					
Alternate Route	IH 27 Southbound					
Houses/Facilities Impacted	None: a few gates/fields exist but no houses					
Hazardous/Surprising Conditions Created	Does not appear as a priority route on AMA Snow & Ice removal plan; Road closure at CR 283 will have very little impact					
End Detour	Hungate Road (close NB lane at Exit MP 100)					
Traffic Control complexity	Low					
Field Site Enclosure						
Field Placement Location	Open space at intersection of CR 283 & IH 27 Service Road					
Direct Access to test roadway	Yes					
Impact to Public (non-use)	None					
Impact to Public (in-use)	None					
Time/Distance to from Lubbock	101 miles, 1.5 hrs					
Nearby Facilities (Medical, Food, Fuel, Hotel)	Canyon TX (6 miles north, 8 mins)					
Cell Phone Reception	1/2 bars 4G					
Vandalism potential	2/10 (low)					
Pavement Description						
Site segment	**0.0 mi**	**0.5 mi**	**1.0 mi**	**1.5 mi**	**2.0 mi**	**2.5 mi**
Surface Type	seal coat	seal coat	seal coat	seal coat	seal coat	seal coat
Surface Condition (patches, texture, friction)	4/5	4/5	4/5	4/5	4/5	4/5
Total Road Width	20'-6"	20'-10"	20'-2"	20'-1"	20'-4"	23'-4"
Lane Width (NB)	10'-6"	10'-5"	9'-6"	9'-6"	9'-10"	11'-0"
Lane Width (SB)	8'-10"	9'-5"	10'-0"	9'-9"	9'-11"	11'-3"
Right Lane Cross Slope	CO 2.6%	CO 2.6%	CO 1.3%	CO 2.9%	CO 3.1%	CO 3.1%
Left Lane Cross Slope	CO 2.6%	CO 3.1%	CO 3.1%	CO 2.3%	CO 3.1%	CO 1.6%
Curves	none	none	none	none	none	none
Long. Slope	Gentle rise	Gentle rise	flat	flat	flat	flat
Plowing Considerations		Gate at 0.9 mi	Gate and dirt road at 1.4 mi	Gate at 1.7 mi		

Figure 2.8. Field Observations and Technical Details, Field Test Site 4a, Randall County, TX

Figure 2.9. View from Abbott Road, North End, Field Test Site 4a, Randall County, TX

Figure 2.10. View looking south, toward South End, Field Test Site 4a, Randall County, TX

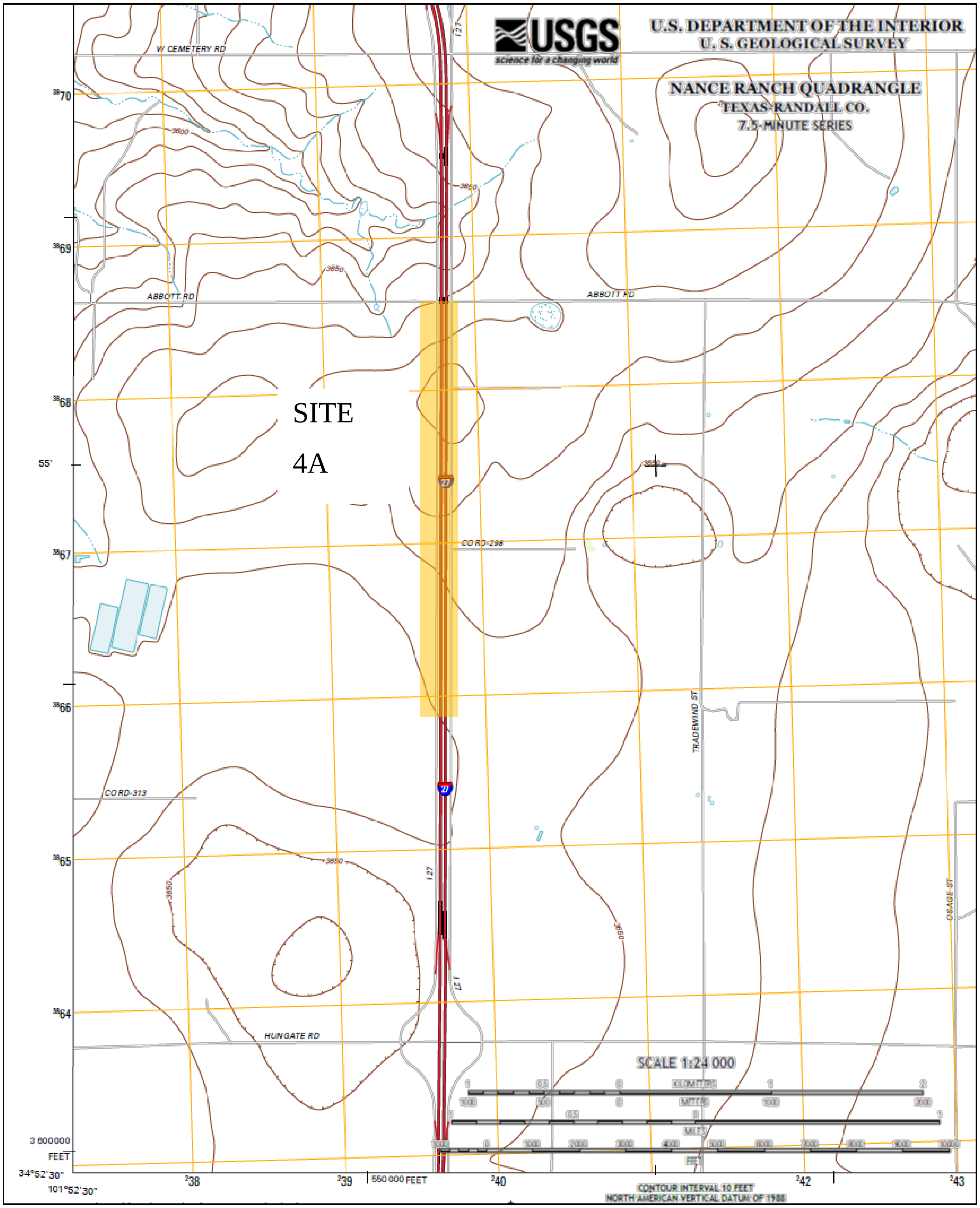


Figure 2.11. Topographic Map, Field Test Site 4a, Randall County, TX (*source:* USGS Topo Map, Nance Ranch Quadrangle)

Based on review of site details and requirements stipulated by the Randall County Maintenance Supervisor, the research team established the field site enclosure at the south end of the test area, about 8,000 feet south of Abbot Road. Figure 2.12 and Figure 2.13 show the field site enclosure. The Randall County Maintenance Office facilitated siting the field enclosure by creating a pad of recycled asphalt pavement upon which to establish an all-weather surface for the area.

Figure 2.12. Field Site Enclosure, South End, Field Test Site 4a, Randall County, TX

The field site enclosure was used to provide secure storage for field equipment and supplies including the plow truck, traffic control signage, light towers, fuel, snow and ice control chemicals, and related research items (Figure 2.14).

Figure 2.13. Material Storage, Field Site Enclosure, Field Test Site 4a, Randall County, TX

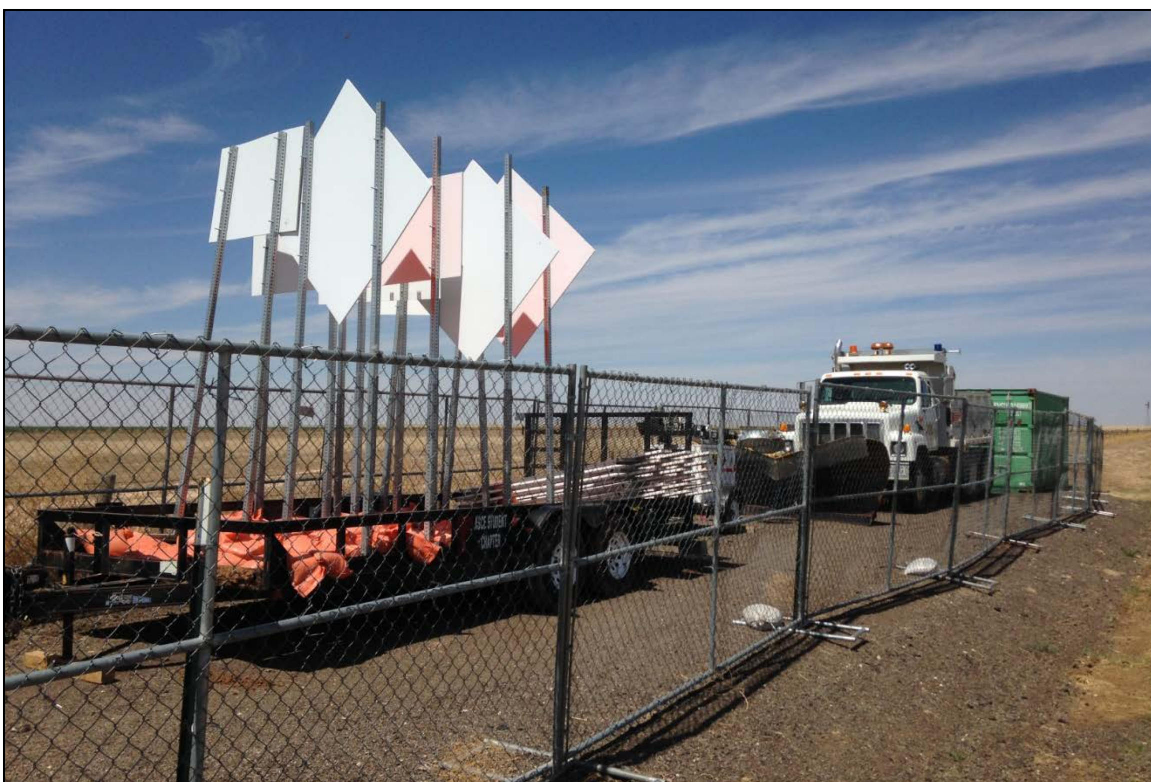


Figure 2.14. Equipment Storage, Field Site Enclosure, Field Test Site 4a, Randall County TX

2.4 Field Test Sections: Service Road, IH 27 Southbound, Randall County, Texas

2.4.1 Test Layout and Delineation

A major part of creating the field test site was to lay out the road test sections for application of snow and ice control chemicals as per the research plan. Figure 2.15 provides a schematic of the test layout. Figure 2.16 shows the road test sections at Site 4a as established by field survey.

	7000	6000	5000	4000	3000	2000	1000	0	
NB Lane		C	RS	C	RS	C	MD	C		NB Lane
SB Lane		RS	C	RS	C	MD	C	MD		SB Lane
Abbott Road	N Runout				Research Test Zone				S Runout	Field Enclosure

De-Icing Treatment Locations

	7000	6000	5000	4000	3000	2000	1000	0	
NB Lane		C	KCB	C	RSB	C	MDA	C		NB Lane
SB Lane										SB Lane
Abbott Road	N Runout				Research Test Zone				S Runout	Field Enclosure

Anti-Icing Treatment Locations

Figure 2.15. Schematic of Test Sections and Treatments (*not to scale*, C = control, MD = Meltdown 20®, RS = road salt, MDA = Meltdown Apex™, RSB = road salt brine, KCB = Kent County Brine)

Both the north end of the site and the south end included a buffer zone to facilitate run-out of the plow truck associated with snow plowing operations during a storm. Test sections for the snow and ice control chemicals were 1000 feet long and facilitated application of different chemicals in both liquid and granular form. Table 2.2 identifies the chemical application zones for each chemical type.

The test zones were delineated by station marker signs at 200-ft intervals. The station marker signs were designed to provide storm treatment and documentation orientation, both day and night, and during severe winter weather (Figure 2.17). As part of the delineation work, the research team sent introductory letters to all property owners with land along the affected section of service road and to adjacent property owners along access roads to the test site. These letters identified the research project and provided basic information about the scope and intent of the field research, and provided contact information for further inquiry. The research team also notified the local Department of Public Safety officer about the project.

Figure 2.16. Test Section Layout, Field Research Site, Randall County, Amarillo District

Table 2.2. Snow and Ice Control Chemical Application Zones, Test Site 4a

Southbound Lane			Northbound Lane		
Treatment Description		Zone	Treatment Description		Zone
Anti-Icing	De-Icing		Anti-Icing	De-Icing	
--	--	Abbott Rd	--	--	Abbott Rd
none	none	Runout	none	none	Runout
none	Road Salt	Sta 60 - 70	Control	Control	Sta 60 - 70
none	Control	Sta 50 - 60	Kent Cty Brine	Road Salt	Sta 50 - 60
none	Road Salt	Sta 40 - 50	Control	Control	Sta 40 - 50
none	Control	Sta 30 - 40	Mfr. Salt Brine	Road Salt	Sta 30 - 40
none	Meltdown 20®	Sta 20 - 30	Control	Control	Sta 20 - 30
none	Control	Sta 10 - 20	Meltdown Apex™	Meltdown 20®	Sta 10 - 20
none	Meltdown 20®	Sta 0 - 10	Control	Control	Sta 0 - 10
none	none	Runout	none	none	Runout
--	--	Enclosure	--	--	Enclosure

Figure 2.17. Station Markers to Delineate Test Sections, Field Research Site

2.4.2 Traffic Control Plan

Based on the meeting with the Randall County Maintenance Supervisor and the Amarillo District Director of Operations, it was apparent that to safely work at the subject site, it would be necessary to implement temporary road closures during winter storms.

To facilitate this, Amarillo District Traffic Engineer, Mr. Mike Fowler, P.E., prepared a traffic control plan which was consistent with traffic control rules, regulations and practices in the area. Figure 2.18 shows the overall site area for traffic control. Figure 2.19 shows the traffic control plan. Figure 2.20 is an image showing traffic control signage being deployed.

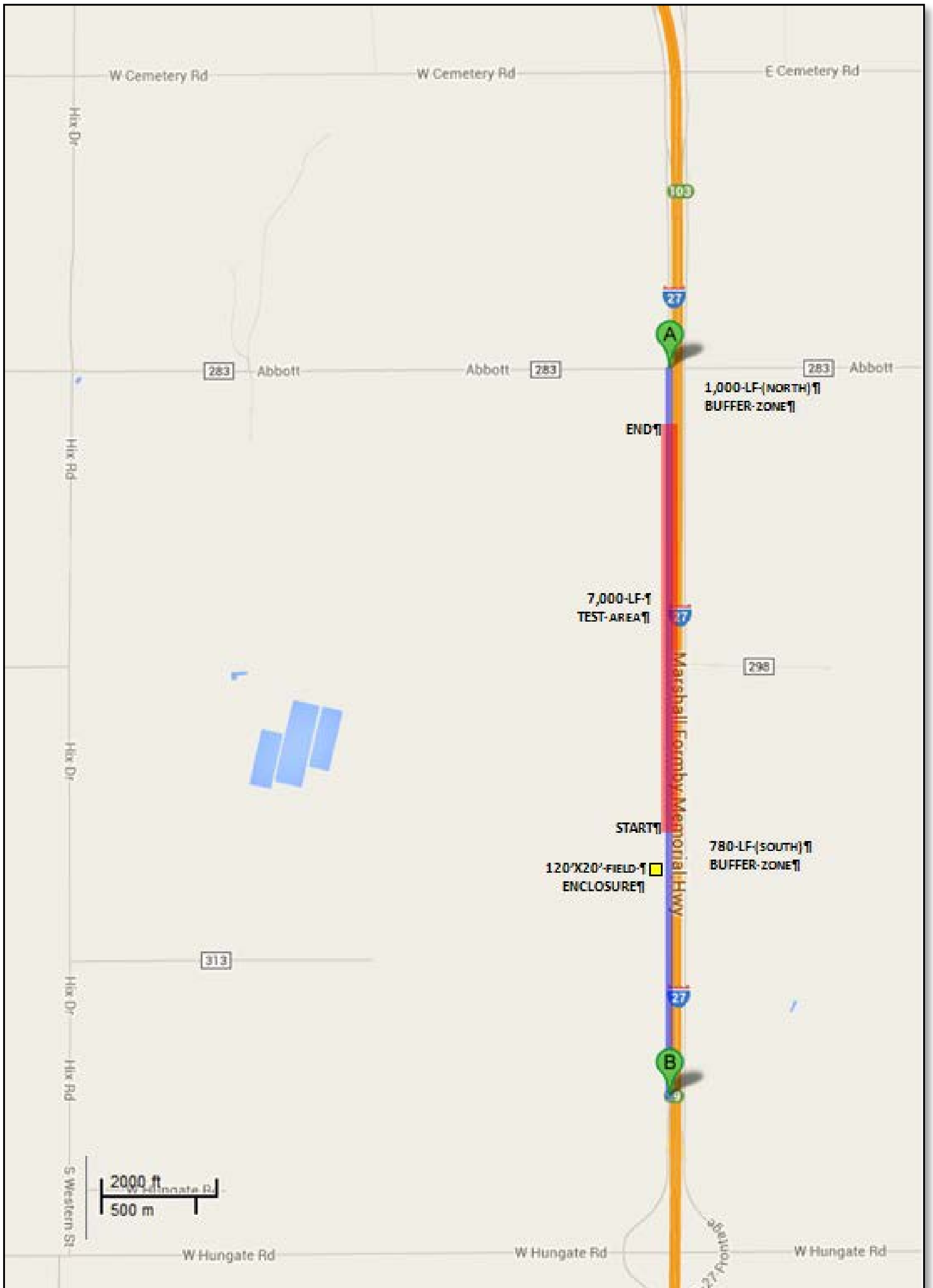


Figure 2.18. Traffic Control Area, Field Research Site, Randall County, Amarillo District

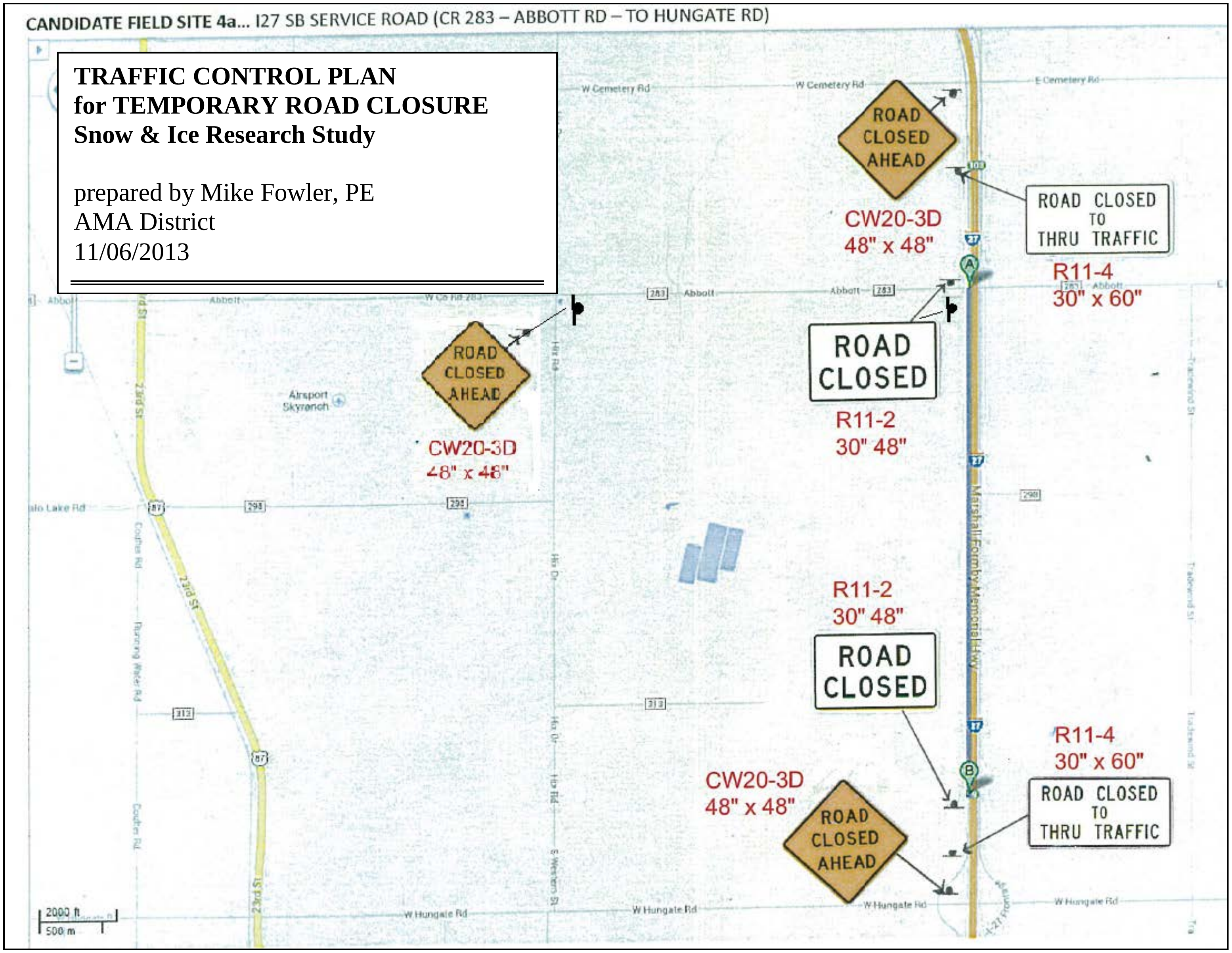


Figure 2.19. Traffic Control Plan, Field Research Site, Randall County, Amarillo District

Figure 2.20. Deploying Traffic Control Signage for Road Closure, Storm Event 1, 12/20/2013

2.4.3 Operational Readiness, Winter 2013-14 Storm Monitoring

The research team achieved operational readiness for winter storm data gathering at the field research site on December 11, 2013. This included but was not limited to set-up of the field research site as described.

2.5 Winter 2014-15: Service Road, IH 27 Southbound, Randall County, Texas

2.5.1 Winter 2014-15 Operations

In an effort to obtain additional winter storm data under Task 5 of the research study, TxDOT authorized Modification 3 on August 7, 2014, which, among other things, extended the project an additional year. The research team met on October 16, 2014, and subsequently by email to discuss the placement of field test sections for chemical de-icing and anti-icing treatments for the 2014-15 winter season. The research team submitted a memorandum requesting review and comment from the TxDOT project monitoring committee (PMC). Some supportive comments were received, and the site set-up moved forward.

2.5.2 Re-Use of the Existing Field Site

The Winter 2014-15 field site was again located on the southbound IH-27 frontage road between the Cemetery Road and Hungate Road crossings. However, the field site was modified to accommodate an updated research design.

During the 2013-14 winter season, the site consisted of a single 7000-ft section of roadway divided into fourteen 1000-ft long, one-lane test segments with distributed locations for treatment with both anti-icing and de-icing chemicals and untreated control sections. For Winter 2014-15, the research team designed an updated configuration to allow better replication of both de-icing and anti-icing chemical treatments, and to separate the anti-icing treatment segments from the de-icing segments. Figure 2.21 shows the positions of the de-icing treatment sections as an orange line for the northern segment (0N to 8000N ft) and the anti-icing treatment section as an orange line in the southern portion of the frontage road (0S to 4000S ft). The field storage site was located in the same place as the previous year, which was between the 0N and 0S points.

For field experiments, the research design compared two anti-icing chemicals – road salt brine (RSB) and Meltdown Apex™ (MDA) – in the anti-icing section, and two de-icing chemicals – road salt (RS) and Meltdown 20® (MD) – in the de-icing section. Figure 2.22 provides a schematic of the Winter 2014-15 test segments and treatments. Control sections received no chemical treatment.

2.5.3 De-icing Treatment Section

The test layout retained 1000-ft long treatment segments for the de-icing chemicals to allow space for turning the granular spreaders on and off as we moved the application vehicle through the treatment segments. By shifting our starting point, noted as 0N, south 600 ft from the Winter 2013-14 position, we had room for a total of eight treatment segments in each lane. Numbered signs were placed at 200-ft intervals along the fence line west of the frontage road to further divide the test segments.

As shown in Figure 2.22, the research design provided four replicates for each treatment. The layout of the treatment segments was balanced with two of each chemical treatment in each lane. The control section locations separated the chemical treatments, which prevented mixing of chemicals due to over-spread of chemical from the treated segments. The four treatment replicates for each chemical supported more robust statistical evaluation of the observed data.

Figure 2.21. Locations of field treatment test sections (*source:*Yahoo Maps, 2014)

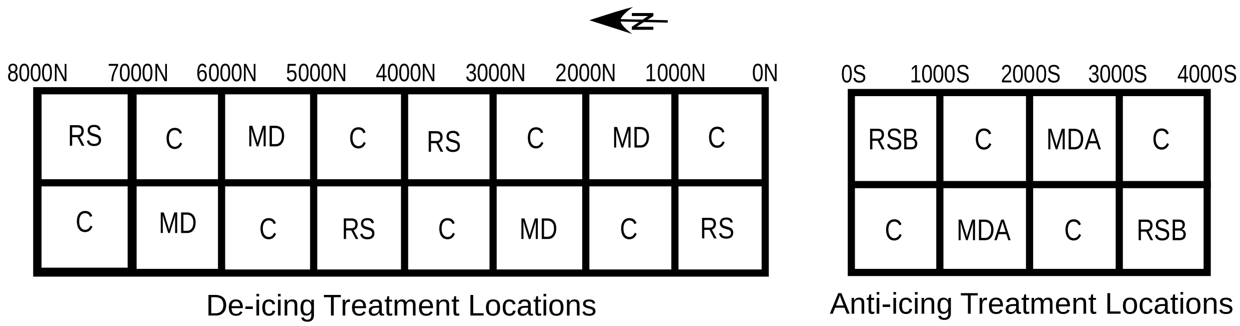


Figure 2.22. Schematic of Test Sections and Treatments (*not to scale*, C = control, MD = Meltdown 20®, RS = road salt, MDA = Meltdown Apex™, RSB = road salt brine)

2.5.4 Anti-icing Treatment Section

The Winter 2014-15 field site layout provided four 1000-ft treatment segments in each lane in the anti-icing treatment section. Numbered signs were placed at 100-ft intervals along the fence line west of the frontage road to further divide the test segments. We recognized that the appropriate conditions for anti-icing treatment are quite specifically based on antecedent and predicted weather conditions. We also understood that anti-icing could be followed by plowing and additional chemical application after the snowfall, perhaps with the same liquid chemical solution. The southern (anti-icing) test section allowed separate anti-icing treatment and observation to help quantify concerns reported by TxDOT maintenance professionals about risk of slick roads after application of Meltdown Apex™. We were limited in the total length of this section based on the distance of 5000 ft from our storage site to the IH-27 exit.

2.5.5 Updated Field Site Enclosure

Another significant update of the field site was the expansion of the home base location. Figure 2.23 shows an aerial view of the site as of late November 2014. For Winter 2013-14, we had one fenced area that enclosed one laydown storage container, a portable toilet, the plow truck, and our traffic control trailer. For the storm events, we mobilized a recreational vehicle to house our team on site.

For Winter 2014-15, we added a second secure enclosure to the south that contained a second laydown storage container that had been equipped with lights and heating, and we no longer used the recreational vehicle. All equipment, material, and personnel were in place, trained, and ready to respond to winter storms by late November 2014.

Figure 2.23. Aerial view of Winter 2014-15 Field Site (*source*: Google Earth™ image, November 25, 2014)

2.6 Summary

The candidate sites identified herein for Winter 2012-13 (Lubbock), Winter 2013-14 (Canyon), and Winter 2014-15 (Canyon) were made secure and were prepared for field research operations. Ultimately the Lubbock site was not used. However, the Canyon site was used for both the 2013-14 and 2014-15 winter seasons. Chapter 3 presents the research methods and operational procedures used to gather field data at this site.

CHAPTER 3
FIELD RESEARCH METHOD

3.1 Introduction

3.1.1 Overview

Field testing research is used to replicate actual winter roadway maintenance conditions, yet such studies are challenging to accomplish because of ever changing conditions in the field environment where some variables are difficult to control or even to document. In this context, the snow and ice field study for this project was designed to measure or manipulate relevant variables to the extent practicable. This chapter summarizes the research plan used for the field trials.

Observations spanned three winter seasons, Winter 2012-13, Winter 2013-14, and Winter 2014-15. During the first winter season, the field research site (Reese Technology Center, Lubbock, TX) experienced no candidate research storms, so no data were collected. The next two winters did provide some snow and ice storms at the field site located on the southbound IH 27service road in Randall County, about 5 miles south of Canyon, Texas.

3.1.2 Qualitative Observational Approach

The field trials were designed to obtain a comparative determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions. That is, the field research essentially consisted of a side-by-side comparison of the performance of typical snow and ice control chemicals at an established field site.

The basic research method was to respond to candidate storms at the field test site in a manner similar to how TxDOT maintenance forces would work such storms, and then document and compare the treatment results. This included both anti-icing and de-icing winter maintenance strategies. The research team applied TxDOT's typical snow and ice control chemicals at recommended rates, we slushed and plowed the pavement test sections as would be done under operational conditions, and we observed the impact of our activities on the roadway surface for the duration of the storm.

The primary data gathering method, therefore, was observational. We observed the roadway surface condition at specific intervals associated with maintenance activities during and throughout a winter storm, and we documented this condition through video, still images, and – for a limited number of storms – through decelerometer tests. These observational data were captured, summarized and analyzed using statistical methods. For this reason, the findings of the field study are essentially *qualitative*. Although numerical summaries, rankings, comparisons and evaluations are performed, the basis for most of this work was the visual *appearance* of pavement surface – snow-covered, slushy or bare – and in a few cases, an indication of its slipperiness.

3.2 Research Operational Plan

3.2.1 Site Preparation

The research team achieved operational readiness for Winter 2013-14 field operations on December 11, 2013, and we achieved operational readiness for Winter 2014-15 on December 19, 2014. From that date forward, all equipment, material, and personnel were in place, trained, and ready to respond to winter storms. As discussed in Chapter 2, this included but was not limited to set-up of the field research site about 5 miles south of Canyon, Texas along the service road of southbound IH 27 between Cemetery Road and Hungate Road.

A research team of six persons typically mobilized for each storm, with other research team members slated as backup (Figure 3.1). The primary storm response team for Winter 2013-14 consisted of Mr. Earnest Terrell (equipment, materials, site operations, image data), Mr. Timothy Wood (information technology, image data, site operations), Dr. Andrew Jackson (principal investigator, data backup), Dr. Ken Rainwater (snow plowing, site operations), Mr. Michael Nichols (site operations), and Dr. Bill Lawson (video data, backup snow plowing, technical oversight, research site manager).

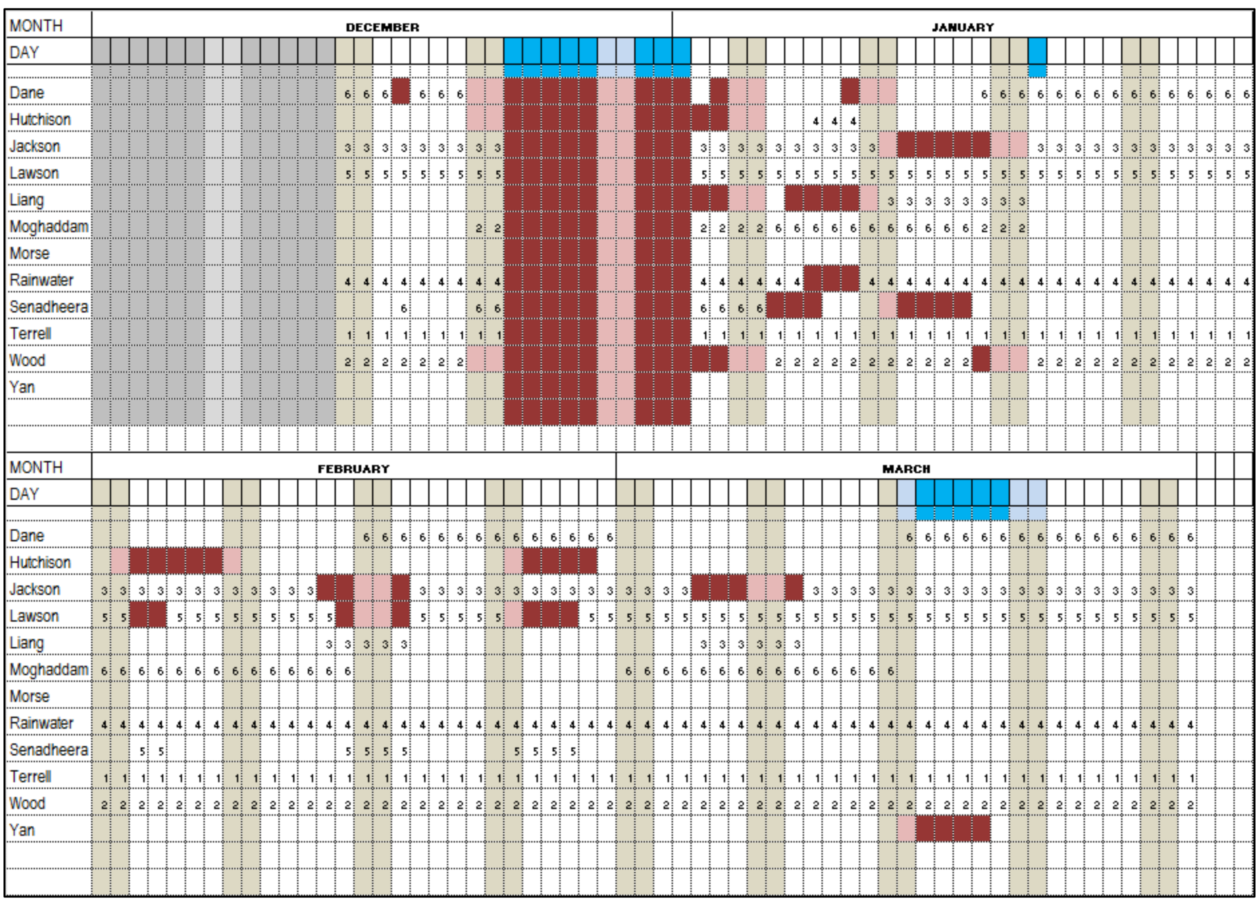


Figure 3.1. Winter Weather Storm Mobilization Research Team Assignments

The primary storm response team for Winter 2014-15 consisted of Mr. Felipe Estrada (equipment, materials, site operations, image data), Mr. Timothy Wood (information technology, image data, site operations), Dr. Andrew Jackson (principal investigator, data backup), Dr. Bill Lawson (video data, site operations, backup snow plowing), Mr. Alex Smith (site operations), and Dr. Ken Rainwater (video data, snow plowing, technical oversight, research site manager).

Major equipment for the project included a 1-ton truck for deployment of traffic control and anti-icing chemical, 1-ton truck for deicing chemical, minivan custom-equipped for photo imaging, TxDOT 6CY dump truck with 10-ft reversible snow plow, on-site field office, on-site weather station, light tower, and other tools and research materials (Figure 3.2)

Figure 3.2. Equipment and Material Storage Enclosure, Field Research Site

3.2.2 Monitoring the Weather

Regular monitoring of winter weather forecasts informed storm response decision making. The research team continuously monitored the weather at the research site, closely monitoring forecasts from multiple weather sources including the Weather Channel, Weather Underground, AccuWeather, and the National Weather Service. In particular, we developed a close working relationship with meteorologists at the National Weather Service, Amarillo who provided us with pinpoint forecasts for our field research site upon request, when a candidate storm was approaching.

We also monitored winter weather notices, advisories, warnings, and other correspondence from the National Weather Service, Lubbock.

To maintain operational readiness, every two weeks (or more frequently as conditions warranted) we inspected the field research site, equipment, and materials to confirm all systems were functional. We also convened a debriefing session following each storm mobilization to review our planning, preparation, storm response, and data. This allowed us to benefit from lessons learned. To that end, we continuously developed and refined our research plans and procedures throughout the winter research season.

3.2.3 Storm Mobilization and Research Operations

The research team mobilized for winter storm events on the basis of forecasted weather information. Candidate storms included those that met pre-established criteria as well as storms which were marginal in terms of forecasted snowfall accumulation and weather conditions. The research team erred on the side of preparedness, doing the best we could with the weather that came to the field test site.

Typical practice was for storm mobilization to commence with a callout decision made by the research site manager with collaboration by the principal investigator. The research site manager convened a pre-mobilization conference including a project safety meeting. The research team mobilized from the Texas Tech campus to the research site and commenced research operations. The process began with staging of research vehicles and equipment at the site and deployment of traffic control signage for road closure in accordance with the pre-approved traffic control plan. Having achieved a controlled (closed) research site, the team commenced setup of the on-site weather station, pavement temperature recording stations at the north and south ends of the test area, and data capture of a full set of pre-storm roadway surface photo images for the test area.

Following setup, the team initiated field operations specific to the subject storm to consist of application of anti-icing and/or deicing chemicals, depending on the weather. Anti-icing (liquid) chemicals included Meltdown Apex™ and salt brine. Deicing (solid granular) chemicals included Meltdown 20® and road salt applied at target concentrations as per the research plan.

Field operations including chemical application, slushing, plowing, and data collection continued for the duration of the winter storm, the goal being to work the storm and obtain data from a condition of bare pavement (prior to the storm) to bare pavement (after all snow/ice was removed or melted). Upon completion of the storm, the research team stored materials and equipment, cleaned up the site, removed the traffic control signage, and demobilized.

3.3 Independent Variables

Ideally it would be possible to conduct field trials that isolate and control all of the variables associated with snow and ice control operations. Practically, however, it was necessary to limit the scope of the field trials to address a manageable number of variables. Tables 3.1 through 3.5 identify the key independent variables associated with this study. These variables are grouped into the following categories: test site location, weather, roadway surface, treatment layout, and snow and ice operations. In addition to the variable name, each table includes a description of the variable, and the measurement approach used during the field trials.

Table 3.1 Test Site Location Variables

Variable Name	Variable Description	Approach
Field Test Site	The field test site location where the trials will be performed.	• The primary site for field testing was Site 4A, Southbound Service Road for IH 27 between Cemetery Road and Hungate Road, Randall County, Texas. Refer to Chapter 2. • For the safety of all, the field testing was done on closed sections of roadway. • A closed section allows better control of some variables.
Backup Site		Alternative sites were identified. A backup site was not proposed.

Table 3.2 Weather Variables

Variable Name	Variable Description	Approach
Storm Type Snow	Snow Event.	An acceptable snow event for field testing satisfies the following criteria: • Pavement Temperature: 32°F or less prior to snowfall • Predicted Accumulation: 3 inches or more • Wind Speed: Less than 10 mph • Event Duration: 24 hours or longer
Storm Type Ice	Ice Event.	An acceptable ice event for field testing satisfies the following criteria: • Accumulation: 1/4 in of ice or more • Event Duration: 24 hours or longer

Table 3.2 Weather Variables, continued

Variable Name	Variable Description	Approach
Snow Accumulation	The amount of snow for a storm event, measured in inches	Snow accumulation was measured and recorded at half-hour intervals throughout the duration of the field test. Measurements were be taken along the field test site at three locations; north, middle, and south.
Snowfall intensity	The intensity of snowfall, expressed in inches per hour.	Snowfall intensity was calculated based on the snowfall accumulation vs. time data.
Atmospheric Temperature	The ambient temperature, in degrees F, measured within five feet of the ground surface.	Atmospheric temperature was measured and recorded for the duration of the event at 15-minute intervals using an on-site portable weather station instrumentation.
Pavement Temperature	The temperature of the roadway pavement surface, in degrees F.	Pavement temperature was measured and recorded at half-hour intervals by means of an infrared temperature sensor at the pavement surface locations where snowfall accumulation is measured.
Storm Duration	The duration from beginning to the end of precipitation in the form of snow or ice.	The storm must have adequate duration to yield sufficient accumulation of snow and ice such that winter maintenance operations can be performed.
Event Duration	The time period from when the atmospheric temperature cooled below 32° F until the temperature warmed above 32° F.	The required duration is long enough that melting will not occur naturally. • Atmospheric temperature at or below freezing for a predicted duration of 24 hours or longer
Wind Speed	The wind velocity, measured in miles per hour.	Wind speed was recorded at 15-minute intervals using weather station instrumentation.
Wind direction	The direction from which the wind originates.	Wind direction was recorded concurrently with wind speed using weather station instrumentation.

Table 3.3 Roadway Surface Variables

Variable Name	Variable Description	Approach
Roadway type	The type of roadway surface to which snow and ice control chemicals will be applied.	Field trials were performed on a road having a seal-coat pavement surface. • Seal coat surfacing is representative of most Texas roads • Concrete pavement is not available at the field test site
Surface Texture	A measure of the roughness profile of the pavement surface in units of millimeters.	Use the Sand Patch Test to identify the mean texture depth. • Testing was done at four locations along the 7000 ft section of test road. • Test areas in the wheel paths.
Surface Friction	A measure of pavement surface friction in terms of a non-dimensional coefficient.	Use the British Pendulum Test at the same four locations as the surface texture tests.

Table 3.4 Treatment Layout Variables

Variable Name	Variable Description	Approach
Treatment width	The width of the test section lane, in feet.	Snow and ice control chemicals were applied for the full lane width. A buffer zone was used between test sections to avoid chemical mixing
Treatment length	The length of treatment section, in feet.	Snow and ice control chemicals were applied for the full length of each test section, which was set to 1000 ft. Within each test section, four (4) observation points were set at 200 foot intervals
Application Rate: Anti-icing	The application rate of liquid chemical, in gallons per lane mile.	Use TxDOT nominal application rates: • Mfr salt brine… 60 gals/lane mile • Kent Cty salt brine… 60 gals/lane mile • Meltdown Apex™… 20 gals/lane mile
Application Rate: De-icing	The application rate of granular chemical, in pounds per lane mile.	Use TxDOT nominal application rates: • Road salt… 300 lbs/lane mile • Meltdown 20®… 150 lbs/lane mile

Table 3.5 Snow and Ice Operations Variables

Variable Name	Variable Description	Approach
Snowfall accumulation between anti-icing and first plowing	The amount of snowfall, in inches, between the anti-icing application and first plowing.	Snowfall accumulation was set at a minimum of 1.5 inches.
Snow fall accumulation between de-icing and first plowing	The amount of snowfall in inches between the de-icing chemical application and plowing.	Snowfall accumulation was set at a minimum of 1.5 inches.
Snow fall accumulation between subsequent plowings	The amount of snowfall in inches between the plowings.	Subsequent snowfall accumulation was set at a minimum of 1.0 inches.
Traffic Load 1: Post Anti-icing	The number of vehicle passes necessary to spread the anti-icing chemical, prior to the storm.	• Single axle vehicles were used. • The pre-storm speed was 45 mph, max, subject to safety considerations. • The number of vehicles passes per treatment lane was set at 20.
Traffic Load 2: Storm Traffic	The number of vehicle passes during the storm necessary to slush the chemical.	• Single axle vehicles were used. • The in-storm speed was 20 mph, max, subject to safety considerations. • The number of vehicles passes per treatment lane was set at 20. • Vehicle passes began after a minimum of one inch of snowfall accumulation has occurred.
Snow Plowing	Removal of snow by mechanical means.	• Plow Truck: 6 CY • Plow: 10-ft reversible plow • Blade Set: Mild steel and/or carbide blade only • Plow speed: 20 mph, nominal

3.4 Dependent Variables

3.4.1 Overview

Field observations focused on the condition of the pavement surface for each defined pavement test section identified in Figure 2.15 (Winter 2013-14) and Figure 2.22 (Winter 2014-15. Weather data were recorded during the entire storm event. Pavement condition data were recorded throughout the storm event at periodic intervals corresponding to key roadway maintenance activities, such as "prior to de-icing", "after slushing", after plowing, and so forth. The research team captured three kinds of pavement condition data:

- Video data
- Image data (photos)
- Decelerometer data

These raw data were reduced to constitute the key dependent variables measured for the study. That is, these data were used to assess and evaluate the effectiveness of the various snow and ice control chemical treatments applied during winter storms at the test site.

3.4.2 Video Data

The effectiveness of snow and ice control chemicals relative to preventing a bond between snow/ice and the pavement surface was the key dependent variable for Task 5. One type of data obtained to measure this effect consisted of capturing video of the road surface during each storm in order to document the pavement condition as would be seen by "the maintenance worker in the truck" (Figure 3.3, Figure 3.4).

3.4.2.1 Video Data Capture The research team took digital videos of the pavement surface, usually with narration, for both the northbound and southbound lanes of the defined roadway test section, at key points throughout the storm. Video data would typically be captured prior to the storm, prior to application of anti-icing or de-icing chemical, after application of anti-icing or de-icing chemical, after slushing, before plowing, after plowing, after re-application of chemical, re-slushing, and re-plowing, and finally, after completion of the storm. Operational considerations such as storm intensity, equipment issues, or personnel availability sometimes prevented capturing video for every aspect of the storm, but the research team captured as much video as we could. Video files were archived, labeled, and catalogued for analysis.

3.4.2.2 Video Data Reduction The portion of IH27 service road comprising the research test site was delineated through a series of 1000-ft test sections for both the northbound lane and southbound lane. The configuration of the test sections in Winter 2013-14 featured 14 test sections north (7,000 ft of pavement) per Figure 2.15. In Winter 2014-15, the site featured 16 test sections north (8,000 ft of pavement) and 8 test sections south (4,000 ft of pavement) per Figure 2.22. But in all cases the test sections were 1,000 ft long, and within these test sections, stations were marked at intervals, typically 200 ft.

Figure 3.3**.** Snowy pavement surface condition (still image from video capture)

Figure 3.4**.** Clearing pavement surface condition (still image from video capture)

Video data reduction consisted of capturing the condition of the pavement for each 1000-ft test section of pavement, for lane, for each video. This was done using a “mini-Delphi Method.” The Delphi method is a structured communication technique, originally developed as a systematic, interactive forecasting method, which relies on a panel of experts to assess variable datasets (Rowe and Wright 2001). It is based on the principle that decisions from an expert group of individuals are more accurate than those of non-experts. In this case, the Delphi method was modified as the experts reviewed the videos in a face-to-face environment.

As used in this study, the mini-Delphi process consisted of visual assessment of the videos by a panel comprised of three members of the research team. Videos depicted the test site before, during, and after treatment, and videos revealed a wide variety of road conditions ranging from completely dry and clear, to wet, to partially covered with snow, ice or slush, to completely covered with various types of frozen precipitation. The goal of the mini-Delphi process was to identify the pavement condition for each test section. The process consisted of viewing each video with independent assessments of pavement surface condition by each member of the panel. As part of the mini-Delphi process, periodic calibrations were made during the analysis as panel members would cross-check their results in order to confirm that assessments were reasonable.

The Delphi panel visually observed and documented the surface condition of each test section of roadway using three separate metrics:

1. Pavement Snow and Ice Condition Index

   The Pavement Snow and Ice Condition (PSIC) index (Blackburn, et al. 2004) describes the road condition in one of seven levels. These levels range from a pavement surface that remains in a bare/wet condition at all times (Condition 1) to a pavement surface that is covered with a significant buildup of packed snow and ice (Condition 6) and even a pavement surface that is exposed to drifting and excessive unplowed snow to warrant temporary closure (Condition 7). The index can be used to evaluate both within-event and end-of-event Level of Service achieved by the winter maintenance treatments for comparing the effectiveness of the different strategy/tactic combinations (see Figure 3.5).

2. AASHTO/SICOP Reference Images

   The AASHTO/SICOP reference images (AASHTO 2007) are a performance-based method to visually assess the pavement condition associated with winter maintenance at various points in time using pictorial reference templates as an aid to condition observers (see Figure 3.6).

3. Percent Snowy Road Surface

   Percent snowy road surface is a visual estimate of the percentage of snow-covered pavement surface within a given area (1,000-ft test section of one pavement lane).

Condition	Description
1	All snow and ice is prevented from bonding and accumulating on the road surface. Bare/wet pavement surface is maintained at all times. Traffic does not experience weather-related delays other than those associated with wet pavement surfaces, reduced visibility, incidents, and “normal” congestion.
2	Bare/wet pavement surface is the general condition. There are occasional areas having snow or ice accumulations resulting from drifting, sheltering, cold spots, frozen melt-water, etc. Prudent speed reduction and general minor delays are associated with traversing those areas.
3	Accumulations of loose snow or slush ranging up to 2 inches are found on the pavement surface. Packed and bonded snow and ice are not present. There are some moderate delays due to a general speed reduction. The roads are passable at all times.
4	The pavement surface has continuous stretches of packed snow with or without loose snow on top of the packed snow or ice. Wheel tracks may range from bare/wet to having up to 1.5 inches of slush or unpacked snow. On multilane highways, only one lane will exhibit these pavement surface conditions. The use of snow tires is recommended to the public. There is a reduction in traveling speed and moderate delays due to reduced capacity. The roads are passable.
5	The pavement surface is completely covered with packed snow and ice that has been treated with abrasives or abrasive/chemical mixtures. There may be loose snow of up to 2 inches on top of the packed surface. The use of snow tires is required. Chains and/or four-wheel drive may also be required. Traveling speed is significantly reduced and there are general moderate delays with some incidental severe delays.
6	The pavement surface is covered with a significant buildup of packed snow and ice that has not been treated with abrasives or abrasives/chemical mixtures. There may be 2 inches of loose or wind-transported snow on top of the packed surface due to high snowfall rate and/or wind. There may be deep ruts in the packed snow and ice that may have been treated with chemicals, abrasives, or abrasives/chemical mixtures. The use of snow tires is the minimum requirement. Chains and snow tire equipped four-wheel drive are required in these circumstances. Travelers experience severe delays and low travel speeds due to reduced visibility, unplowed loose, or wind-compacted snow, or ruts in the packed snow and ice.
7	The road is temporarily closed. This may be the result of severe weather (low visibility, etc.) or road conditions (drifting, excessive unplowed snow, avalanche potential or actuality, glare ice, accidents, vehicles stuck on the road, etc.).

Figure 3.5. Pavement Snow and Ice Condition (PSIC) Index (*source* NCHRP 526).

Figure 3.6: AASHTO Reference Standards for Winter Roadway Conditions

7: Wheelpath Bare

8: Loose Snow Covered

9: Packed Snow Covered

10: Frost

11: Thin Ice Covered

12: Thick Ice Covered

Figure 3.6: AASHTO Reference Standards for Winter Roadway Conditions, continued

The video data capture consisted of identifying and comparing the surface condition of the road for each test section as per the three evaluation metrics. Data were recorded on a standard form (Figure 3.7) from which the numerical data were tabulated for subsequent analysis.

TxDOT 0-6793
VIDEO IMAGE EVALUATION
QUALTITATIVE ASSESSMENT BASED ON AASHTO/SICOP IMAGES, PSIC

EVENT 2

DSCN: 7996 IMAGE DATE/TIME: 1014 AM 2/6/14

FILM DURATION: ______ REVIEW BY: wm 5/1/14

PAVEMENT CONDITION: ______

OBSERVATIONS: ***SOUTH → NORTH***

STATION	TREATMENT	% BARE	AASHTO	PSIC	COMMENTS
SOUTH RUNUP	nothing	10	9	5	
0-10	control	30	5	4	WP visible. (not bare)
10-20	md-20	40	5	4	WP visible. "
20-30	control	30	6	4	WP visible "
30-40	road salt	50	~~4~~5	4	paint visible "
40-50	control	30	5	4	" " "
50-60	road salt	40	5	4	" " "
60-70	control	10	6	4	" " "
NORTH RUNDOWN	nothing	10	9	5	

OBSERVATIONS: ***NORTH → SOUTH***

STATION	TREATMENT	% BARE	AASHTO	PSIC	COMMENTS
NORTH RUNUP	nothing				
70-60	road salt				
60-50	control				
50-40	road salt				
40-30	control				
30-20	md-20				
20-10	control				
10-0	md-20				
SOUTH RUNDOWN	nothing				

Figure 3.7: Example form used to capture pavement condition metrics from video.

3.4.3 Image Data (photos)

During each storm, in addition to video, sets of high-resolution still images (photos) were taken of the pavement surface.

3.4.3.1 Image Data Capture The research team took digital images of the pavement surface at pre-established locations in the roadway test sections, at key points throughout the duration of each storm. Image sets would typically be captured after application of anti-icing or de-icing chemical, after slushing, before plowing, after plowing, and after re-application of chemical, re-slushing, and re-plowing. Operational considerations such as storm intensity, equipment issues, or personnel availability sometimes prevented capturing image data for every aspect of the storm, but the research team captured as much image data as we could.

Locations for the images were pre-defined based on layout of the pavement test sections. Since each test section was 1,000 ft in length and if images were taken at 200 ft intervals (per the delineation), this would support six image locations per test section (Figure 3.8). But it was decided that no images would be collected from the ends of the test sections because of the potential for overspray of snow and ice control chemical during treatment from one section to the next. Therefore, each test section offered four potential locations for images, and we captured three to four images per test section during an image set.

The researchers used a Nikon D5100 Digital SLR camera with a 55mm lens to take the pictures. To control lighting and other image quality factors, the camera was fixed on a frame within a purpose-built environmental shroud which was attached to the back of one of the research vehicles (Figure 3.9). Examples of the pavement images can be seen in Figure 3.10, 3.11, and 3.12. Figure 3.10 is a typical image of the road surface before any snowfall or treatment has occurred. Figure 3.11 is a typical image of the road surface after being blanketed by snowfall. Figure 3.12 is an example of an image taken post snowfall and post treatment. All image files were archived, labeled, and catalogued for analysis.

3.4.3.2 Image Data Reduction Photographs showed a wide variety of road surface conditions ranging from completely dry and clear, to wet, to completely covered with various types of frozen precipitation. The goal of the image data reduction process was to differentiate between percent visible pavement and snow-covered pavement for each image captured. To this end, efforts were made to design a computer program that would process the images and output the percentage of percent visible pavement versus snow-covered pavement for each image. However, image analysis proved too complex for reliable computer-aided processing. After consulting a photographic expert, it was determined that the best tool to use for this task was, in fact, the human eye. Therefore, visual analysis of the images was done by the research team using the mini-Delphi Method, in a manner similar to that previously described for the video data.

Figure 3.8. Images were taken at 200-ft intervals as delineated in each test section (station marker in background)

Figure 3.9. The camera was fixed on a frame within a purpose-built environmental shroud

Figure 3.10. Clear Pavement

Figure 3.11. Snow Covered Pavement

Figure 3.12. Treated Pavement with Melting Snow

The road surface was assessed in terms of percent total visible pavement. Figure 3.13 shows the form used for the mini-Delphi process. The “LANE” column indicates either the Northbound (NB) or Southbound (SB) lane. The “STATION” column indicates at which station each of the images was captured. Side-by-side images were captured at each of the indicated stations (one set in the northbound lane and one set in the southbound lane). The “CHEMICAL” columns indicate which snow and ice control chemical (if any) was used at each station. The next series of columns, bounded by the “SNOW” and “CLEAR” cells, is where the quantitative assessment by the mini-Delphi panelists was recorded.

The values ranging from 0 to 100 refer to the approximate percentage of asphalt visible (which will also be referred to as ‘percent visible pavement’ in this report). The blank cells below these ‘percent visible pavement’ values were where each of the Delphi panelists indicated what percentage of the total image fell under each of the ‘percent visible pavement’ values. For instance, if the entire image was clear of snow, as in Figure 3.10, the survey member would input a value of 100% under the 100 column. This would indicate that 100% of the image showed the pavement to be 100% clear of snow and ice. If the image was similar to Figure 3.11, it would be reasonable to input a value of 100% under the 0 column. This would indicate that 100% of the image showed completely snow-covered pavement.

STORM DATE: 2/5/14
CAPTURE TIME: 10:22 PM (IMAGE STAMP)

DESCRIPTION: AFTER PLOWING, BEFORE DEICING, BLOWING SNOW

REVIEWER: WM
REVIEW DATE: 4/9/2014

		CHEMICAL		SNOW					SLUSH					CLEAR	
LANE	STATION	ANTI-ICE	DE-ICE	0	10	20	30	40	50	60	70	80	90	100	AASHTO
NB	2	Ø	Ø	5								65		30	4
	4			10								50	40		4
	6												70	30	4
	8				10							90			6
	12									70		30			6
	14									80				20	6
	16											80		20	6
	18									60			20	20	6
	22			10			30			30			20	10	6
	24				10								80	10	6
	26				40					20				40	6
	28				10								50	40	6
	32												40	60	6
	34				10					10				80	4
	36						20			10				70	6
	38						30						10	60	6
	42				20	20						30		30	6
	44			20		30					30			30	6
	46					40						20		40	7
	48				40						20		40		7
	52				60	8			40						6
	54						40				60				7
	56					20						40	40		6
	58				10		20						20	50	~~8~~ 4
	62			80	20										4
	64			50	40	10									8
	66			80		20									8
	68			80	20										8
SB	68				70				20	10					8
	66			60		30				10					8
	64			30	40										8
	62			50		30		20							8
	58			70	20	10									8
	56			50	20	30									8
	54			20	40					30	10				8
	52			30	20	10			~~80~~	10	30				7
	48			60	20					10	10				8
	46			40			20	40							8
	44			20	20	30					20		10		8
	42			50		30		20							7
	38			50		20							30		8
	36			50	20	10							20		7
	34			70		10							20		6
	32			80			20								8
	28				50	50									8
	26			40	20			10				30			8
	24			60	20			20							6
	22			50			50								8
	18			30		20		50							5
	16			50	10					10			30		7
	14			20	10		20					50			6
	12			30	10				50	10					6
	8			30		20		50							5
	6			60	10		30								8
	4			60							20			20	8
	2			40		60									6 8

TxDOT 0-6793
SNOW ICE CHEMICAL: DATA ANALYSIS

Figure 3.13. Delphi survey form for pavement image data

The center (50%) column, shaded in gray and marked "SLUSH", was used to account for any visible slush in each image. As an example, for Figure 3.12, it would be reasonable to input a value of 30% under 0 (completely snow covered), 20% under 10, 20% under 50 (slush), and 30% under 100 (completely clear). The values input for each image sum to 100%.

As part of the mini-Delphi process, the members periodically conferred with each other to determine if everyone was judging the images with the same general standards for percent visible pavement and slush. While this departed from certain Delphi survey details in the sense that each participant knew which values came from which member, it did achieve the cross-check requirement. While these cross-checks were not completed for each image, it was clearly seen that all three survey members were judging each image in a reasonably similar and consistent manner.

Once each member's assessment for each image had been input into the form (Figure 3.13), an overall percent visible pavement was calculated for each image, for each person. This was done using Equation 1:

$$Percent\ Bare\ Pavement = \frac{\sum(C * P)}{\sum P} \qquad \text{Equation 1}$$

where C is the 'percent visible pavement' value that corresponds to a particular P which is the percent of the image that each survey member assigned under each 'percent visible pavement' value.

This process yielded the overall percent visible pavement per image. Averages and standard deviations were calculated for each location using the overall percent visible pavement values obtained from each member. These image averages were later aggregated by test section – either 9 or 12 total images per section depending on whether imaged data were captured at 3 or 4 locations per section – and used to calculate overall averages and standard deviations for sections having like treatments. The results of these overall averages are presented and discussed in the results section of this report. Additionally, the percentage of visible pavement, snow covered pavement, and slush were each calculated for each image. These values were plotted in bar charts and will be discussed in the results section of this report.

3.4.4 Decelerometer Data

For Winter 2014-15, in addition to video and image data, the researchers obtained pavement friction data using a decelerometer.

3.4.4.1 Decelerometer Data Capture An NAC Dynamic Friction Decelerometer (DFD) and the Decel Smartphone App (DSA) were available for selected winter storms. The DFD was coupled with a laptop computer, while the DSA was loaded onto a Samsung tablet. After comparing the two approaches, the DSA was used for the actual data collection (Figure 3.14).

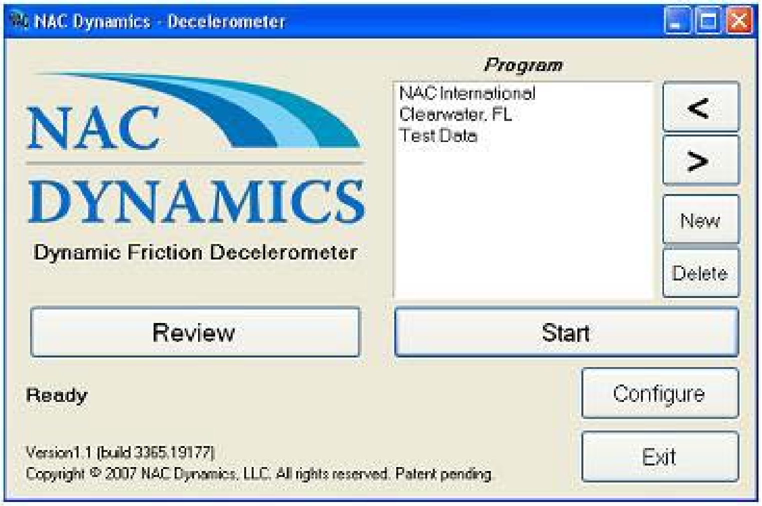


Figure 3.14. Main Menu Screen, NAC Dynamic Friction Decelerometer

The DSA was mounted on a support holder attached to the windshield of a Ford Focus, which was used as the test vehicle for all decelerometer tests in order to achieve consistency of data comparisons. One member of the research team drove the Focus, while a second member handled data capture. The anti-lock brake system on the vehicle was disabled prior to the tests by removing its fuse. For each test, the driver started from a stationary position and smoothly accelerated to 20 mph, then braked. The DSA then reported the deceleration as a percent of the acceleration of gravity, or percent G. Dry pavement yielded percent G values near and sometimes about 100%, while lower values could be observed after anti-icing chemical were applied or after the snow began (Figure 3.15).

Figure 3.15. Apply Brake Test Run Prompt, NAC Dynamic Friction Decelerometer

3.4.4.2 Decelerometer Data Reduction Three DSA tests were performed in each test section during each test run, similar to the approach used for the image data collection. This yielded 24 data points in the anti-icing portion of the test site (8 test sections with 3 readings each) and 48 data points in the de-icing portion of the test site (16 test sections with 3 readings each) for each data set. Overall averages and standard deviations were calculated for the test sections having like treatments for each test run, and the ANOVA was performed in the same manner as was used for the video and image datasets. These results are presented in Chapters 4 and 5.

3.5 Field Data Collection

Field data collection was accomplished using a systematic process, beginning with monitoring the weather. The researchers continuously monitored National Weather Service and other weather forecasts to identify potential storms that could meet our storm criteria. As noted in Section 3.3, these criteria generally included 1 to 3 in of snow, persistent temperatures cold enough for adhesion of snow and/or ice to the pavement, and the proper combination of snow and other freezing precipitation for accumulation on the pavement. The mobilization procedure was planned to allow set up of the site traffic control and initial anti-icing application during the day before the snow storm, with snowfall or icing commencing later that night or the next day.

Our typical response team included five to six team members with four vehicles (TechMRT minivan, TechMRT crane truck, TechMRT flatbed truck, and Ford Focus rental car), with the occasional addition of a 4WD pickup from the Water Resources Center, plus the 6CY plow truck which was stored on site. The minivan was used on-site to collect images of pavement at selected points in the different treatment sections. The flatbed truck carried the de-icing chemical (Meltdown 20® [MD] and road salt [RS]) spreader. The crane truck carried the anti-icing chemical tanks (Meltdown Apex™ [MDA] and road salt brine [RSB]). The Ford Focus rental car was used for consistent performance of the decelerometer tests. All the vehicles were available for slushing of chemical applications and collection of video data.

The typical order of field operations is shown in the following list. This process was initiated by a storm callout decision, followed by a team safety meeting prior to mobilization.

1. Mobilize from TTU campus to field test site.
2. Distribute traffic control signs to proper locations and achieve closed test site.
3. Set up portable weather station and pavement thermocouples with datalogger.
4. Move snow plow truck out of fenced enclosure and make ready for operations.
5. Set up light tower/generator near office trailer.
6. Distribute temporary traffic cones along test sections to guide snow plow driver.

7. Begin taking pavement temperature measurements at the north and south ends of the closed test section with handheld infrared temperature sensor, also record snow/ice accumulation if appropriate.
8. Obtain baseline pavement photos and decelerometer tests on bare pavement prior to precipitation and chemical application. This was done only during the first storm or two, as bare pavement conditions did not vary significantly between storms.
9. Obtain narrated digital videos with hand-held cameras at appropriate times to describe the road and weather conditions along both the anti-icing and de-icing test sections.
10. Apply anti-icing chemicals to appropriate sections of the test site as shown in Figure 2.15 (Winter 2013-14) or Figure 2.22 (Winter 2014-15). This included the use of a shadow truck to observe/confirm that the correct amount of chemical was applied. After application, the chemical was slushed with 20 vehicle passes.
11. Photo and decelerometer data collection.
12. After sufficient accumulation of snow and ice (at least 1 in), plow both de-icing and anti-icing sections.
13. Apply de-icing chemicals to their appropriate test sections as depicted in Figure 2.15 or Figure 2.22. This included the use of a shadow truck to observe/confirm that the correct amount of chemical was applied. After application, the chemical was slushed with 20 vehicle passes.
14. Photo and decelerometer data collection.
15. If snow accumulation continued, repeat steps 12-14.
16. Continue to work storm until roadway returns to bare pavement condition.
17. Capture final video, photo and decelerometer data sets.
18. Return plow truck and light tower/generator to secure research storage area.
19. Collect or lay down traffic control signs.
20. Disconnect and store portable weather station and datalogger.
21. Lock up storage site and de-mobilize to TTU campus.

In general terms, the above research process constituted the field operational plan for each storm. And in general terms, the research team followed this plan during each storm mobilization. However, given that our research activities centered on unpredictable winter weather events with multiple persons, vehicles, and other factors involved, variations occurred in practice. For example, sometimes the storm “fizzled” and did not yield sufficient precipitation to support field operations. At other times the snow was so heavy the site was overcome and we got stuck. Equipment malfunction or breakdown occasionally impacted data collection. Sometimes the temperatures warmed so quickly at the end of a storm that complete final data sets could not be obtained, and sometimes very cold temperatures set in for extended periods such that field operations could not conclude with a return to the bare pavement condition. For these and other practical reasons, the general research method and procedures could not always be achieved.

3.5 Summary

The goal of the field research was to replicate TxDOT winter roadway maintenance conditions in order to obtain a side-by-side comparison of how selected snow and ice control chemicals perform on Texas roads. The methods and procedures described in this chapter explain how the research team accomplished site operations and measured the effectiveness of different chemical treatments throughout the duration of each storm event. The video data, image (photo) data, and friction data thus obtained for each test section have been analyzed to evaluate the effectiveness of the chemicals. Chapter 4 presents the field data, and Chapters 5 and 6 present the results for anti-icing and de-icing, respectively.

CHAPTER 4
FIELD DATA

4.1 Introduction

4.1.1 Overview

This chapter presents data obtained from the field trials conducted under Task 5 of the research study. Each year the research team endeavored (planned) to mobilize for at least three candidate storms as per the project agreement, but in actuality the team mobilized for every storm practicable. Rarely did a storm satisfy the pre-set candidate storm criteria, so the research team did the best they could with the weather that came.

Field observations focused on the condition of the pavement surface for each defined pavement test section. Weather data were recorded for each storm event both onsite, from National Weather Service Amarillo, and from the local SchoolNET weather station in Canyon, TX. Pavement condition data were recorded throughout each storm event at periodic intervals corresponding to key roadway maintenance activities, such as "prior to de-icing", "after slushing", after plowing, and so forth. The research team captured three kinds of pavement condition data:

- Video data
- Image data (photos)
- Decelerometer data

Using the methods and procedures described in Chapter 3, these raw data were reduced to constitute the key dependent variables measured for the study. That is, these data were used to assess and evaluate the effectiveness of the various snow and ice control chemical treatments applied during winter storms at the field test site.

4.1.2 Data Presentation

Data were collected for each year of the study, that is, Winter 2012-13, Winter 2013-14 and Winter 2014-15. Typical data presentation is by storm mobilization event for each research year. In addition to a description of the storm, summary data are presented for the weather, video data, image data, and decelerometer data as applicable. Appendices provide the raw data for selected storms.

4.2 Year 1, Winter 2012-13 Field Data

4.2.1 Overview, Winter 2012-13 Climate

The research test site for Winter 2012-13 was located at Reese Technology Center, Lubbock, TX, as described in Chapter 2. Table 4.1 summarizes all winter storm events recorded during this season based on National Weather Service climate data for Lubbock, TX.

Table 4.1. Winter 2012-13 Storm Events with Snow Accumulations for Lubbock, TX (source: Storm Events Database and US Daily Snowfall Data, National Climatic Data Center)

Event ID	Location	Begin Date	Begin Time	Event Type	Snow Accumulation (inches)
415901	Lubbock (Zone)	12/10/2012	932	Winter Weather	0.2
418646	Lubbock (Zone)	12/25/2012	800	Winter Weather	0.1
419728	Lubbock (Zone)	1/4/2013	500	Winter Weather	0.1
428421	Lubbock (Zone)	2/21/2013	200	Winter Weather	
430464	Lubbock (Zone)	2/25/2013	330	Blizzard	3.4
434243	Lubbock (Zone)	4/10/2013	600	Winter Weather	0.4

Our research team was fully prepared to conduct field trials during the winter 2012/2013. We had secured a site lease at Reese Technology Center in Lubbock, purchased or acquired the appropriate chemicals, prepared and acquired all of the appropriate equipment (plows, spreaders, sprayers), and trained personnel in the operation of the equipment. Further the site had been surveyed and a detailed field protocol developed including appropriate means of documenting results. However, the Lubbock area experienced a notably mild winter and no appropriate winter storm occurred for which we could execute the field trial.

In January 2013 the research team considered moving the test site 125 miles north to the back-up site at Oldham County Airport, but after consultation with the RTI Director, and considering the date, significant resource input into the Reese Center location, and superiority of Reese Center compared to the alternate options at the at time, the group decision was to continue to use Reese Center as the test site. While Reece Center did receive one snow event in late February 2013, this event was not appropriate for a field trial due to blizzard (high wind) conditions and high pavement surface temperatures during the 12 hours prior to the storm (exceeded 70°). This precluded a reliable evaluation of the influence of snow and ice control chemicals.

4.2.2 Winter 2012-13 Field Research Mobilization Summary

The research team did not mobilize and no field data were recorded for Winter 2012-13. TxDOT authorized a modification extending the contract one year to facilitate Task 5 data gathering in Winter 2013-14.

4.3 Year 2, Winter 2013-14 Field Data

4.3.1 Overview, Winter 2013-14 Climate

The research test site for Winter 2013-14 was located along the southbound IH27 service road, about five miles south of Canyon, TX, as described in Chapter 2. Table 4.2 summarizes all winter storm events recorded during this season based on National Weather Service climate data for Canyon, TX. The National Weather Service characterized this winter as “cold and dry.”

Table 4.2. Winter 2013-14 Storm Events with Snow Accumulations for Canyon, TX (source: Storm Events Database, National Climatic Data Center)

Event ID	Location	Begin Date	Begin Time	Event Type	Snow Accumulation (inches)
476674	Randall (Zone)	10/18/2013	2030	Cold/Wind Chill	
483905	Randall (Zone)	11/21/2013	2300	Winter Weather	
484692	Randall (Zone)	11/23/2013	1100	Winter Storm	
480284	Randall (Zone)	11/25/2013	1740	Winter Weather	
491202	Randall (Zone)	12/21/2013	700	Winter Weather	
	Randall	12/22/2015			2
488228	Randall (Zone)	12/23/2013	1600	Freezing Fog	
503405	Randall (Zone)	2/4/2014	100	Winter Weather	1.5
503356	Randall (Zone)	2/5/2014	400	Cold/Wind Chill	
503372	Randall (Zone)	2/5/2014	1000	Winter Weather	
502046	Randall (Zone)	2/6/2014	1600	Cold/Wind Chill	1
502071	Randall (Zone)	2/8/2014	2300	Freezing Fog	
502028	Randall (Zone)	2/10/2014	400	Winter Weather	
509021	Randall (Zone)	3/1/2014	1740	Winter Weather	
515789	Randall (Zone)	4/13/2014	1700	Winter Weather	
515759	Randall (Zone)	4/13/2014	2230	Cold/Wind Chill	
511420	Randall (Zone)	4/14/2014	2200	Cold/Wind Chill	
516262	Randall (Zone)	5/1/2014	400	Cold/Wind Chill	

4.3.2 Winter 2013-14 Field Research Mobilization Summary

During the second winter of field trials, Winter 2013-14, the research team mobilized for three predicted winter weather storms as summarized in Table 4.3. With reference to the National Weather Service storm history, the storms for which we mobilized essentially comprised every possible winter storm event available.

Table 4.3. Winter 2013-14 Storm Events in Canyon, TX

Event	Start/ End Date	Storm Type/ Treatment	Snow Accumulation Forecast/ Actual (inches)	Storm Period/ Duration (hours)	Max Wind Speed (mph)	Candidate Storm?
2-1	12/21/13 12/21/13	Snow (Anti-icing)	2” / 0.5-0.7”	1000-1300 (3 hrs)	7-13	No/ No Data
2-2	2/5/14 2/6/14	Snow (De-icing)	2” / 1.0-1.5” very cold	1800-0600 (12 hrs)	8-16	No/ Limited Data
2-3	3/2/14 3/2/14	Snow (De-icing)	1-2” / 0.7-1.0”	1000-1500 (5 hrs)	13-23	No/ Some Data

The first predicted storm yielded about ½ in of snow accumulation, well below our target criterion of 3 in snow. We performed anti-icing treatment but temperatures rose and the snow melted such that we were not able to obtain complete data. Storm 2 generated 1 to 1½ inch of fine powdery snow under very cold conditions. We initiated de-icing and were able to obtain limited data. Storm 3 yielded about 1 inch of snow accumulation, still below our target criterion, but the storm developed in such a way that we were able to generate a reasonably complete dataset.

Following are detailed profiles of each storm event including identification of the field data obtained during the mobilization. As applicable, the appendixes provide data for selected storms including weather, video, images (photos), and decelerometer readings.

4.3.3 Storm 2-1 Mobilization (12-21-2013)

4.3.3.1 Storm 2-1 Summary Based on notice from the National Weather Service of a “winter weather advisory” for the area of the research site, followed by conversations with TxDOT maintenance personnel in Canyon and Amarillo, TechMRT personnel made the callout decision to mobilize for this storm at 9:15am, Friday, December 20, 2013. Figure 4.1 shows a temperature profile and mobilization summary of the storm.

We performed anti-icing operations and prepared for data gathering on December 21, 2013. However, this event produced less than 1 inch of snow accumulation (Figure 4.2). Details are:

- Total snow accumulation of about ½in to ¾ in
- We did perform anti-icing (one application) and slushed this before the storm
- Snowfall occurred very quickly, over a 3-hour window, and most within 15 minutes
- More snow was expected, but did not fall.
- The existing snow melted before we could perform any plowing or other operations.

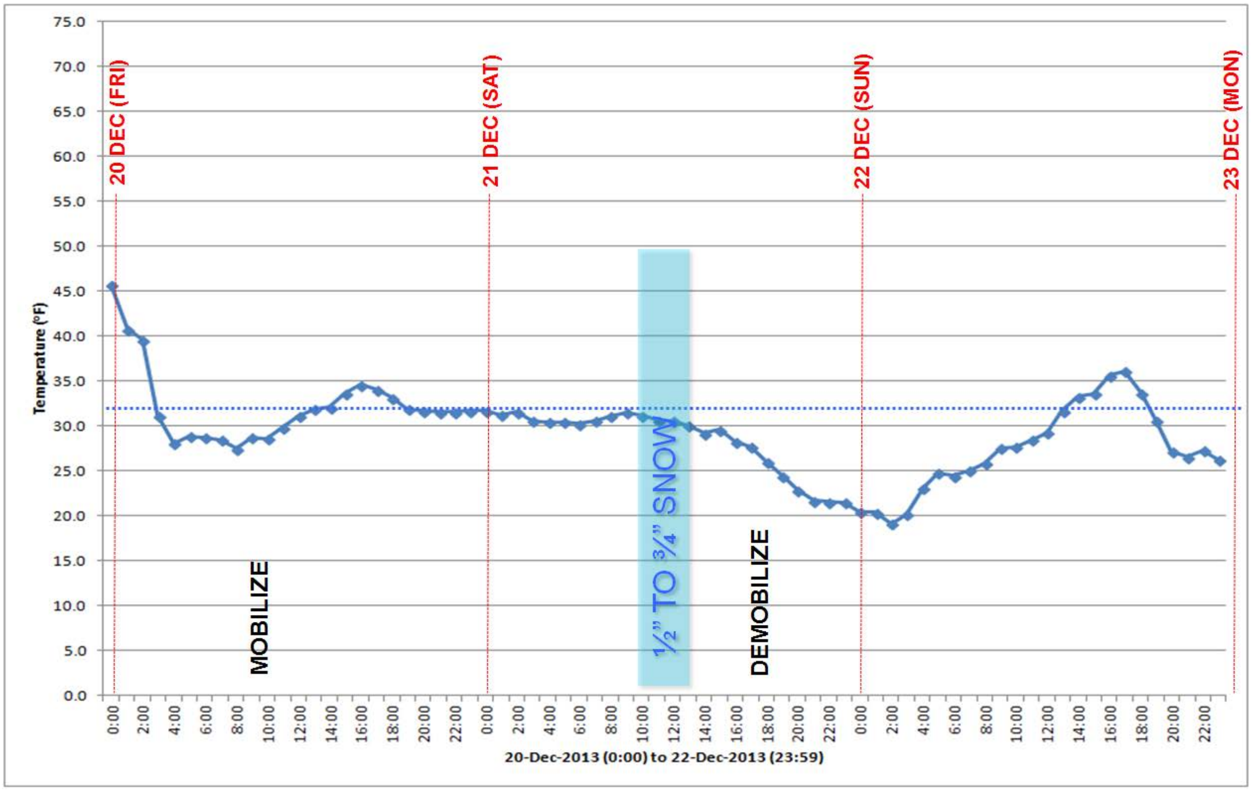


Figure 4.1. Ambient Temperature Profile and Mobilization Summary, Storm Event 2-1

The team de-mobilized from the site at 3:45pm, December 21, 2013, having collected only pre-storm data and having performed no plowing or deicing. This winter storm did not yield snow and ice control chemical effectiveness data. Summary observations for Storm Mobilization 1 are:

1. No comparative data obtained from Event 1.
2. Obtained pre-treatment condition images prior to anti-icing.
3. Obtained post-slushing images following anti-icing.
4. Did not apply de-icing chemical, slush, or plow the snow.
5. The storm fizzled and the existing snow melted, even as we were waiting for more snow.
6. No analyses, qualitative or quantitative, were performed.

This storm did facilitate a “first mobilization” which was invaluable training for future operations.

Figure 4.2. Approximately ½-inch snow accumulation for Storm 2-1

4.3.3.2 Storm 2-1 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 3 videos
- Image data… 2 data sets
- Decelerometer data… none

The project file contains working data summaries associated with Storm 2-1, Winter 2013/14.

4.3.4 Storm 2-2 Mobilization (02-05-2014)

4.3.4.1 Storm 2-2 Summary The forecast for this event predicted snow accumulations of about 2 inches and very cold temperatures (15 deg F to 0 deg F). Due to the very cold weather, the snowflakes were fine, light, and dry, with snowfall occurring over a long duration. While this forecast did not match our winter storm acceptance criteria, given the uncertainties including our research needs, we determined it was better to err on the side of preparedness. Figure 4.3 shows a temperature profile and mobilization summary of the storm.

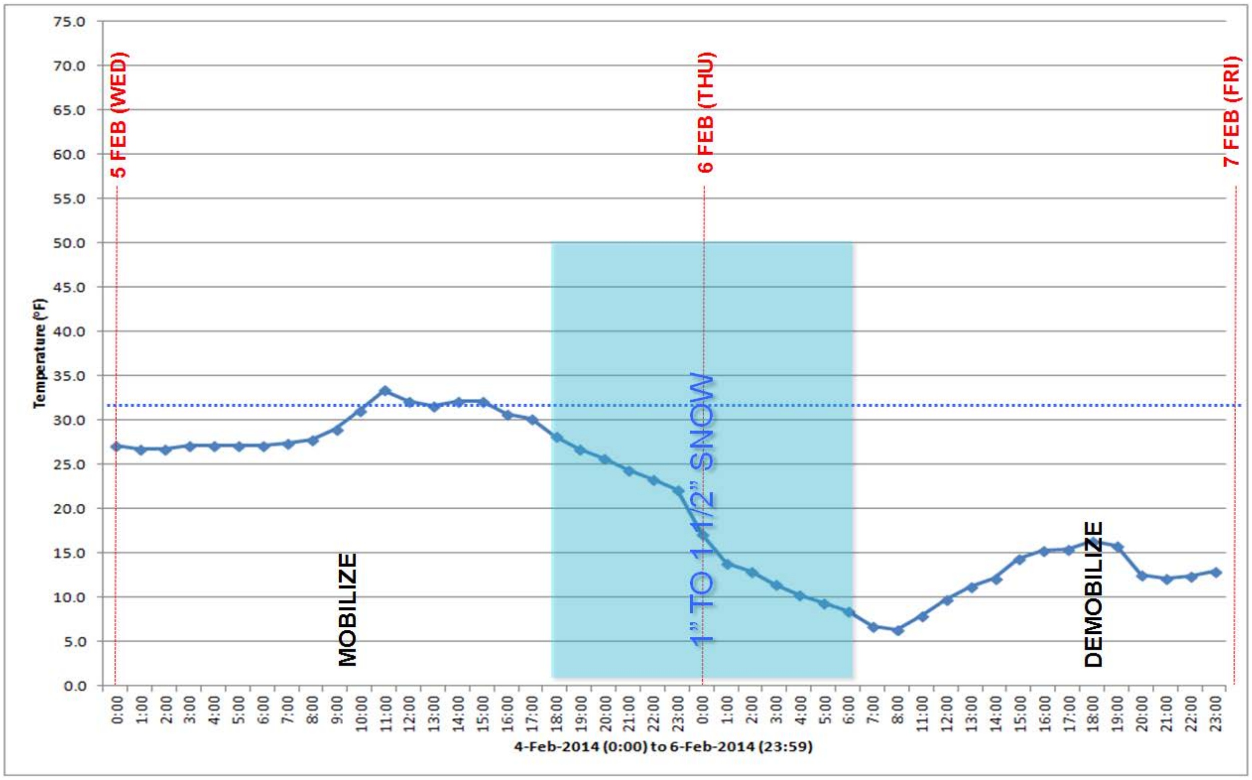


Figure 4.3. Ambient Temperature Profile and Mobilization Summary, Storm Event 2-2

TechMRT personnel made the callout decision to mobilize for this storm at 9:30am, Wednesday, February 5, 2014. Per the forecast, snow commenced at 6pm Wednesday, February 5, and continued through 6am Thursday, February 6. Accumulations of about 1 to 1½ inch were measured at the research site. Details are as follows:

- Total snow accumulation of 1 to 1½ - inches (varied)
- *Very* cold temperatures (15 – 0 deg F) and windy
    - Too cold to anti-ice
- Fine, light, dry, powdery snow flakes
- Uneven snow coverage over test area
- One de-icing application
- Below-freezing temperatures persisted for 3 days after storm

It was too cold to anti-ice, with pavement temperatures near 0 deg F prior to and during snowfall. Also, due to the very cold temperatures and very dry snow, it was difficult to ascertain effectiveness of the deicing chemical. Snow accumulations were light and powdery, creating non-uniform drifts with thickness variations from lane to lane and from end to end across the site (Figure 4.4). For these reasons, this storm yielded very limited data. Demobilization was completed by 6pm, February 6, 2014.

Figure 4.4. Very Cold Temps, Dry Powdery Snow, Variable Snow Accumulation on Road Surface Prior to Storm Event 2-2

4.3.4.2 Storm 2-2 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 7 videos
- Image data… 3 data sets
- Decelerometer data… none

The project file contains working data summaries associated with Storm 2-2, Winter 2013/14.

4.3.5 Storm 2-3 Mobilization (03-02-2014)

4.3.5.1 Storm 2-3 Summary The forecast for this event predicted snow accumulations of about 1 to 2 inches. Again, this forecast did not match our winter storm acceptance criteria, but given our need for data, we determined it was better to err on the side of preparedness. Refer to Figure 4.5 for a temperature profile and mobilization summary of the storm.

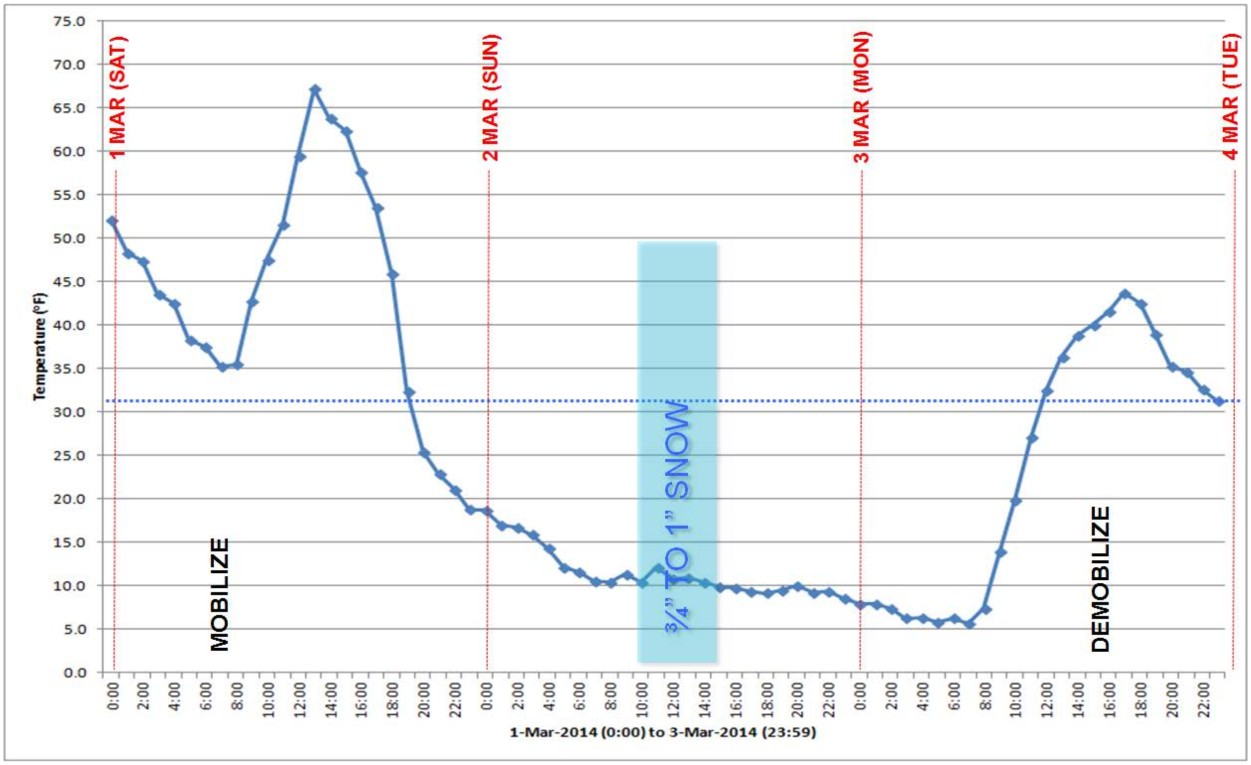


Figure 4.5. Ambient Temperature Profile and Mobilization Summary, Storm Event 2-3

TechMRT personnel made the callout decision to mobilize at 7am, Saturday, March 1, 2014. Snow commenced at 10am Sunday, March 2, and continued through 3pm. Accumulations approaching 1 inch were measured at the research site and were reasonably uniform. Details are as follows:

- Total snow accumulation of about ¾ in to 1in
- Due to forecasted rain prior to the snow/ice, we did not perform anti-icing
- One de-icing application
- Very cold temperatures until day following application
- Most data were collected the day following application, during warming temperatures

Low pavement temperatures and forecast conditions (rain turning to freezing rain, then snow) did not support anti-icing for this event. Although snow accumulations were low and only allowed for one deicing chemical application, this storm did facilitate collection of both video image data and still image data for the roadway surface (Figure 4.6).

Very cold temperatures following cessation of snowfall prohibited evaluation of treatment on Sunday; data collection mostly occurred on Monday, March 3, as pavement temperatures rose. The research team completed on-site operations at 1:15pm. Demobilization was completed by 4pm, March 3, 2014.

Figure 4.6. Road Surface Condition Before Plowing, Drive Lane Treated w/Road Salt/ Opposite Lane Control

4.3.5.2 Storm 2-3 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 20 videos
- Image data… 8 data sets
- Decelerometer data… none

See Appendix A for data summaries associated with Storm 2-3, Winter 2013/14.

4.4 Year 3, Winter 2014-15 Field Data

4.4.1 Overview, Winter 2014-15 Climate

The research test site for Winter 2014-15 re-used the southbound IH27 service road site located five miles south of Canyon, TX. As described in Chapter 2, the site was modified for Winter 2014-15 such that the north portion of the site was expanded from 14 to 16 test sections (8,000 ft long) and a south portion containing 8 test sections (4,000 ft long) was added. Table 4.4 summarizes all winter storm events recorded by the National Weather Service for Canyon, TX during this season.

Table 4.4. Winter 2014-15 Storm Events with Snow Accumulations for Canyon, TX (source: Storm Events Database, National Climatic Data Center)

Event ID	Location	Begin Date	Begin Time	Event Type	Snow Accumulation (inches)
543097	Randall (Zone)	11/6/2014	400	Cold/Wind Chill	
542559	Randall (Zone)	11/10/2014	2300	Cold/Wind Chill	
550545	Randall (Zone)	11/16/2014	600	Winter Weather	
	Randall	11/17/2014			3
550362	Randall (Zone)	12/29/2014	1800	Cold/Wind Chill	
557089	Randall (Zone)	1/2/2015	2200	Winter Weather	
557870	Randall (Zone)	1/3/2015	1800	Cold/Wind Chill	2.5
557701	Randall (Zone)	1/21/2015	1500	Winter Storm	
	Randall	1/22/2015			11
557941	Randall (Zone)	2/4/2015	1200	Winter Weather	
557974	Randall (Zone)	2/22/2015	0	Winter Weather	
	Randall	2/23/2015			0.5
	Randall	2/24/2015			2
563641	Randall (Zone)	2/25/2015	0	Winter Weather	
	Randall	2/27/2015			2
	Randall	3/5/2015			0.5

4.4.2 Winter 2014-15 Field Research Mobilization Summary

During this third winter of field trials, Winter 2014-15, the research, the research team mobilized for six predicted winter weather storms as summarized in Table 4.5. Three of the predicted storms (1, 3, and 6) yielded less than ½ in of snow accumulation, well below our target criterion of 1 to 3 in, and therefore did not generate sufficient data for the project objectives. Storm 2 quickly generated over 10 in of snow, well beyond our target criterion, causing very difficult driving conditions. After the snow stopped, the snow was easily completely removed by the plow alone without de-icing treatment, also causing insufficient conditions for further data collection. Storms 4 and 5 did meet our target criterion and generated complete datasets for analysis purposes.

Table 4.5. Winter 2014-15 Storm Events in Canyon, TX

Storm	Start Date	End Date	Snow	Chemical Applications	Data Collection	Comments
3-1	1/12/2015	1/14/2015	<0.5 in	1 anti-icing	Photos, videos, weather, pavement temperatures	Too little to plow or de-ice
3-2	1/21/2015	1/22/2015	>10 in	1 anti-icing	Photos, videos, weather, pavement temperatures	Plowed once, no adhesion of ice to pavement, no de-icing or further data
3-3	2/16/2015	2/17/2015	0.2 in	1 anti-icing	Photos, videos, weather, pavement temperatures, decelerometer	Too little to plow or de-ice
3-4	2/21/2015	2/23/2015	1.25 in	2 anti-icing, 1 de-icing	Photos, videos, weather, pavement temperatures, decelerometer	Plowed twice, first storm to meet target criteria
3-5	2/25/2015	2/27/2015	2-3 in	2 anti-icing, 2 de-icing	Photos, videos, weather, pavement temperatures, decelerometer	Plowed three times, best storm relative to target criteria
3-6	3/3/2015	3/5/2015	<0.5 in	1 anti-icing	Photos, videos, weather, pavement temperatures, decelerometer	Too little to plow or de-ice

Following are the descriptions of each storm event including identification of the field datasets obtained during the mobilization. As applicable, the appendixes provide data for selected storms including weather, video, images (photos), and decelerometer readings. Analyses of the datasets is found in Chapter 5.

4.4.3 Storm 3-1 Mobilization (01/12-14/2015)

4.4.3.1 Storm 3-1 Summary The decision to mobilize for this storm was made at 6:09 p.m., Sunday, January 11, 2015, based on the National Weather Service (NWS) forecast for a wintry mix, including freezing rain and snow. Anti-icing operations and initial photo data gathering were performed on January 13, 2015. Snow occurred overnight, but only produced about ½ inch of accumulation. The storm fizzled and the existing snow melted quickly during the morning. Figure 4.6 shows the variations in temperature measurements gathered while on-site, as well as the small window of light snow.

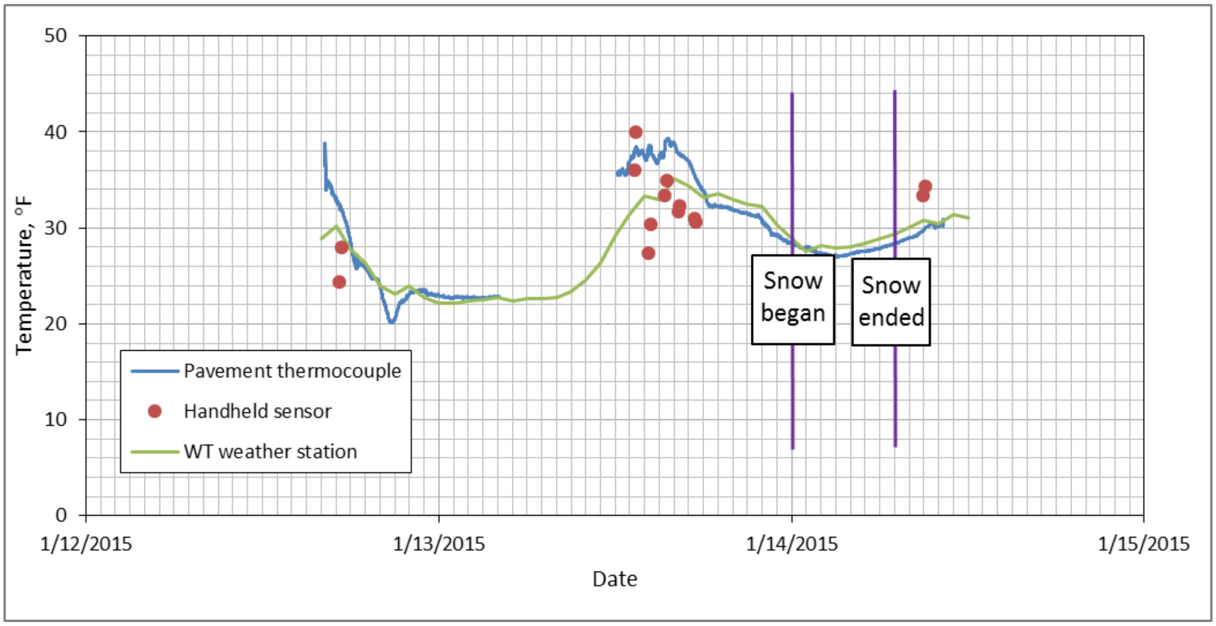


Figure 4.6. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-1

Details of Storm 3-1 were as follows.

- Total snow accumulation of less than ½ inch
- One anti-icing application was performed
- Visible difference between treated and control sections only, as the small amount of snow did not accumulate on the treated sections with both chemicals
- Accumulated snow quickly melted

The team de-mobilized at 11:00 a.m. on January 14, 2015, having performed no plowing or de-icing. This winter storm did not yield snow and ice control chemical effectiveness data. Qualitative analyses only were performed, but were not sufficient for statistical analyses.

4.4.3.2 Storm 3-1 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 1 dataset
- Image data… 2 datasets
  - one after anti-icing application and slushing
  - one after the snow accumulation
- Decelerometer data… none

The project file contains working data summaries associated with Storm 3-1, Winter 2014/15.

4.4.4 Storm 3-2 Mobilization (01/21-22/2015)

4.4.4.1 Storm 3-2 Summary A storm event capable of producing 4 to 8 in of snow was predicted by the NWS to start in the evening of Wednesday, January 21st. The decision to mobilize was made on January 20, at 4:41 p.m. Initial anti-icing operations and photo data gathering were performed prior to the event. Figure 4.7 shows the variations in temperature measurements gathered while on-site, as well as the time window for the heavy snow storm.

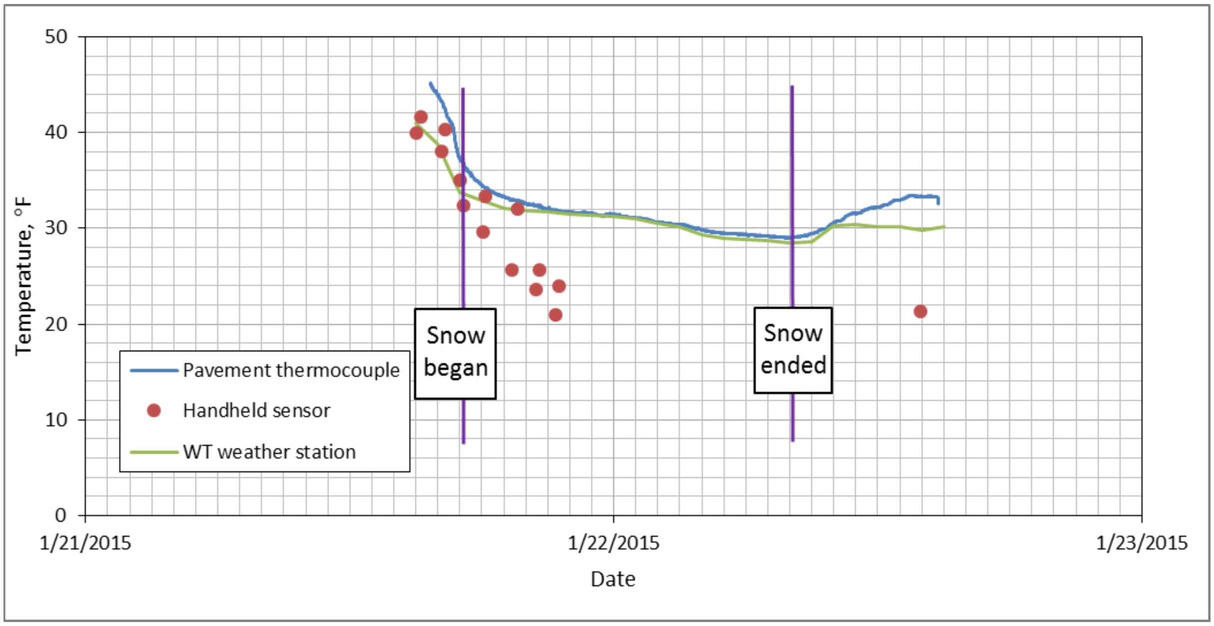


Figure 4.7. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-2

Snow began in the early evening of January 21 and quickly intensified. By 9:30 p.m. over 3 in had accumulated on the pavement, and the first plow run began. Unexpected circumstances prevented the full plowing of the test site, as the heavy snowfall and quick accumulation made all vehicular traffic at the test site difficult, and the plow truck had to be towed back onto the paved road after an unsuccessful multi-point turnaround. Once the plow resumed operations, the accumulation of snow was so heavy such that the team was unable to keep up. Operations were halted by 3:00 a.m. with eventual accumulation of snow of over 10 in. Plow operations resumed on the morning of January 22. Although several inches of snow had accumulated over the pavement surface, the snow did not adhere and was easily completely removed by the plow, so no de-icing chemicals were applied. Details were as follows.

- Total snow accumulation of 10 to 12 in
- One anti-icing application was performed
- First plowing during heavy snow was impossible to complete
- Accumulated snow was completely removed by second plow on the next morning
- No de-icing chemical applications performed

- No visible difference between test sections due to heavy snowfall

The team de-mobilized by 3:00 p.m. on January 23, 2015. This winter storm did not yield snow and ice control chemical effectiveness data. Qualitative analyses only were performed, but were not sufficient for statistical analyses.

4.4.4.2 Storm 3-2 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 4 datasets
  - After anti-icing application, slushing, and beginning of snowfall
  - After 2 hr of snow, before plowing
  - After 1 in of snow accumulated on pavement, before plowing
  - Following the first plow run after 3 in of snow on pavement
- Image data… 3 datasets
  - After anti-icing application and slushing
  - After plowing during heavy snowfall
  - After second plowing
- Decelerometer data… none

The project file contains working data summaries associated with Storm 3-2, Winter 2014/15.

4.4.5 Storm 3-3 Mobilization (02/16-17/2015)

4.4.5.1 Storm 3-3 Summary The NWS predicted a snow event for February 16, 2015, with ½ in of snow predicted to fall during the night, with the possibility of more during the following day. Figure 4.8 shows the variations in temperature measurements gathered while on-site, as well as the small window of light snow.

Although the prediction was low, the decision to mobilize was made at 9:02 a.m. on February 16th so that the first attempt at decelerometer data collection could be experienced. Anti-icing operations, video and photo data gathering, and initial decelerometer runs were performed once the site was operational. Overnight snowfall accumulated to only around 0.2 inches of snow, mostly off the pavement. Additional photos and decelerometer runs were taken but nothing else was possible. Details were as follows.

- Total snow accumulation of 0.2 inches
- One anti-icing application was performed
- Little moisture on the pavement
- No visible difference in sections

The team de-mobilized around noon on February 17, 2015. This winter storm also did not yield snow and ice control chemical effectiveness data. Qualitative analyses only were performed, but were not sufficient for statistical analyses.

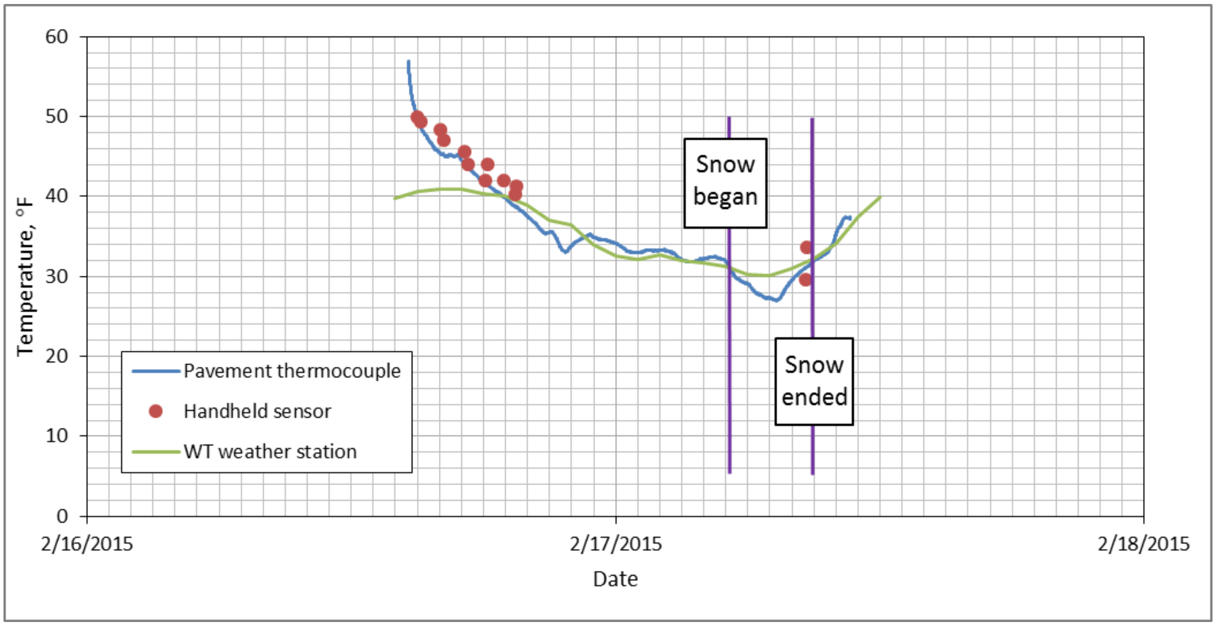


Figure 4.8. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-3

4.4.5.2 Storm 3-3 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 1 dataset, anti-icing only
  - After anti-icing application and slushing
- Image data… 3 datasets
  - Dry bare pavement prior to storm, all test sections
  - After anti-icing application and slushing, anti-icing sections only
  - After snowfall, anti-icing sections only
- Decelerometer data… 2 datasets, anti-icing only
  - Dry bare pavement prior to storm
  - After anti-icing application and slushing

The project file contains working data summaries associated with Storm 3-3, Winter 2014/15.

4.4.6 Storm 3-4 Mobilization (02/20-23/2015)

4.4.6.1 Storm 3-4 Summary Storm 3-4 was the first event to meet our target criterion of 1 to 3 in of snow accumulation on the pavement in our test sections. The decision to mobilize was made on February 20, 2015 at 4:53 p.m. A snow event capable of 2 to 3 in with prolonged temperatures below freezing was predicted for Sunday, February 22, 2015. Figure 4.9 shows the variations in temperature measurements gathered while on-site, as well as the relatively long time window of light snow.

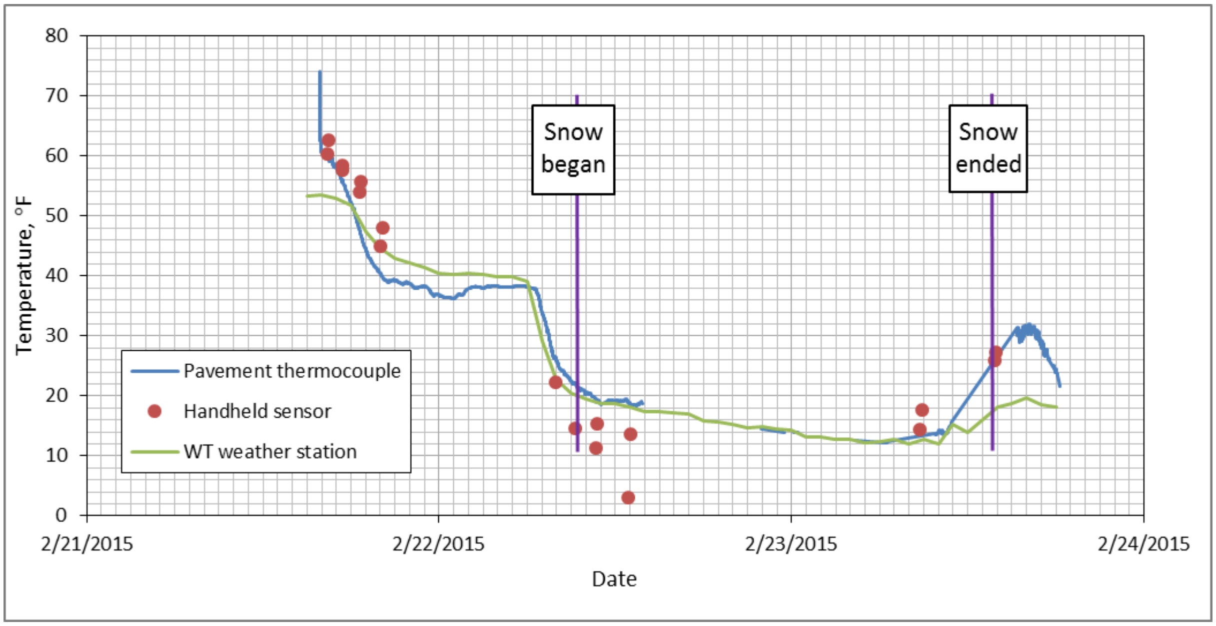


Figure 4.9. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-4

Initial anti-icing chemical applications were done on the evening of February 20, and video and photo image captures and decelerometer tests began on Saturday, February 21. Initial precipitation was mostly intermittent rain and snow that did not stick to the pavement. Consistent snowfall did not occur until Monday morning, February 23 (Figure 4.10).

Figure 4.10. Pavement Condition after Snowfall, Storm 3-4, Winter 2014-15

After 1 in of snow had accumulated and was compacted by multiple vehicle passes, the first plow run was followed by de-icing chemical and the second anti-icing chemical applications. Subsequent video and photo image capture as well as decelerometer runs were performed accordingly after the event. Details were as follows.

- Total snow accumulation of 1-⅛ to 1-¼ in
- Two anti-icing chemical applications were performed, one prior to the storm and the second after the first plow run
- Snow compacted prior to first plow run by multiple vehicle passes
- One de-icing chemical application after the first plow run
- Second plow run after slushing the chemical applications

The team de-mobilized at 6:30 p.m., February 23, 2015. This winter storm did provide useful snow and ice control chemical effectiveness data. Both qualitative and quantitative analyses with appropriate statistical analyses were completed, and these results are presented in Chapter 5.

4.4.6.2 Storm 3-4 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 5 datasets
  - After the first snowfall
  - After over 1 in of snow accumulation
  - After the first plow run
  - After application of the de-icing chemicals and second anti-icing chemicals, slushing both sections
  - After the second plow run
- Image data… 5 datasets
  - Dry bare pavement prior to storm
  - After anti-icing application and slushing
  - After the first snowfall
  - After over 1 in of snow accumulation
  - After application of the de-icing chemicals and second anti-icing chemicals, slushing both sections
- Decelerometer data… 7 datasets
  - Dry bare pavement prior to storm, both anti-icing and de-icing sections
  - After anti-icing application and slushing, anti-icing sections only
  - After the first snowfall, anti-icing sections only
  - After additional snow accumulation and compaction, anti-icing sections only
  - After over 1 in of snow accumulation, both sections
  - After the first plow run, both sections

- After application of the de-icing chemicals and second anti-icing chemicals, slushing both sections, both sections

See Appendix B for data summaries associated with Storm 3-4, Winter 2014/15.

4.4.7 Storm 3-5 Mobilization (02/25-27/2015)

4.4.7.1 Storm 3-5 Summary Storm 3-5 was the second event to meet our target criterion of 1 to 3 in of accumulated snow on the pavement in our test sections. The decision to mobilize was made February 25, 2015, at 1:29 p.m. The NWS forecast predicted ½ to 1 in of snow overnight, with larger amounts of over 2 during the following evening with temperatures holding below freezing. Figure 4.11 displays the variations in temperature measurements gathered while on-site, as well as the small snowfall duration.

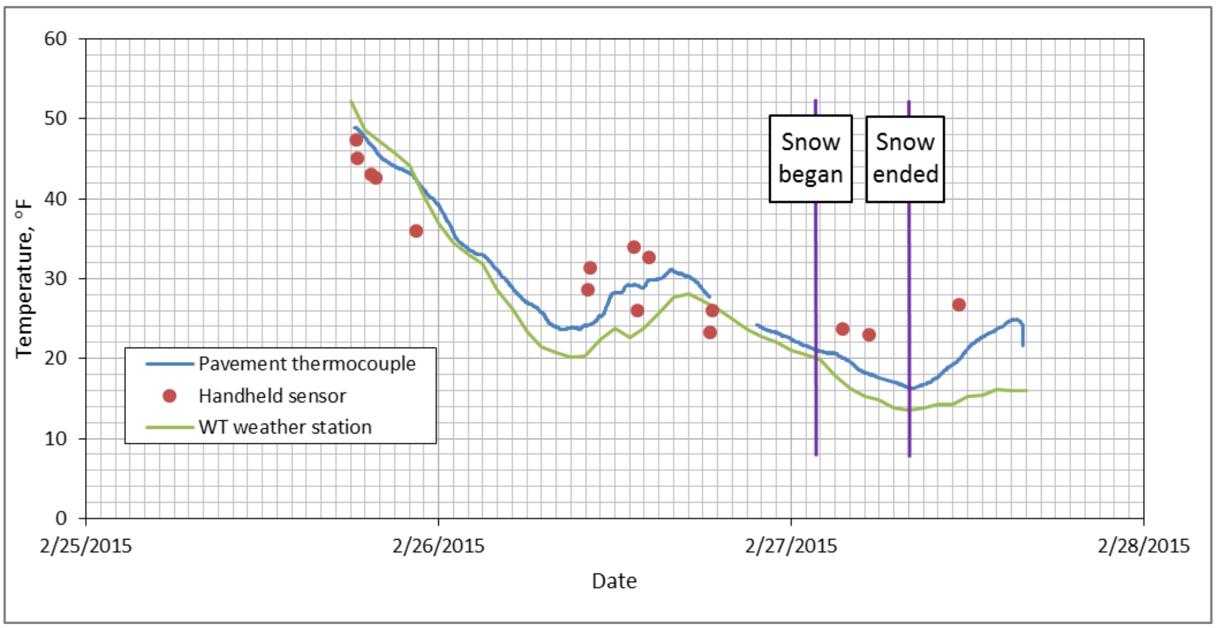


Figure 4.11. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-5

Anti-icing operations, photo data gathering, and decelerometer runs were initially performed. No accumulation occurred overnight for February 25. Significant amounts of snow did not begin until the morning of February 27, and the snow fell over about 6 hr, giving the research team little time to perform our plow runs, chemical applications, and data collections. After the snow was over 1 in deep, multiple vehicle passes were used to compact that show. The first plow run then occurred, followed by a second application of anti-icing chemicals and the first application of de-icing chemicals (Figure 4.12). After slushing and data collection of both sections, a second plow run was performed. A second round of de-icing chemicals was applied and slushed, then a final third plow run occurred. Multiple video and photo image captures were collected, and decelerometer test runs were performed. Details of the storm event response were as follows.

- Total snow accumulation of 2 to 3 in
- Two anti-icing chemical applications were performed, one prior to the storm and the second after the first plow run
- Snow compacted prior to first plow run by multiple vehicle passes
- First de-icing application after the first plow run
- Second plow run after slushing the chemical applications
- Second de-icing application after the second plow run, with slushing
- Third plow run followed

Figure 4.12. Application of Anti-icing and De-icing Chemicals, Storm 3-5, Winter 2014-15

The team de-mobilized by 4:30 p.m., February 27, 2015. This winter storm provided useful snow and ice control chemical effectiveness data. Both qualitative and quantitative analyses with appropriate statistical analyses were completed, and these results are presented in Chapter 5.

4.4.7.2 Storm 3-5 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 8 datasets
    - After anti-icing application and slushing
    - After first snowfall
    - After over 1 in snow accumulated and compacted
    - After the first plow run

    - After application of first de-icing chemicals and second anti-icing chemicals, slushing both sections
    - After second plow run
    - After second de-icing, slushing
    - After third plow run
- Image data… 4 datasets
    - After over 1 in snow accumulated and compacted
    - After the first plow run
    - After application of first de-icing chemicals and second anti-icing chemicals, slushing both sections
    - After third plow run
- Decelerometer data… 5 datasets
    - After anti-icing application and slushing, anti-icing sections only
    - After the first plow run
    - After application of first de-icing chemicals and second anti-icing chemicals, slushing both sections
    - After second plow run
    - After second de-icing, slushing, and third plow run

See Appendix C for data summaries associated with Storm 3-5, Winter 2014/15.

4.4.8 Storm 3-6 Mobilization (03/03-04/2015)

4.4.8.1 Storm 3-6 Summary The NWS predicted 1-½ to 2 in of snow beginning the evening of March 3, 2015, due to an Arctic air mass moving over the test area. Although temperatures were well above freezing on the morning of March 3, the decision to mobilize was made at 10:00 a.m. on that date. Figure 4.13 shows the variations in temperature measurements gathered while on-site, as well as the short time window of snowfall.

Anti-icing operations, video and photo image gathering, and decelerometer runs were begun once the site was operational. Snowfall finally occurred on the afternoon of March 4, but only about ½ in of snow fell over the entire storm. The snow was dry and did not adhere well to the pavement under the windy conditions. Photo data gathering and decelerometer runs were taken for after the snow ended, but the relatively bare pavement did not warrant plowing or further chemical treatment. Details of this event were as follows.

- Total snow accumulation of ½ inch
- One anti-icing application was performed
- Little adherence of dry snow to pavement
- Slight visual differentiation between anti-icing chemicals

The team de-mobilized by 7:00 p.m., March 4, 2015. This winter storm did not yield snow and ice control chemical effectiveness data. Qualitative analyses only were performed, but were not sufficient for statistical analyses.

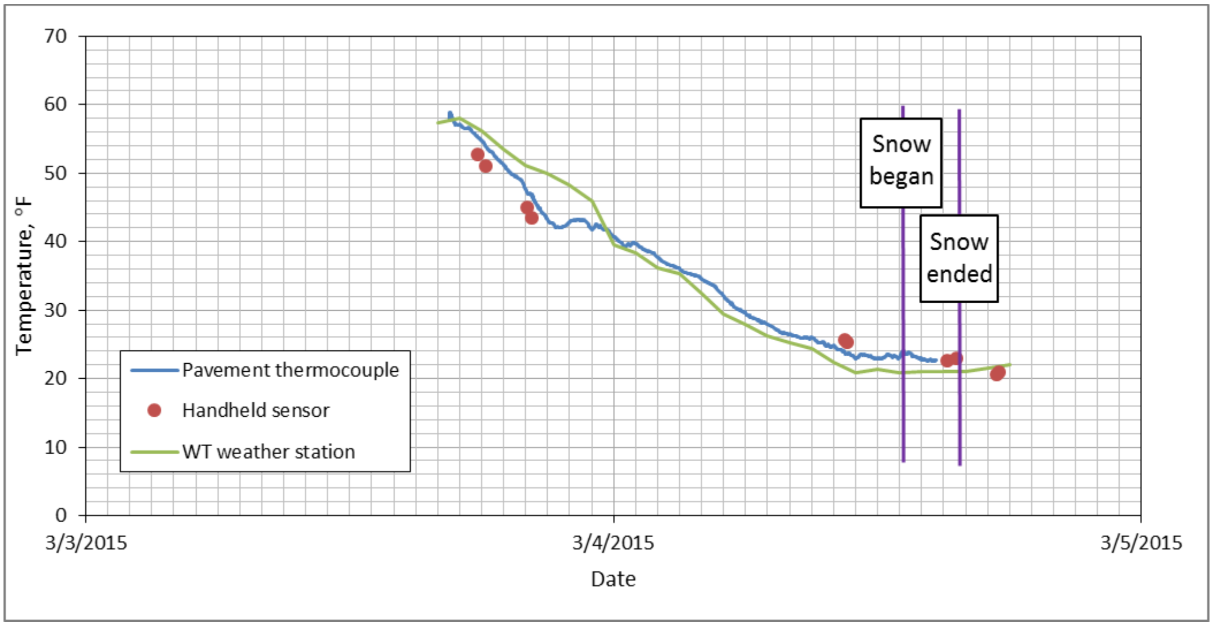


Figure 4.13. Observed variations in pavement (thermocouple and handheld sensor) and atmospheric temperature with snow duration for Storm 3-6

4.4.8.2 Storm 3-6 Data Data collected for this storm and archived in the project file are as follows:

- Weather data… National Weather Service, SchoolNET Canyon
- Video data… 1 dataset
    - Dry bare pavement prior to storm, both anti-icing and de-icing sections
- Image data… 3 datasets
    - Dry bare pavement prior to storm, both anti-icing and de-icing sections
    - After anti-icing application and slushing, anti-icing sections only
    - After snowfall, anti-icing sections only
- Decelerometer data… 3 datasets
    - Dry bare pavement prior to storm, both anti-icing and de-icing sections
    - After anti-icing application and slushing, anti-icing sections only
    - After snowfall, anti-icing sections only

The project file contains working data summaries associated with Storm 3-6, Winter 2014/15.

4.5 Data Selected for Analysis

The field trials conducted under Task 5 of the research study yielded nine winter storm mobilizations. Table 4.6 identifies all of these mobilizations, including assessments about whether the storm provided data suitable for subsequent analyses. The appendixes present the data for selected storms.

Table 4.6. Winter Storm Mobilizations, Task 5 Field Trials

Winter	Storm	Start Date	Snowfall Accumulation	Anti-icing Data*	De-Icing Data*	Data Selected for Analysis?
2012/13						No storm data
2013/14	2-1	12/21/2013	~0.5 in	V, I	None	Insufficient data
2013/14	2-2	2/5/2014	1-1.5 in	None	V, I	Insufficient data
2013/14	2-3	3/2/2014	~1.0 in	None	V, I	De-icing operations
2014/15	3-1	1/12/2015	<0.5 in	V, I	None	Insufficient data
2014/15	3-2	1/21/2015	>10 in	V, I	None	Insufficient data
2014/15	3-3	2/16/2015	0.2 in	V, I, D	None	Insufficient data
2014/15	3-4	2/21/2015	1.25 in	V, I, D	V, I, D	Anti-icing operations De-icing operations
2014/15	3-5	2/25/2015	2-3 in	V, I, D	V, I, D	Anti-icing operations De-icing operations
2014/15	3-6	3/3/2015	<0.5 in	V, I, D	None	Insufficient data
*Note: V = video data, I = image (photo) data, D = decelerometer data						

For anti-icing operations, two storms, Storm 3-4 and Storm 3-5, provided sufficient data for analysis. Anti-icing data from other storms supported qualitative analysis only, and these data were incorporated where possible. Chapter 5 presents the analysis of field data relative to the effectiveness of snow and ice control chemicals for anti-icing operations.

For de-icing operations, three storms, Storm 2-3, Storm 3-4 and Storm 3-5, provided sufficient data for analysis. De-icing data from other storms supported qualitative analysis only, and these data were incorporated where possible. Chapter 6 presents the analysis of field data relative to the effectiveness of snow and ice control chemicals for de-icing operations.

CHAPTER 5
ANTI-ICING RESULTS

5.1 Introduction

This chapter presents results of comparative analyses performed on the data collected from the anti-icing test sections at the field research site. The goal of these analysis was to compare and evaluate the effectiveness of the two typical liquid chemicals TxDOT uses for anti-icing operations, namely, Meltdown Apex™ (MDA) and road salt brine (RSB). For anti-icing, two storms – Storm 3-4 and Storm 3-5 – provided sufficient field data for analysis. Anti-icing data from five other storms supported limited or qualitative analysis only, and these data were incorporated where possible. The methods of data reduction were presented in Chapter 3. Since the primary comparative data for anti-icing were from Winter 2014/15, it is appropriate to highlight the test section layout used for anti-icing data collection (Figure 5.1).

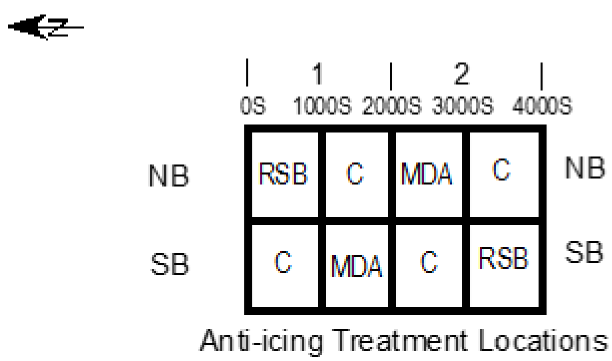


Figure 5.1 Schematic of Test Sections and Treatments (not to scale) C = control, MDA = Meltdown Apex™, RSB = road salt brine

5.2 Photo Image Analysis

The photo images were analyzed according to the mini-Delphi method described in Chapter 3. For Storms 3-4 and 3-5, separate graphical representations of the results for each photo set by test section are provided in Appendix B and Appendix C, respectively. In this chapter, the statistical results for each photo set and treatment, RSB, MDA, and control, are compared statistically.

5.2.1 Storm 3-4 Photos

Five sets of photo images were taken during Storm 3-4. The data were processed by the mini-Delphi method explained previously. The first set was begun at 4:14 p.m. on February 21 for the bare dry pavement before chemical application. The second set began at 8:08 p.m. on February 21 after application of the anti-icing chemicals, so the pavement was wet only where those chemicals were added. The third photo set began at 3:12 p.m. on February 22, after the snow had begun. The snow adhered more readily to the test sections treated with the anti-icing chemicals than the control sections and untreated de-icing sections. The fourth photo set began at 12:50 p.m. on February 23, after 1 in of snow had accumulated on the pavement. This snow was compacted with multiple vehicle traverses to better represent actual roadway conditions. The final photo set was collected starting at 3:24 p.m. on February 23, after the first plowing, second anti-icing application, first de-icing application, and slushing. After the last photo set, a second plow run was performed. By that time, 4:20 p.m. on February 23, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

Data were analyzed using standard statistical methods. The results of data analyses for anti-icing test sections in Storm 3-4 are presented in Figure 5.2. The bar charts provide the overall averages and standard deviations (the error bars represent one standard deviation above and below the mean) for all the data observed in the sections of like treatment (control or chemical application) for each data collection time period, as shown in the category labels. Based on analysis of variance (ANOVA), if there was no significant statistical difference for the observed means across the three treatments, no annotation letter is shown above the bars. If some statistical differences were noted during one observation time as shown by the category label, the letters A, B, or C are shown above the bars to represent which treatment pairs were statistically similar. No differences relative to location were noted in any of the datasets.

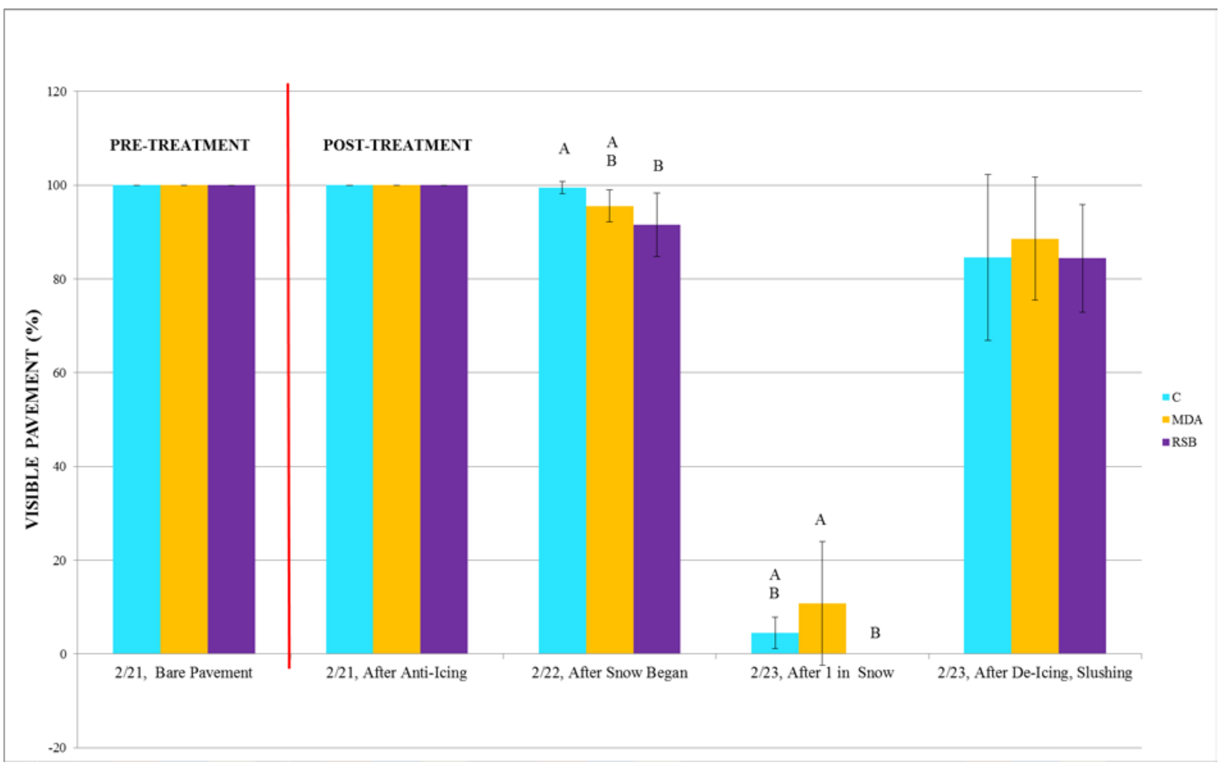


Figure 5.2 Analyses of Anti-icing Section Photos, Storm 3-4

Summary observations from Storm 3-4 are as follows.

1. Anti-icing photo sets 1 and 2 showed all completely clear pavement, so no differences were noted.
2. Anti-icing photo set 3 was collected after snow had just begun to stick to the pavement. The control sections were significantly clearer than those treated with RSB. There was no significant difference between the sections treated with MDA and the controls. No significant difference was seen between MDA and RSB.
3. Anti-icing photo set 4 was collected after 1 in of snow accumulated on the untreated pavement. The sections treated with MDA were significantly clearer than those treated with RSB. No significant difference was noted between the control and MDA sections, nor between the control and RSB sections.
4. Anti-icing photo set 5 was collected after plowing, the second anti-icing chemical application, and slushing. No significant differences were noted among all three treatments. The SB lanes were significantly clearer than the NB lanes.

5.2.2 Storm 3-5 Photos

Four sets of photo images were taken during Storm 5. The first set was begun at 6:50 a.m. on February 27 after the accumulation of over 2 in of snow, followed by compaction by multiple vehicle traverses. The second set began at 9:15 a.m. on February 27 after plowing. The third photo set began at 10:48 a.m. on February 27 after the second application of anti-icing chemicals, first application of de-icing chemicals, and slushing. The fourth photo set began at 1:17 p.m. on February 27 after the third plowing after the second de-icing chemical application. The number of photo sets was limited by the short window of the snow event and the time required for chemical applications and data captures with the various vehicles and team members on site. After the last photo set, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

The results of the photo data analyses for Storm 3-5 are presented in Figure 5.3 in the same style as for Storm 3-4. Occasionally, some statistical differences between the combinations of treatment and lane were noted, so those pairs include NB or SB as lane differentiation. No differences relative to location were noted in any of the datasets.

Summary observations from Storm 3-5 were as follows.

1. Statistical analysis of anti-icing photo set 1, taken after snow accumulation and compaction, showed no significant difference between treatments in the SB lane. In the NB lane, the control sections were significantly less clear than RSB and MDA sections. There was no significant difference between RSB and MDA in either lane.

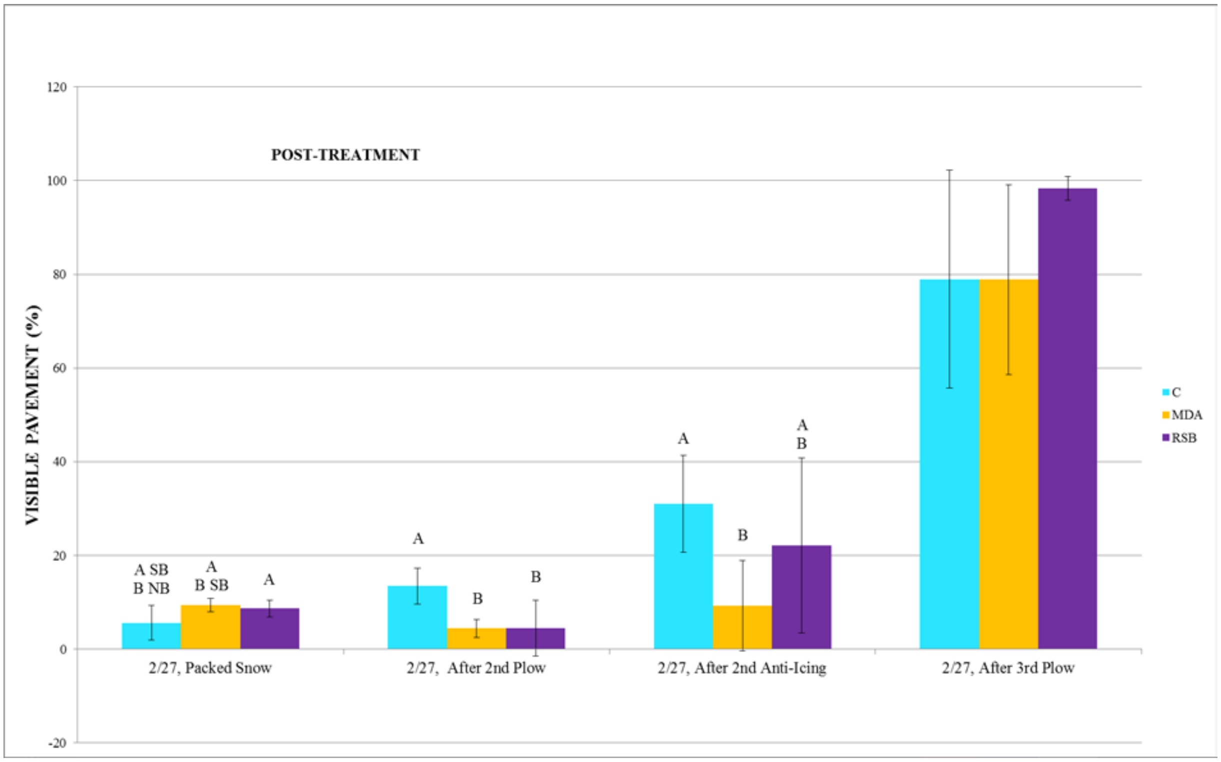


Figure 5.3 Analyses of Anti-icing Section Photos, Storm 3-5

2. Anti-icing photo set 2 was collected after plowing. The control sections were significantly clearer than the RSB and MDA sections. No significant difference was seen between the RSB and MDA sections.
3. Anti-icing photo set 3 was collected after the second anti-icing application and slushing. The control sections were significantly clearer than the MDA sections. There was no significant difference between the control and RSB sections, nor was there a significant difference between RSB and MDA sections.
4. The final anti-icing photo set after the final plowing show no significant differences across all three treatments.

5.3 Video Analysis

The video files were reduced and analyzed according to the mini-Delphi method described in Chapter 3. Overall averages and standard deviations were calculated for each treatment type for each video record. These results were useful as they represented what a TxDOT maintenance worker might report from a "windshield survey" of road conditions during a winter storm. We did not calculate means and standard deviations for the PSIC and AASHTO category values, as the discrete values did not represent a monotonic numerical progression from best to worst roadway conditions. The raw data forms are provided in Appendix B and Appendix C. In this section of the report, the overall averages and standard deviations for the bare pavement results for each video dataset and treatment, RSB, MDA, and control, are compared statistically.

5.3.1 Storm 3-4 Videos

Five useful video datasets were captured after the snow began to accumulate on the pavement during Storm 3-4. Two earlier video datasets showed only bare pavement prior to the snow event on all segments. The data were processed by the mini-Delphi method explained previously. The first video dataset was begun at 9:13 a.m. on February 22, after the snow had begun. The snow first adhered more readily to the test sections treated with the anti-icing chemicals than the control sections and untreated de-icing sections. The second video dataset began at 11:39 a.m. on February 23, after 1 in of snow had accumulated on the pavement and was compacted with multiple vehicle traverses to better represent actual roadway conditions. The third video dataset was collected starting at 1:45 p.m. on February 23, after the first plow run. The fourth video dataset began at 3:07 p.m. on February 23, after the second anti-icing chemical application and slushing. The final video dataset was captured at 4:24 p.m. on February 23, after the second plow run. By that time, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

Figure 5.4 presents the qualitative bare pavement results from the mini-Delphi analysis of the videos taken during Storm 3-4. Across the five video data captures for the anti-icing sections, the averages and variabilities among the three treatments were visually similar as seen in Figure 5.3. After the accumulation of 1 in of snow, the control sections were a little less clear than the treated sections. The MDA and RSB sections had similar amounts of visible pavement. The sizes of the standard deviations as shown by the error bars demonstrated sizable variations across the section and the survey members.

5.3.2 Storm 3-5 Videos

Seven useful video datasets were captured after the snow began to accumulate on the pavement during Storm 3-5. Two earlier video datasets showed only bare pavement prior to the snow event on all segments. The data were processed by the mini-Delphi method explained previously. The first video dataset was begun at 3:42 p.m. on February 26, after the snow had begun. The second video dataset began at 3:38 a.m. on February 27, after snowfall started to adhere to the pavement. The third video dataset was captured after 7:13 a.m. on February 27, after 1 to 2 in of snow had accumulated on the pavement and was compacted with multiple vehicle traverses to better represent actual roadway conditions. The fourth video dataset was collected starting at 7:24 a.m. on February 27, after the first plow run. The fifth video dataset began at 10:08 a.m. on February 27, after the second anti-icing and first de-icing chemical applications and slushing. The sixth video dataset was captured at 1:46 p.m. on February 27, after the second plow run, second de-icing chemical application, and slushing.

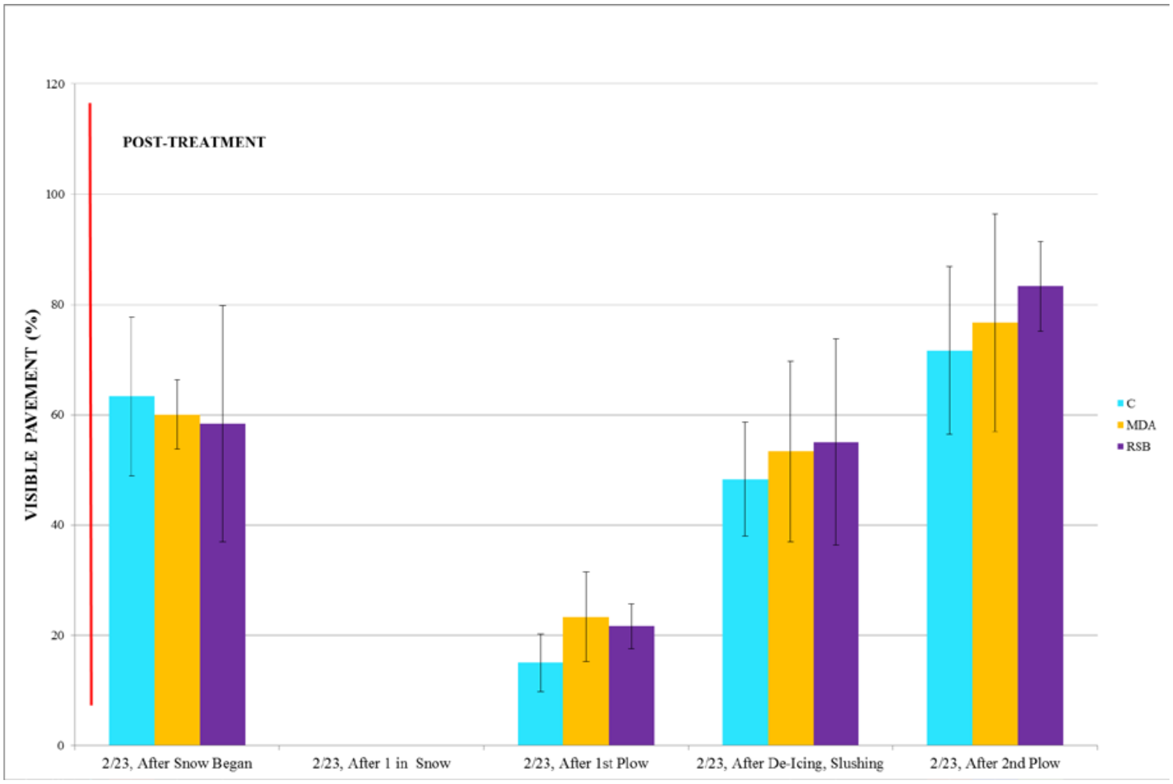


Figure 5.4 Summary of Anti-icing Videos for Visible Pavement, Storm 3-4

The last video dataset began at 3:03 p.m. after the third plow run. By that time, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

Across the seven video data captures for the anti-icing sections in Figure 5.5, the average and standard deviations among the three treatments for Storm 3-5 varied much more than the video data for Storm 3-4. All videos were captured after the first anti-icing application, and the pavement sections were essentially clear for the first video in Figure 5.5. In the second video, the early snow appeared to adhere to the treated sections more readily than the control sections. After the first plowing, the RSB and MDA sections were clearer than the control sections. After the second anti-icing application and slushing, the control sections were clearer than the RSB sections, the control sections were similar to the MDA sections, and the MDA and RSB sections were similar. In the last two videos, the RSB sections were on average the clearest, but the variability in the MDA sections was larger than the variability in the RSB sections. Variations in the wheel path wear zones could have contributed to the differences in the observations of accumulation and melting of snow and slush.

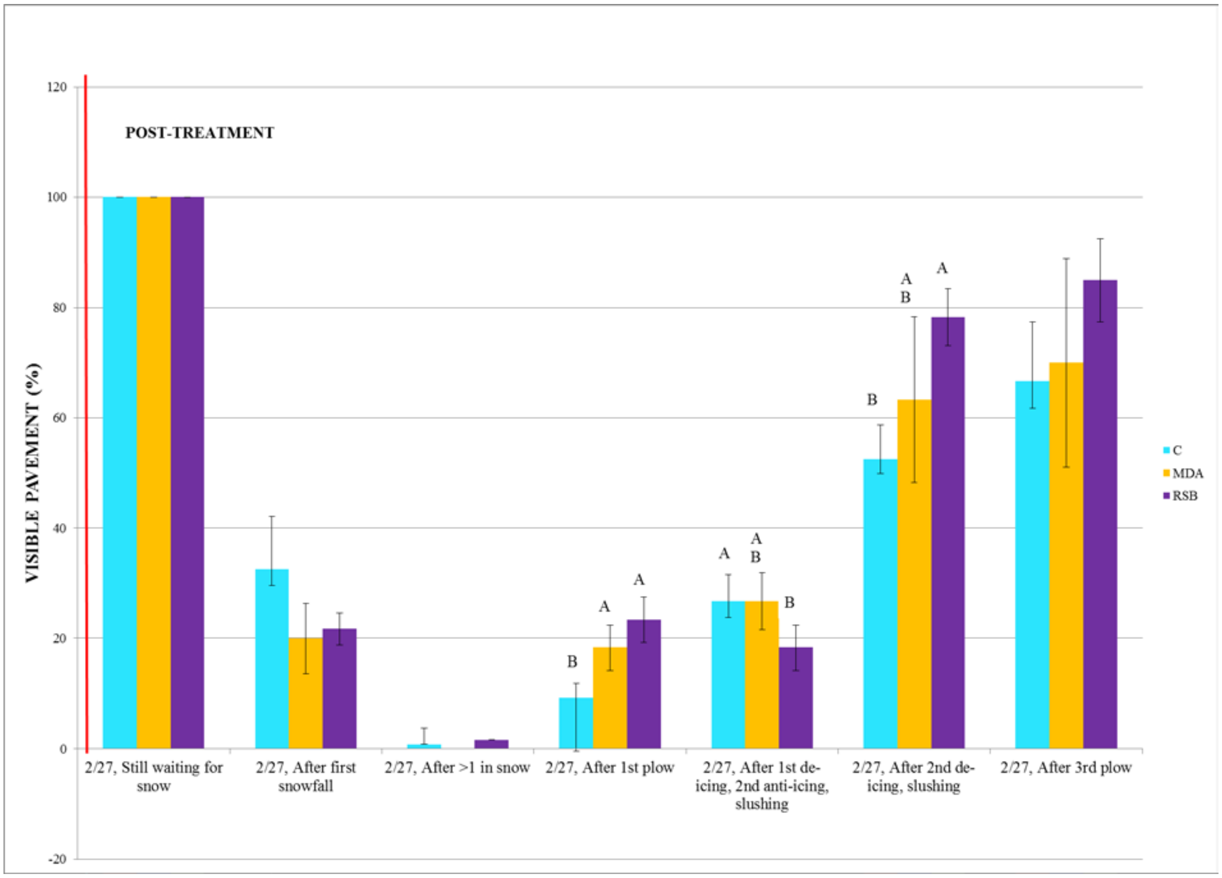


Figure 5.5 Summary of Anti-icing Videos for Visible Pavement, Storm 3-5

5.4 Decelerometer Data Analysis

The NAC Decel Smartphone App (DSA) was used to obtain a measure of pavement surface friction for Storms 3-4 and 3-5. The DSA reported the deceleration as a percent of the acceleration of gravity, or percent G. Dry pavement yielded percent G values near and sometimes above 100 percent, while lower values could be observed after anti-icing chemicals were applied or after the snow began. Three DSA tests were performed in each test section during each test run, similar to the approach used in the photo data collection, leading to 24 data points in the anti-icing sections. The overall averages and standard deviations were calculated for sections of like treatment for each test run, and the ANOVA was used to assess the decelerometer data in the same manner as was used for the photo and video datasets.

5.4.1 Storm 3-4 Decelerometer

Seven sets of decelerometer tests were performed in the anti-icing sections in Storm 3-4. The first set of tests began at 5:38 p.m. on February 21, before application of anti-icing chemicals. The second set of tests started at 8:32 p.m. on February 21, after the first anti-icing chemical applications and slushing. The third set of tests began at 10:40 a.m. on February 22, after the snowfall began. The fourth set of tests began at 1:23 p.m. on February 22, after additional snow accumulation. The fifth set of tests started at 11:57 a.m. on February 23, after over 1 in of snow accumulation and compaction by multiple vehicle passes. The sixth set of tests began at 12:54 p.m. on February 23, after the first plow run. The final set of tests started at 3:26 p.m. on February 23, after the second anti-icing applications and slushing.

The results of the decelerometer data analyses for Storm 3-4 are presented in Figure 5.6 in the same approach as used with the photo and video data analyses. Occasionally, some statistical differences between the combinations of treatment and lane were noted, so those pairs include NB or SB as lane differentiation. No differences relative to location were noted in any of the datasets.

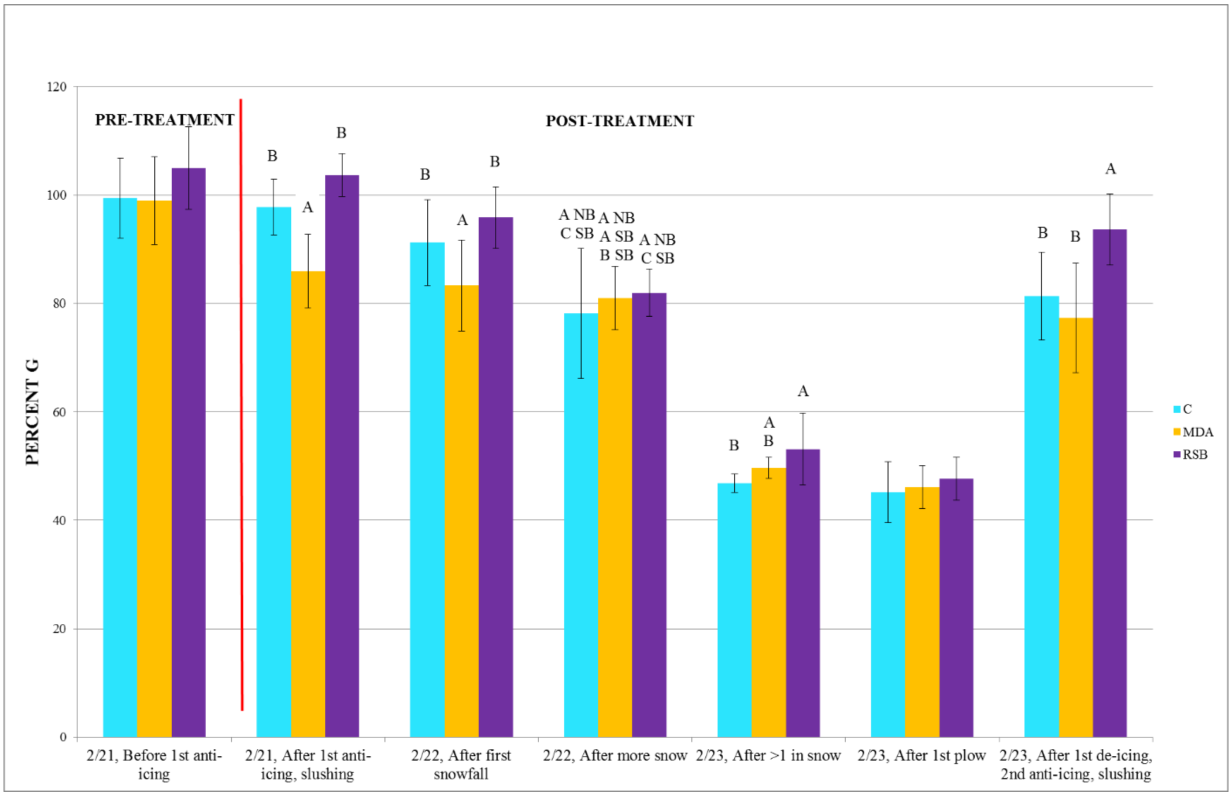


Figure 5.6. Analyses of Anti-icing Section Decelerometer Data, Storm 3-4

Summary observations from Storm 3-4 were as follows.

1. The first set of DSA data in the anti-icing sections showed no evidence that there was a difference in the treatments (p-value = 0.324), nor a difference in the lanes (p-value = 0.431), nor the locations (p-value = 0.739). This result was consistent with a uniform test-bed, so there was no evidence that any remedial measures were required to account for a heterogeneous test-bed.
2. The second set of DSA data was taken after application of both anti-icing chemicals. There was no significant difference between the RSB and control sections, but the MDA had a

significantly lower mean percent G than both the RSB and control sections. We can be 95 percent confident that the true mean for MDA percent G minus the true mean for the control percent G was between -18 percent to -5 percent. To state it more simply, MDA sections were significantly slicker than both the RSB and control sections.

3. Anti-icing DSA dataset 3 was collected after some snow had started adhering to the pavement. No significant difference in percent G was seen between RSB and control sections, but the MDA sections had significantly smaller percent G values than both RSB and control sections.
4. Anti-icing DSA dataset 4 was collected after more accumulation of snow. In the NB lane, no significant differences were noted between all three treatments. In the SB lane, the control sections were significantly slicker than MDA sections, while there were no significant differences in percent G for the MDA and RSB sections, nor for the RSB and control sections.
5. Anti-icing DSA dataset 5 was collected after additional snow accumulation over 1 in followed by compaction. These data showed the control sections were significantly slicker than the RSB sections. No significant difference was seen between the RSB and MDA sections, nor between the MDA and control sections.
6. Anti-icing DSA dataset 6 was collected after plowing. No significant differences in percent G were noted across treatments, lanes, or locations.
7. Anti-icing DSA dataset 7 was collected after de-icing chemicals and a second round of anti-icing chemical were applied. No significant difference was noted between the MDA and control sections, but the RSB sections had significantly higher percent G than the control and MDA sections.
8. The anti-icing DSA tests overall indicated that MDA was generally slicker than RSB. The friction results for the control sections were typically between those of the two chemical treatments.

5.4.2 Storm 3-5 Decelerometer

Five sets of decelerometer tests were performed in the anti-icing sections in Storm 3-5. The first test set began at 8:04 p.m. on February 25, after the first anti-icing chemical applications and slushing. The second round of tests began at 7:32 a.m. on February 27, after the first plow run. The third set of tests began at 10:22 a.m. on February 27, after the second anti-icing applications and slushing. The fourth test set started at 11:53 a.m. on February 27, after the second plow run. The final set of tests began at 2:19 p.m. on February 27, after the third plow run.

The results of the decelerometer data analyses for Storm 3-5 are presented in Figure 5.7 in the same approach as used with the photo data analyses. Occasionally, some statistical differences between the combinations of treatment and lane were noted, so those pairs include NB or SB as lane differentiation.

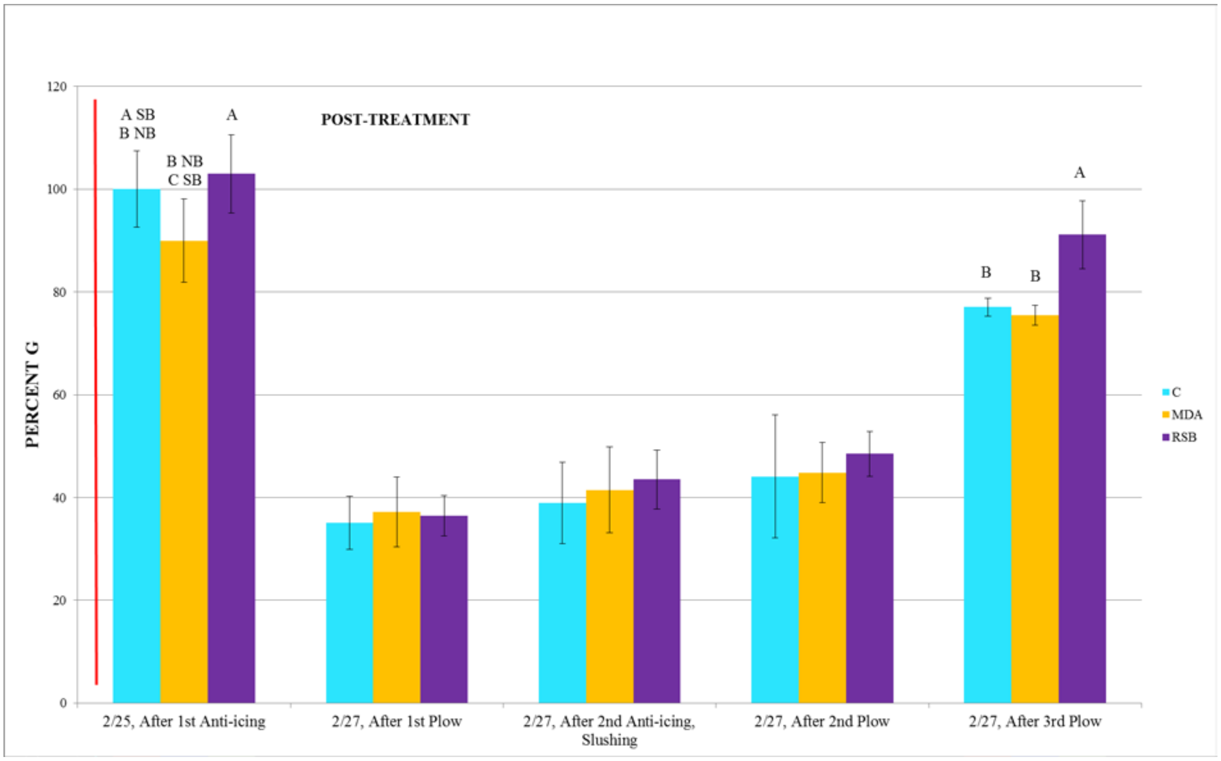


Figure 5.7 Analyses of Anti-icing Section Decelerometer Data, Storm 3-5

Summary observations from Storm 3-5 were as follows.

1. The first anti-icing DSA data set was collected after the first anti-icing chemical applications. No significant difference in Percent G was noted between the RSB and control sections, but the MDA sections were significantly slicker than the RSB sections. The MDA SB sections had significantly lower Percent G values than the control sections, but the MDA NB sections were not significantly different from the control sections.
2. Anti-icing DSA data sets 2, 3, and 4 were collected after plowing, after slushing the second anti-icing applications, and after a subsequent plow run, respectively. No significant differences were seen across any treatments in any of these data sets.
3. Anti-icing DSA data set 5 was collected after the final plowing. The control and MDA sections were not statistically different, and were both significantly slicker than the RSB sections.
4. The anti-icing DSA tests overall indicated that MDA was generally slicker than RSB. The control sections were sometimes between the two chemical treatments.

5.5 Summary of Findings for Anti-Icing Treatment

5.5.1 Comparison of RSB and MDA

The effectiveness of RSB and MDA were observed in two storm events that met our criterion of 1 to 3 in of snow accumulation on the pavement in the test sections. Table 5.1

summarizes the comparisons of performance of the chemicals (RSB vs. MDA) for each of the three data types for both storms. For the photo and video data, the numerical values represent the percentage of visible or bare pavement for the test sections. For the decelerometer data, the numerical values are deceleration as a percentage of the acceleration of gravity.

Table 5.1 Summary of Statistical Comparisons of RSB vs. MDA for Anti-icing Test Sections

Field Test Condition	Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●		●			
Applied anti-icing chemicals	√			√		
After 1st anti-icing, slushing	●		▲(6)		●	▲ (13)
After first snowfall	●	●	▲(5)		●	
After more snow			●			
After >1 in snow	■(11)	●	●	●	●	
After 1st plow		●	●	●	▲(5)	●
Applied de-icing chemicals	√			√		
Applied anti-icing chemicals again	√			√		
After 1st de-icing, 2nd anti-icing, slushing	●	●	▲(12)	●	●	●
After 2nd plow		●				●
Applied de-icing chemicals again				√		
After 2nd de-icing, slushing					●	
After 2nd de-icing, slushing, 3rd plow				●	●	▲(16)

●	RSB=MDA
▲	RSB>MDA with percentage difference
■	MDA>RSB with percentage difference
√	Chemical application

Based on analyses of the photo and video datasets, typically no statistically-significant differences were noted in the performance of the RSB and MDA anti-icing chemical applications relative to the amount of visible bare pavement at various times in the two storm events. The photo datasets typically show no statistically-significant difference between the performances of sections treated with MDA anti-icing chemical vs. sections treated with RSB anti-icing chemical. Seven of the eight post-treatment datasets showed this response. One dataset showed that RSB performed worse than sections treated with MDA.

The video datasets typically showed no statistically-significant difference between the performance of sections treated with RSB anti-icing chemical vs. untreated (control) sections. Eleven of the twelve post-treatment datasets showed this response. One video dataset showed that RSB-treated sections performed better than sections treated with MDA.

The decelerometer tests allowed us to consider TxDOT staff anecdotal observations that MDA application to dry pavement prior to a storm event caused slicker moist pavement conditions than RSB. Our pre-snow and post-anti-icing treatment observations showed no statistically-significant difference between sections for six of eleven decelerometer datasets. However, five of eleven datasets showed the MDA-treated test sections could be 10 to 20 percent slicker (slower deceleration) than the RSB-treated test sections.

5.5.2 Comparison of RSB vs. Control

The effectiveness of RSB and MDA were not only compared to each other but were also observed relative to untreated field test sections (control). Table 5.2 summarizes the comparison of performance of RSB vs. control for each of the three data types for Storm 3-4 and Storm 3-5. For the photo and video data, the numerical values represented the percentage of visible or bare pavement for the test section. For the decelerometer data, the numerical values were deceleration as a percentage of the acceleration of gravity.

Table 5.2 Summary of Statistical Comparisons of RSB vs. C for Anti-icing Test Sections

Field Test Condition	Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●		●			
Applied anti-icing chemicals		√			√	
After 1st anti-icing, slushing	●		●		●	●
After first snowfall	●	●	●		●	
After more snow			●			
After >1 in snow	■(8)	●	▲(6)	●	●	
After 1st plow		●	●	■(9)	▲(14)	●
Applied de-icing chemicals		√			√	
Applied anti-icing chemicals again		√			√	
After 1st de-icing, 2nd anti-icing, slushing	●	●	▲(12)	●	■(8)	●
After 2nd plow		●				●
Applied de-icing chemicals again					√	
After 2nd de-icing, slushing					▲(26)	
After 2nd de-icing, slushing, 3rd plow				●	●	●

●	RSB=C
▲	RSB>C with percentage difference
■	C>RSB with percentage difference
√	Chemical application

The photo datasets typically displayed no statistically-significant difference between the performances of sections treated with RSB anti-icing chemical vs. untreated (control) sections. Six of the eight post-treatment datasets showed this response. Two datasets showed that sections treated with RSB performed worse than untreated control sections.

The video datasets typically indicated no statistically-significant difference between the performances of sections treated with RSB anti-icing chemical vs. untreated (control) sections. Nine of the twelve post-treatment datasets showed this response. Two video datasets showed that RSB-treated sections performed better than untreated control sections, and one video dataset showed that RSB-treated sections performed worse than control.

In like manner for the photo and video data, the decelerometer datasets typically exhibited no statistically-significant difference between the performances of sections treated with RSB anti-icing chemical vs. untreated (control) sections. Nine of the eleven post-treatment datasets showed this response. Two decelerometer datasets showed that RSB-treated sections performed better than untreated control sections, such that the RSB application yielded a pavement surface less slick than untreated pavement.

5.5.3 Comparison of MDA vs. Control

Table 5.3 summarizes the comparison of performance of MDA vs. control for each of the three data types for Storm 3-4 and Storm 3-5. For the photo and video data, the numerical values represented the percentage of visible or bare pavement for the test section. For the decelerometer data, the numerical values were deceleration as a percentage of the acceleration of gravity.

The photo datasets typically exhibited no statistically significant difference between the performances of sections treated with MDA anti-icing chemical vs. untreated (control) sections. Six of the eight post-treatment datasets showed this response. Two datasets indicated that sections treated with MDA performed worse than the untreated control sections.

The video datasets typically displayed no statistically-significant difference between the performances of sections treated with MDA anti-icing chemical vs. untreated (control) sections. Eleven of the twelve post-treatment datasets showed this response. One video dataset showed that MDA-treated sections performed better than untreated control sections.

In like manner for the photo and video data, the decelerometer datasets typically indicated no statistically-significant difference between the performances of sections treated with MDA anti-icing chemical vs. untreated (control) sections. Eight of the eleven post-treatment datasets showed this response. However, three decelerometer datasets showed that MDA-treated sections performed worse than untreated control sections, such that the MDA application yielded a pavement surface that was slicker than untreated pavement for these three sections.

Table 5.3 Summary of Statistical Comparisons of MDA vs. C for Anti-icing Test Sections

Field Test Condition	Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●		●			
Applied anti-icing chemicals	√			√		
After 1st anti-icing, slushing	●		■(12)		●	■(10)
After first snowfall	●	●	■(8)		●	
After more snow			●			
After >1 in snow	●	●	●	●	●	
After 1st plow		●	●	■(9)	▲(9)	●
Applied de-icing chemicals	√			√		
Applied anti-icing chemicals again	√			√		
After 1st de-icing, 2nd anti-icing, slushing	●	●	●	■(22)	●	●
After 2nd plow		●				●
Applied de-icing chemicals again				√		
After 2nd de-icing, slushing					●	
After 2nd de-icing, slushing, 3rd plow				●	●	●

●	MDA=C
▲	MDA>C with percentage difference
■	C>MDA with percentage difference
√	Chemical application

5.5.4 Overall Comparison of RSB and MDA for Anti-icing Applications

Analyses of the photo and video datasets for anti-icing applications associated with two storm events typically showed no statistically-significant difference in the amount of visible bare pavement for pavement sections treated with RSB vs. sections treated with MDA anti-icing chemical. Decelerometer tests indicated that the MDA-treated test sections could be 10 to 20 percent slicker (lower deceleration) than the RSB-treated test sections.

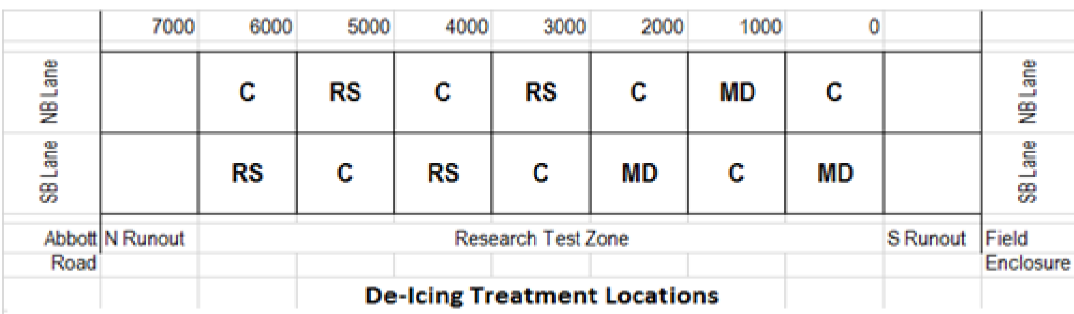
How does the performance of these chemicals compare to pavement sections having "no treatment"? Again, photo and video datasets for anti-icing applications associated with two storm events typically showed no statistically-significant difference in the amount of visible bare pavement for sections treated with RSB or MDA anti-icing chemical compared to untreated control sections. Similarly but less prominent, decelerometer tests suggested that the MDA-treated test sections could be slicker (lower deceleration) than untreated sections.

CHAPTER 6
DE-ICING RESULTS

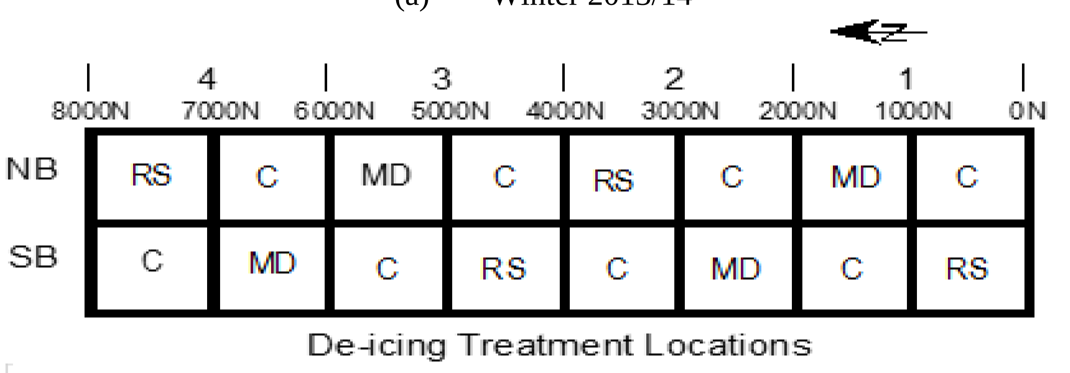
6.1 Introduction

This chapter presents results of comparative analyses performed on the data collected from the de-icing test sections at the field research site. The goal of these analyses was to compare and evaluate the effectiveness of the two typical granular chemicals TxDOT uses for de-icing operations, namely, Meltdown 20® (MD) and road salt (RS). For de-icing, three storms – Storm 2-3, Storm 3-4 and Storm 3-5 – provided sufficient field data for analysis. De-icing data from one other storm supported limited analysis only, and these data were incorporated where possible. The methods of data reduction were presented in Chapter 3.

The primary comparative data for de-icing were from Winter 2013/14 and from Winter 2014/15, both of which used the Canyon field test site. Figure 6.1 shows the de-icing test section layouts for data collection during each winter season.



(a) Winter 2013/14



(b) Winter 2014/15

Figure 6.1 Schematic of De-icing Test Sections and Treatments at the Canyon Field Test Site (not to scale) C = control, MD = Meltdown 20®, RS = road salt

For the three identified storms that provided de-icing data, field operations for both variations of the field test site layout were specifically used for de-icing only. Further, each storm provided reasonably uniform snowfall coverage by lane such that results could be averaged for test sections having like treatments for both lanes, with minor variations accounted for. Thus, while the field test site layouts in both years were not identical, for the purposes of statistical analyses of de-icing results, the site layouts were sufficiently similar to support side-by-side comparisons of de-icing chemical effectiveness among the different treatments.

6.2 Photo Image Analysis (Quantitative Data)

The photo images were analyzed according to the mini-Delphi method described in Chapter 3. For Storms 2-3, 3-4 and 3-5, separate graphical representations of the results for each photo set by test section are provided in Appendix A, Appendix B and Appendix C, respectively. In this chapter, the statistical results for each photo set and de-icing treatment – RS, MD and control – are compared statistically.

6.2.1 Storm 2-3 Photos

For Storm Event 2-3, seven sets of images were taken. The data were processed by the mini-Delphi method explained previously. The first photo dataset was taken at 5:34 pm, March 1, while the weather was still warm and the roads were clear. The second photo dataset was taken at 10:31 am, March 2, after snow had accumulated on the road and before plowing or application of deicing chemical had occurred. Dataset 3 was taken a short time later at 11:07 am, once the test strip had been plowed but before deicing chemicals were applied. Dataset 4 was taken the same day at 2:19 pm after deicing and slushing had been accomplished, and just before another plow run had been made. Dataset 5 was taken at 2:51 pm the same day, after deicing, slushing, and plowing. Dataset 6 was not taken until 9:56 am, March 3. It was taken after another round of slushing had been completed and as the temperature was warming. At this point, the sun was out and the snow was beginning to melt. Dataset 7 was taken at 10:28 am after another plow run had been completed. Temperatures were continuing to rise and the snow was melting more rapidly. A final data capture was taken of wet pavement, once the snow had melted, and was taken simply as index images to show what wet pavement looked like.

Figure 6.2 presents the quantitative results obtained from Storm 2-3. Data for this event were evaluated in one block as the storm produced relatively uniform snowfall across the site. This figure shows a comparison of the average visible pavement percentages by capture date and treatment status, and is marked with error bars indicating one standard deviation in either direction of the mean. The bar charts use the same approach to provide the overall averages and standard deviations (the error bars represent one standard deviation above and below the mean) for all the data observed in the sections of like treatment (control or chemical application) for each data collection time period, as shown in the category labels. Based on the ANOVA, if there was no significant statistical difference for the observed means across the three treatments, no annotation letter is shown above the bars. If some statistical differences were noted during one observation time as shown by the category label, the letters A, B, or C are shown above the bars to represent which treatment pairs were statistically similar.

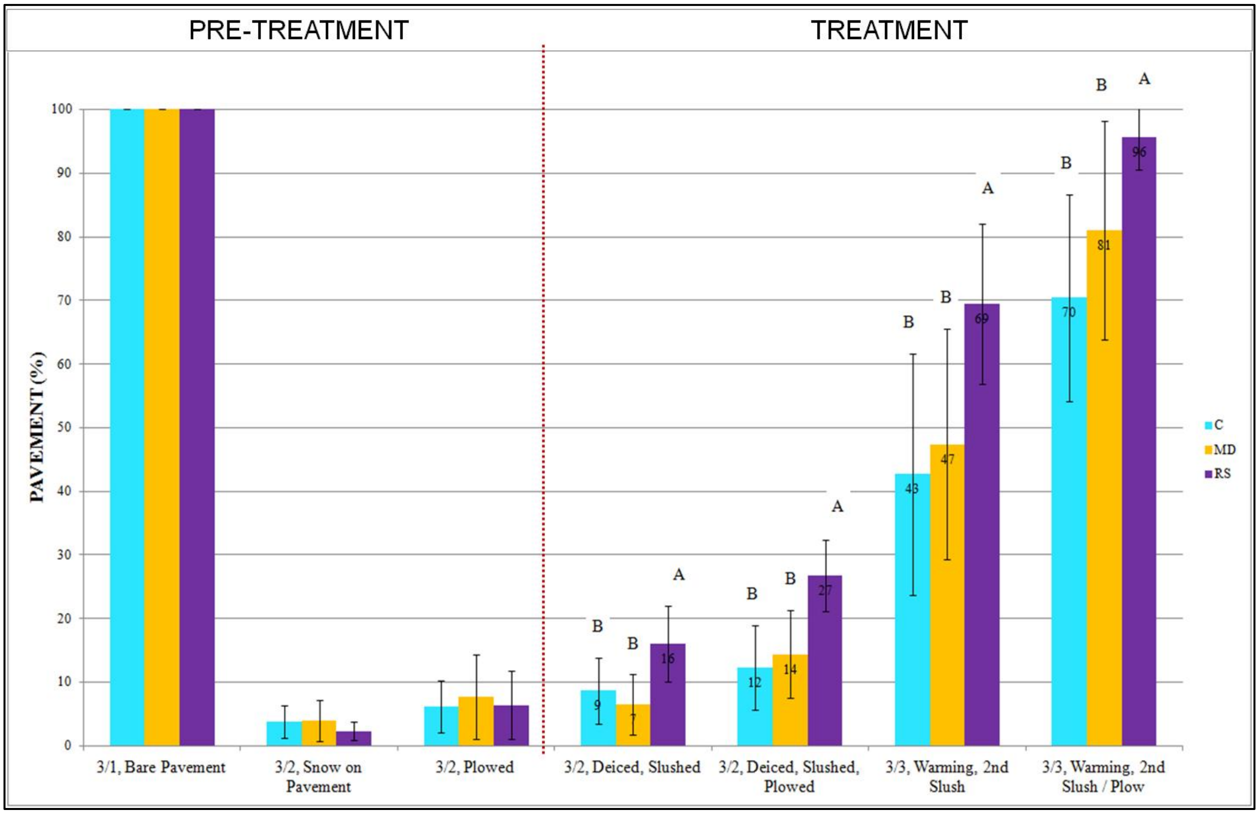


Figure 6.2 Analyses of De-icing Section Photos, Storm 2-3

The sections treated with road salt appear to be the clearest while there seems to be little difference between the Meltdown 20® and control sections. In all cases, the percent visible pavement for road salt is statistically different compared to both Meltdown 20® and control, while Meltdown 20® and control are not statistically different. In summary, for Storm Event 2-3, the observations are:

1. Quantitative data facilitated a head-to-head comparison of the average percentage of visible pavement for three treatment conditions: control (C), Meltdown 20® (MD), and road salt (RS).
2. At a summary level, RS (at the TxDOT standard application rate of 300 lb/lm) achieved a *statistically-significant* improvement in percentage of visible pavement:
   - RS over C (+7 to +26, avg +19%)
   - RS over MD (+9 to +22, avg +15%)
3. At a summary level, MD (at the TxDOT recommended application rate of 150 lb/lm) achieved about the same average percentage of visible pavement as C (difference not statistically significant).

4. In the early stages of treatment, for all treatment conditions, the road had a large amount of snow-covered pavement (73% to 93%).

6.2.2 Storm 3-4 Photos

Five sets of photo images were taken during Storm 3-4. The data were processed by the mini-Delphi method explained previously. The first photo set was begun at 4:14 p.m. on February 21 for the bare dry pavement before chemical application. The second set began at 8:08 p.m. on February 21. The third photo set began at 3:12 p.m. on February 22, after the snow had begun. The fourth photo set began at 12:50 p.m. on February 23, after 1 in of snow had accumulated on the pavement and this snow was compacted with multiple vehicle traverses to better represent actual roadway conditions. The final photo set was collected starting at 3:24 p.m. on February 23, after the first plowing, first de-icing application, and slushing. After the last photo set, a second plow run was performed. By that time, 4:20 p.m. on February 23, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

The results of the photo data analyses for Storm 3-4 are presented in Figure 6.3 in the same approach as used for Storm 2-3.

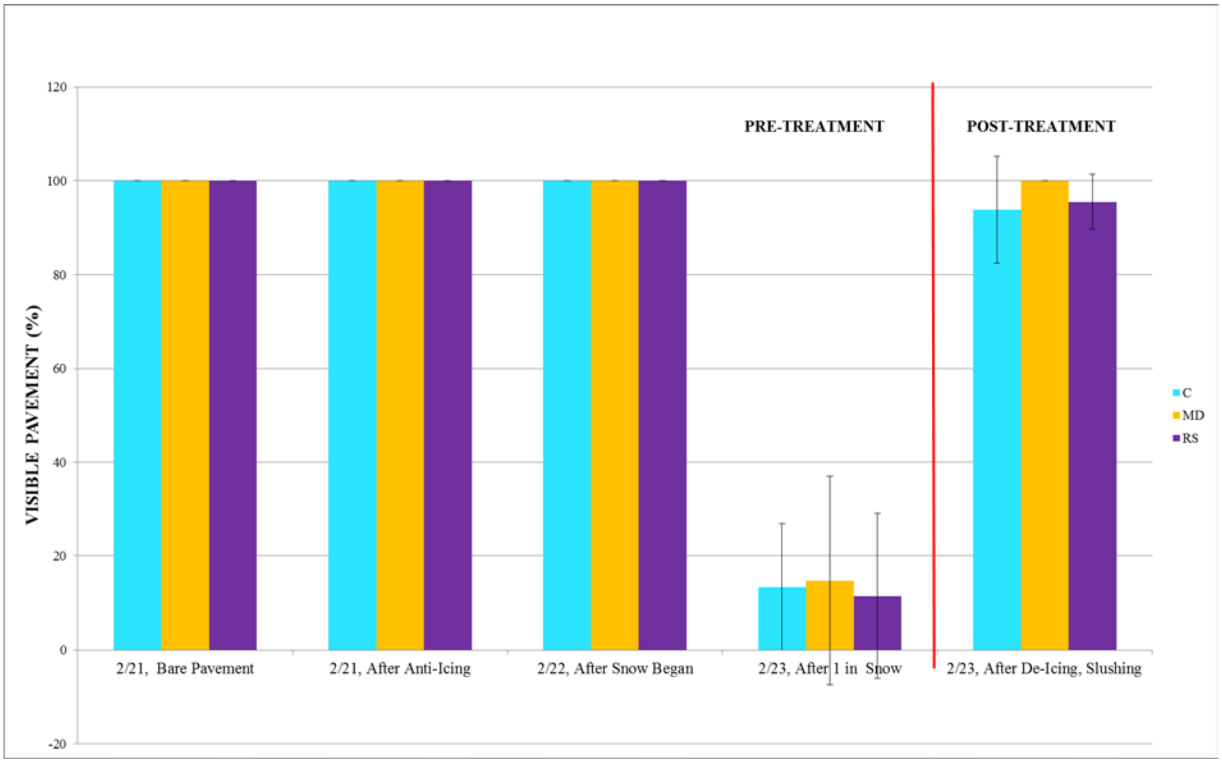


Figure 6.3 Analyses of De-icing Section Photos, Storm 3-4

Summary observations from Storm 3-4 were as follows.

1. De-icing photo sets 1, 2, and 3 showed all completely clear pavement, so no differences were noted.
2. De-icing photo set 4 was collected after 1 in of snow accumulated on the untreated pavement. No significant differences were noted among all three treatments. The SB lanes were significantly clearer than the NB lanes, as the wind conditions and snowfall rate affected the adherence of the snow on the crowned roadway.
3. De-icing photo set 5 was collected after plowing, application of de-icing chemicals, and slushing. No statistically-significant differences were seen across the three treatments.

6.2.3 Storm 3-5 Photos

Four sets of photo images were taken during Storm 3-5. The first set was begun at 6:50 a.m. on February 27 after the accumulation of over 2 in of snow, followed by compaction by multiple vehicle traverses. The second set began at 9:15 a.m. on February 27 after plowing. The third photo set began at 10:48 a.m. on February 27 after the first application of de-icing chemicals, and slushing. The fourth photo set began at 1:17 p.m. on February 27 after the third plowing after the second de-icing chemical application. The number of photo sets was limited by the short window of the snow event and the time required for chemical applications and data captures with the various vehicles and team members on site. After the last photo set, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun.

The results of the photo data analyses for Storm 3-5 are presented in Figure 6.4 in the same manner as for Storm 2-3 and Storm 3-4. Occasionally, some statistical differences between the combinations of treatment and lane were noted, so those pairs include NB or SB as lane differentiation. No differences relative to location were noted in any of the datasets.

Summary observations from Storm 3-5 were as follows.

1. De-icing photo set 1, taken after snow accumulation and compaction, showed no significant differences across the treatments, which was expected as no chemicals had been applied yet.
2. De-icing photo set 2, similar to the second anti-icing photo set 2, showed that the control sections were significantly clearer than the RS and MD sections. No significant difference was seen between the RS and MD sections. Again, no chemical application had yet occurred in the de-icing sections.
3. De-icing photo set 3 was collected after application of de-icing chemicals and slushing. No significant differences were seen across the treatments. The large variability in each treatment type influenced this finding.
4. The final de-icing photo set was collected after the final plowing after a second de-icing chemical application. There was no significant difference between RS and MD sections in

either lane. MD sections were significantly clearer than control sections, but there was no significant difference between RS and control sections.

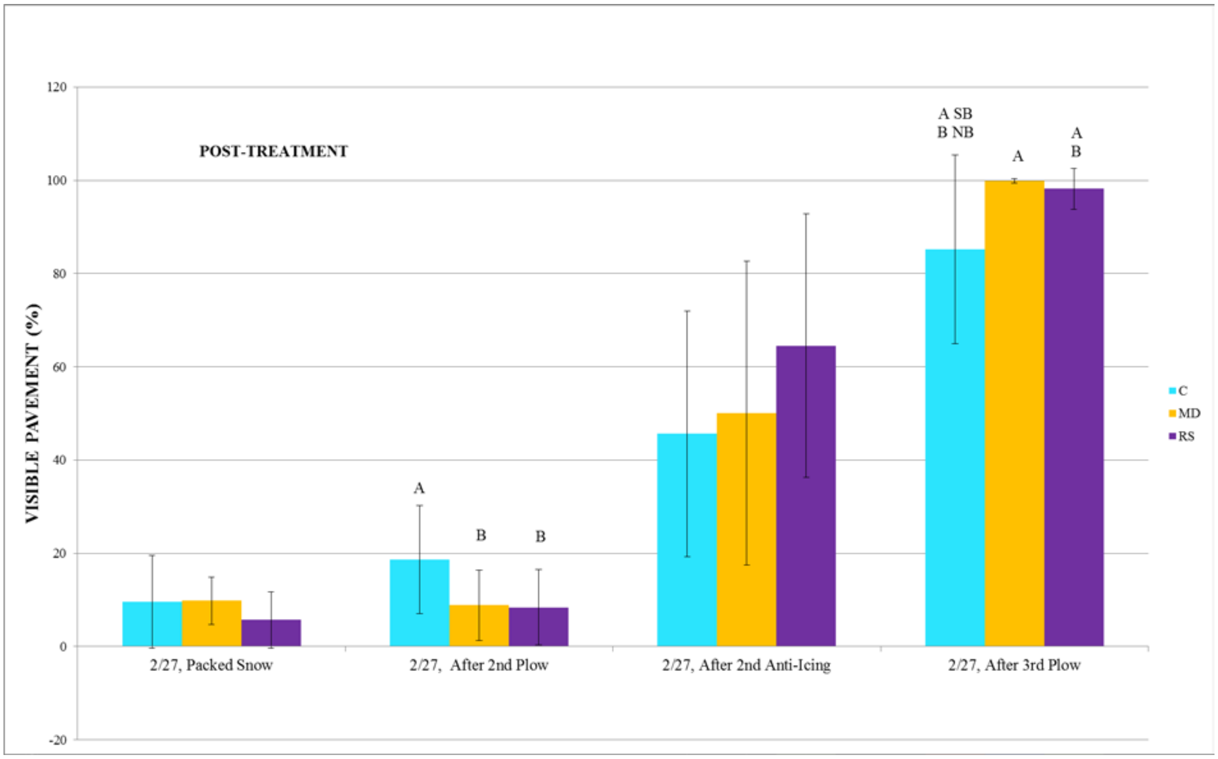


Figure 6.4 Analyses of De-icing Section Photos, Storm 3-5

6.3 Video Analysis

The video files were analyzed according to the mini-Delphi method described in Chapter 3. Overall averages and standard deviations were calculated for all three survey members and each treatment type for each video recording time. These results were useful as they represented what a TxDOT maintenance worker might report from a “windshield survey” of road conditions. We did not calculate means and standard deviations for the PSIC and AASHTO category values, as the discrete values did not represent a monotonic numerical progression from best to worst roadway conditions. The overall averages and standard deviations for the bare pavement results for each video dataset and treatment, RS, MD, and control, are compared statistically.

6.3.1 Storm 2-3 Videos

6.3.1.1 Percent Bare Pavement Seven video datasets were captured after commencing de-icing treatment during Storm 2-3. The first photo dataset was taken at 5:34 pm, March 1, while the weather was still warm and the roads were clear. The second photo dataset was taken at 10:31 am, March 2, after snow had accumulated on the road and before plowing or application of deicing chemical had occurred. Dataset 3 was taken a short time later at 11:07 am, once the test strip had been plowed but before deicing chemicals were applied. Dataset 4 was taken the same day at 2:19 pm after deicing and slushing had been accomplished, and just before another plow run had been made. Dataset 5 was taken at 2:51 pm the same day, after deicing, slushing, and plowing. Dataset 6 was not taken until 9:56 am, March 3. It was taken after another round of slushing had been completed and as the temperature was warming. At this point, the sun was out and the snow was beginning to melt. Dataset 7 was taken at 10:28 am after another plow run had been completed. Temperatures were continuing to rise and the snow was melting more rapidly.

Figure 6.5 presents the bare pavement results as per the Delphi analysis of the video datasets taken during Storm 2-3. The seven video data captures showed that the averages and variability of the four post-treatment datasets were statistically similar except for Dataset 6, where RS performed better than MD or control. The RS sections appeared to have the greatest amount of visible pavement, with MD and C being statistically similar for all test sections.

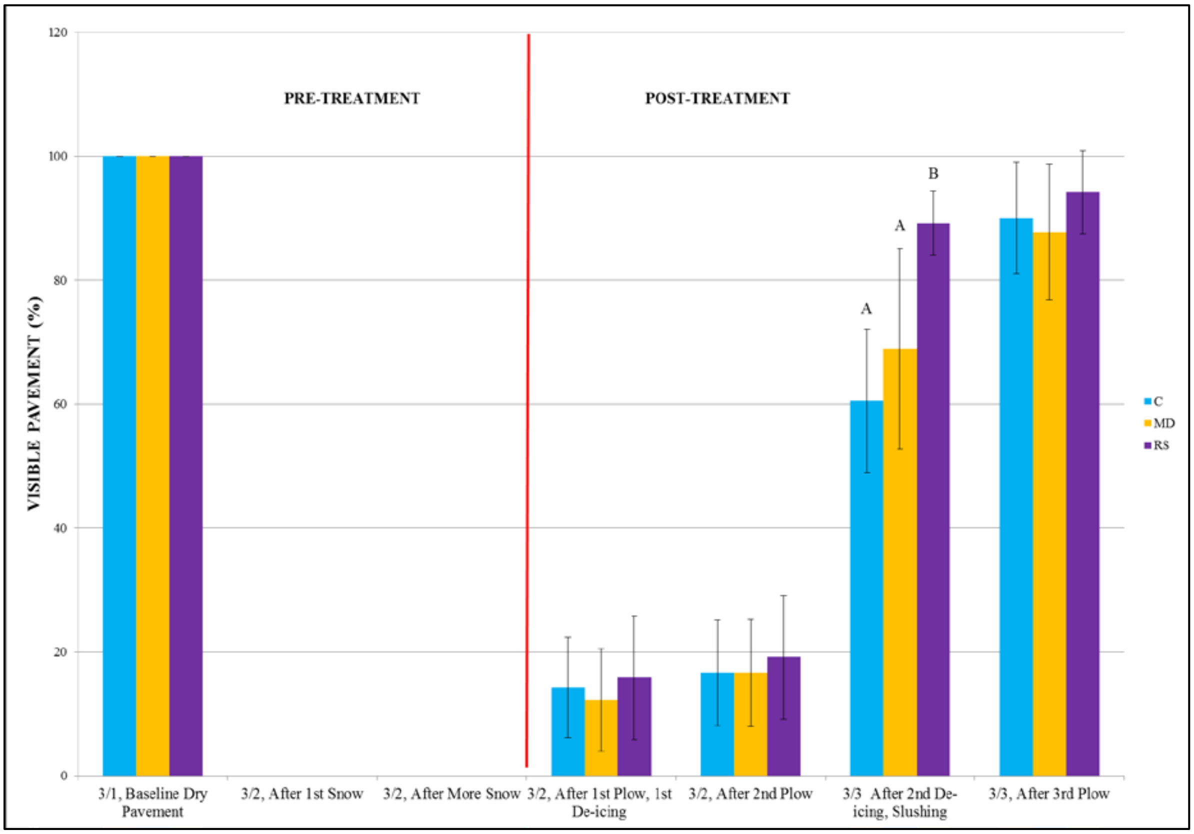


Figure 6.5 Summary of De-icing Videos for Visible Pavement, Storm 2-3

6.3.1.2 PSIC Index and AASHTO Reference Images In addition to estimating percent bare pavement, the Storm 2-3 video datasets were also evaluated relative to two published reference standards for winter roadway maintenance operations: the Pavement Snow and Ice Condition (PSIC) Index and the AASHTO reference images. The methods are described in Chapter 3, and Figure 6.6 and Figure 6.7 present the findings for these comparisons.

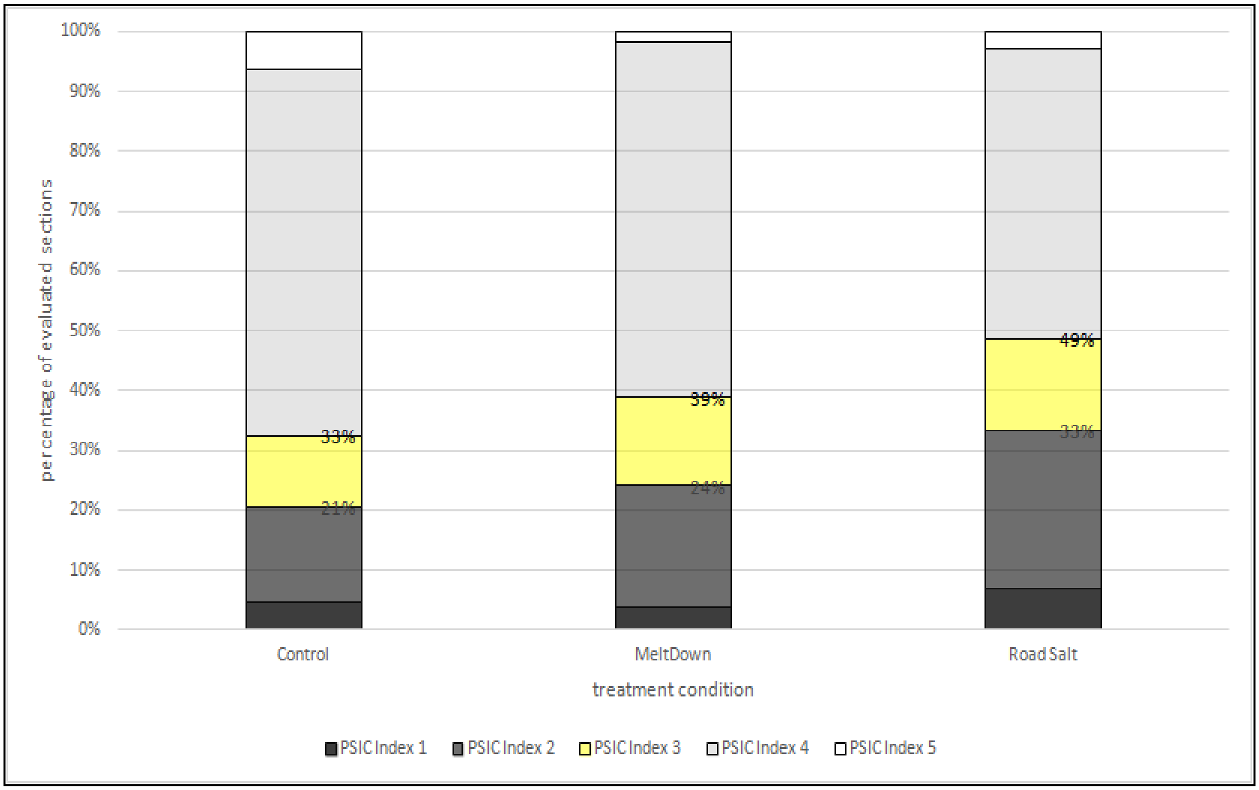


Figure 6.6. Storm 2-3, Pavement Snow & Ice Condition (PSIC) Index per Video Data

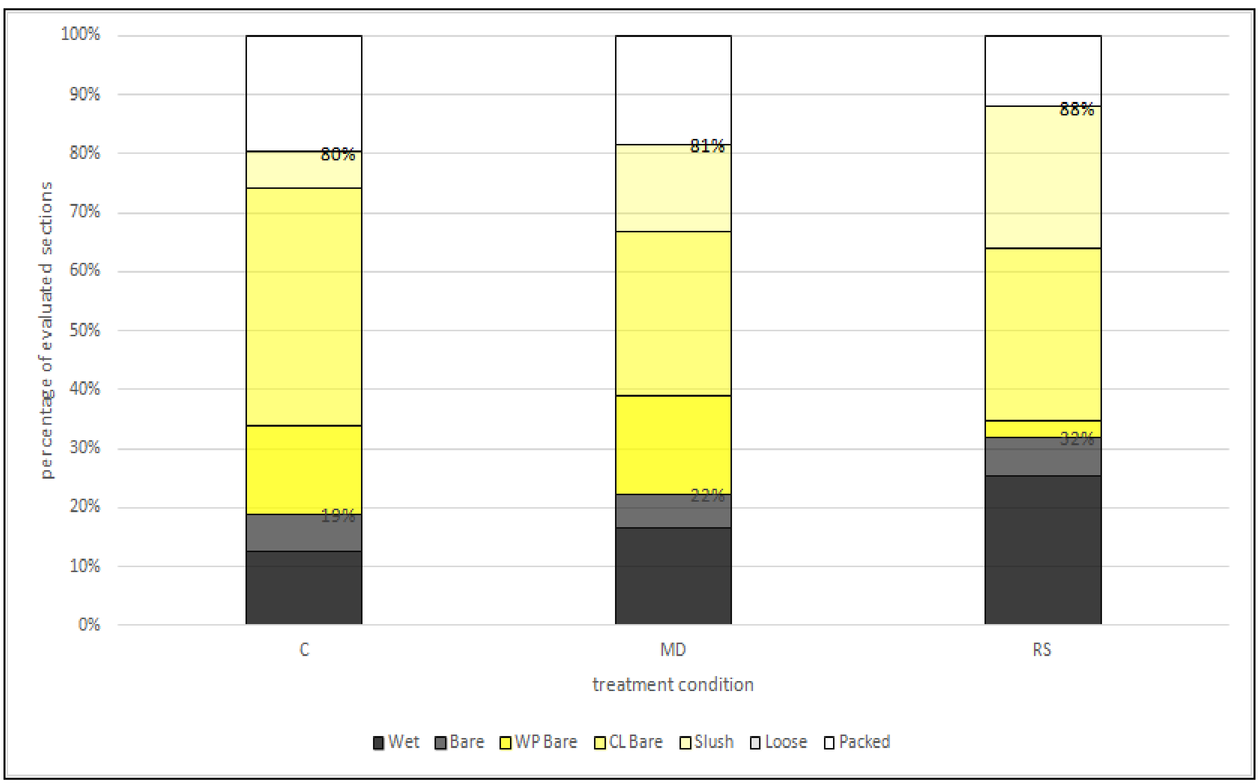


Figure 6.7. Storm 2-3, AASHTO Reference Images per Video Data

Graphically, the chart images in Figures 6.6 and 6.7 depict visible (or bare) pavement using darker colors (gray to dark gray) and they depict snow-covered pavement using lighter colors (white, light gray). Transitional conditions – slushy or partially bare/snow-covered pavement – are depicted using shades of yellow. Data for each pavement surface condition for each reference standard from all post-treatment video datasets for Storm 2-3 are averaged by category. Accordingly the category averages as per the reference standards provide an ordinal indication of how clear or snowy the pavement surface is, with lower values corresponding to more bare pavement and higher values corresponding to more snow-covered pavement. But the size of the difference between reference categories is not consistent.

The following summary observations for Storm 2-3 are supported for both the PSIC Index and the AASHTO reference images:

- RS at the TxDOT application rate (300 lb/lm) achieved a slightly higher average percentage of *visible* pavement than either MD or C
- RS at the TxDOT application rate (300 lb/lm) achieved a slightly higher average percentage of *clearing* pavement than either MD or C.
- MD at the TxDOT recommended application rate (150 lb/lm) achieved about the same average percentage of both visible pavement and clearing pavement as C.

Due to the ordinal nature of the variables, tests for statistical significance of these differences were not evaluated. Further, the mini-Delphi study demonstrated that usage of both the PSIC Index and the AASTHO reference images was subject to significant variation among raters. Significant, unresolvable scatter in the data existed for the Winter 2014/15 video data and for this reason, use of the reference standards was discontinued. The researchers noted it was difficult to achieve consistent interpretation of the reference standards, and it was equally difficult to consistently apply the reference standards when characterizing the road surface condition. One observation was that the PSIC Index and AASHTO reference standards probably are better suited to evaluation of roadway conditions for heavier snow storms than were depicted in our data.

6.3.2 Storm 3-4 Videos

Five useful video datasets were captured after the snow began to accumulate on the pavement during Storm 3-4. Two earlier video datasets showed only bare pavement prior to the snow event on all segments. The data were processed by the Delphi method explained previously. The first video dataset was begun at 9:13 a.m. on February 22, after the snow had begun. The second video dataset began at 11:39 a.m. on February 23, after 1 in of snow had accumulated on the pavement and the snow was compacted with multiple vehicle traverses to better represent actual roadway conditions. The third video dataset was collected starting at 1:45 p.m. on February 23, after the first plow run. The fourth video dataset began at 3:07 p.m. on February 23, after the second anti-icing chemical application and slushing. The final video dataset was captured at 4:24

p.m. on February 23, after the second plow run. By that time, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun. Figure 6.8 presents the visible pavement results for videos taken during Storm 3-4.

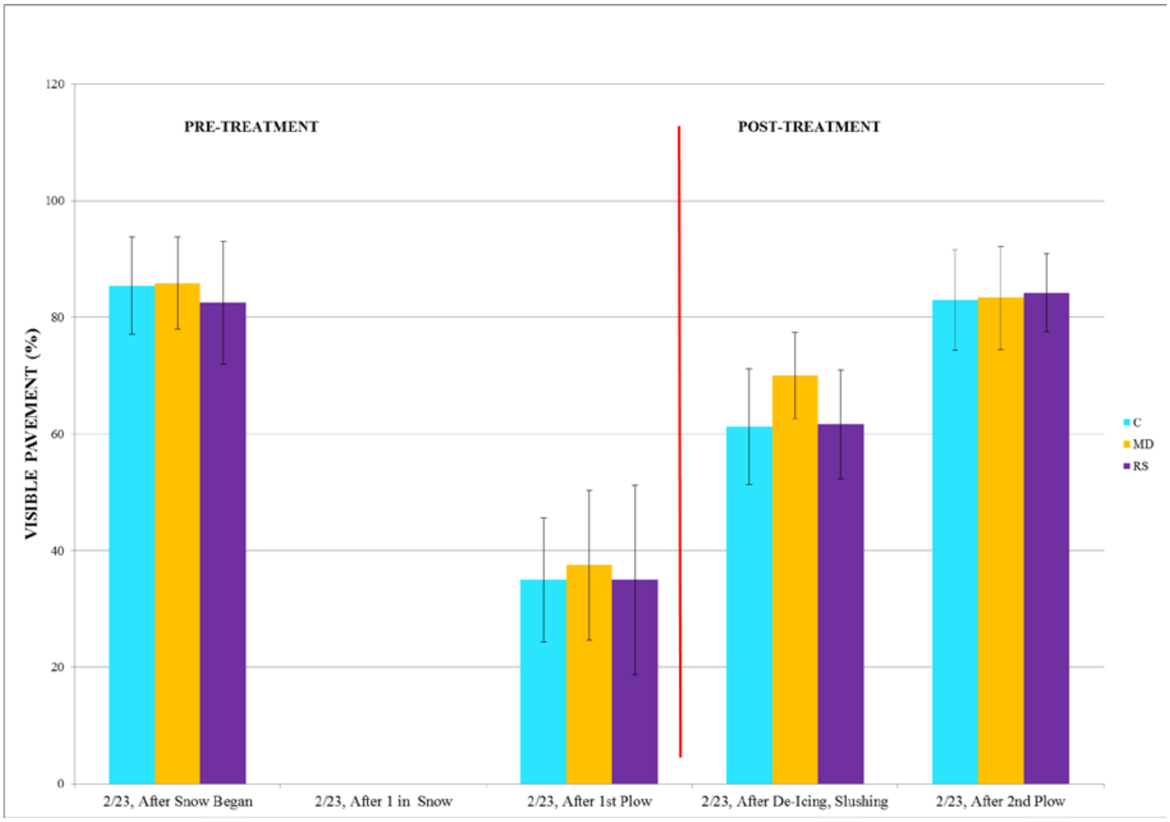


Figure 6.8 Summary of De-icing Videos for Visible Pavement, Storm 3-4

The five video data captures for the de-icing sections in Figure 6.8 show that the averages and variability of the three treatments were statistically similar at all the observation times. After de-icing and slushing, the MD sections appeared to have the greatest amount of visible pavement, but all three treatments were similar after the second plowing.

6.3.3 Storm 3-5 Videos

Seven useful video datasets were captured after snow began to accumulate on the pavement during Storm 3-5. Two earlier video datasets showed almost all bare pavement prior to the snow event on all sections. The data were processed by the mini-Delphi method explained previously. The first video dataset commenced at 3:42 p.m. on February 26, after the snow had begun. The second video dataset began at 3:38 a.m. on February 27, after snowfall started to adhere to the pavement. The third video dataset was captured after 7:13 a.m. on February 27, after 1 to 2 in of snow had accumulated on the pavement and was compacted that snow with multiple vehicle traverses to better represent actual roadway conditions. The fourth video dataset was collected starting at 7:24 a.m. on February 27, after the first plow run. The fifth video dataset began at 10:08

a.m. on February 27, after the second anti-icing and first de-icing chemical applications and slushing. The sixth video dataset was captured at 1:46 p.m. on February 27, after the second plow run, second de-icing chemical application, and slushing. The last video dataset began at 3:03 p.m. after the third plow run. By that time, the ambient and pavement temperatures were rising, and melting of the remaining snow and slush had begun. Figure 6.9 presents the visible pavement results for videos taken during Storm 3-5.

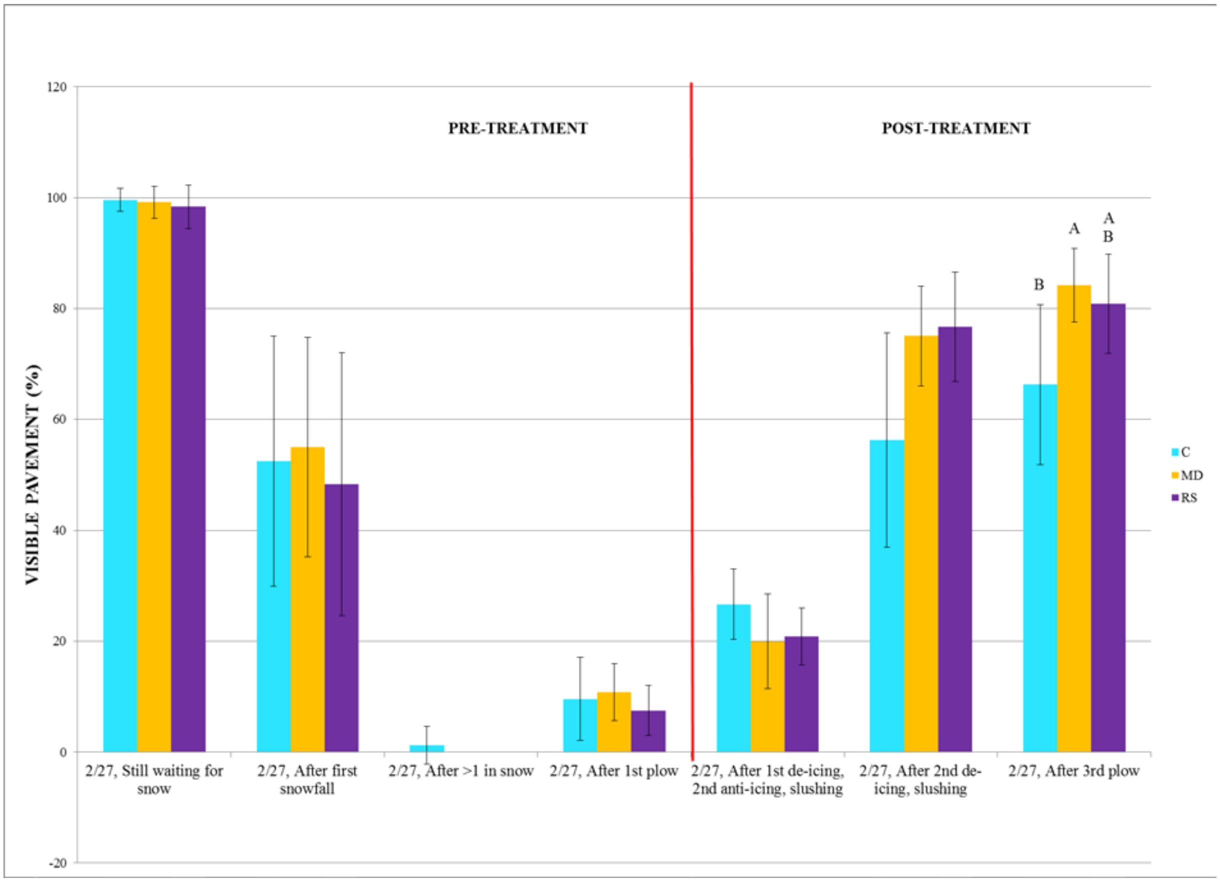


Figure 6.9 Summary of De-icing Videos for Visible Pavement, Storm 3-5

The video sets for de-icing sections from Storm 3-5 show more variability than those seen in Storm 3-4. Prior to the de-icing treatment, the means and standard deviations were similar for all three treatment conditions. After the de-icing treatment, the last two video sets showed that RS and MD sections were visually similar and showing more visible pavement on average compared to the control sections. Variations in the wheel path wear zones could have contributed to the differences in the observations of accumulation and melting of snow and slush.

6.4 Decelerometer Data

The NAC Decel Smartphone App (DSA) was used to obtain a measure of pavement surface friction for Storms 3-4 and 3-5. The DSA reported the deceleration as a percent of the acceleration of gravity, or percent G. Dry pavement yielded percent G values near and sometimes above 100 percent, while lower values could be observed after anti-icing chemicals were applied or after the snow began. Three DSA tests were performed in each test section during each test run, similar to the approach used in the photo data collection, leading to 48 data points in the de-icing sections. The overall averages and standard deviations were calculated for the sections of like treatments for each test run, and the ANOVA was used to assess the decelerometer data in the same manner as was used for the photo and video datasets.

6.4.1 Storm 3-4 Decelerometer

Four sets of decelerometer tests were performed in the de-icing sections in Storm 3-4. The first test set began at 5:38 p.m. on February 21, before application of anti-icing chemicals. The second set of tests started at 11:57 a.m. on February 23, after over 1 in of snow accumulation and compaction by multiple vehicle passes. The third set of tests began at 12:54 p.m. on February 23, after the first plow run. The final set of tests started at 3:26 p.m. on February 23, after the de-icing applications and slushing.

The results of the decelerometer data analyses for Storm 3-4 are presented in Figure 6.10 in the same manner as was used with the photo data analyses.

Summary observations from Storm 3-4 are as follows.

1. The first set of DSA data in the de-icing sections was collected on dry pavement, before the storm. No significant differences were seen across the treatments. The MD sections in the SB lane had slightly lower percent G values than the MD sections in the NB lane.
2. De-icing DSA dataset 2 followed the accumulation of over 1 in of snow on the pavement followed by compaction. No significant difference was seen across the three treatments. The SB lane was generally slicker than the NB lane, but the balanced nature of the test section configurations prevented differences across the treatments.
3. De-icing DSA dataset 3 was collected after plowing. No significant difference was seen across the three treatments. The SB lane was generally slicker than the NB lane, but the balanced nature of the test section configurations prevented differences across the treatments.
4. De-icing DSA dataset 4 was collected after de-icing chemical application and slushing. No significant differences were noted across treatments, lanes, or locations.

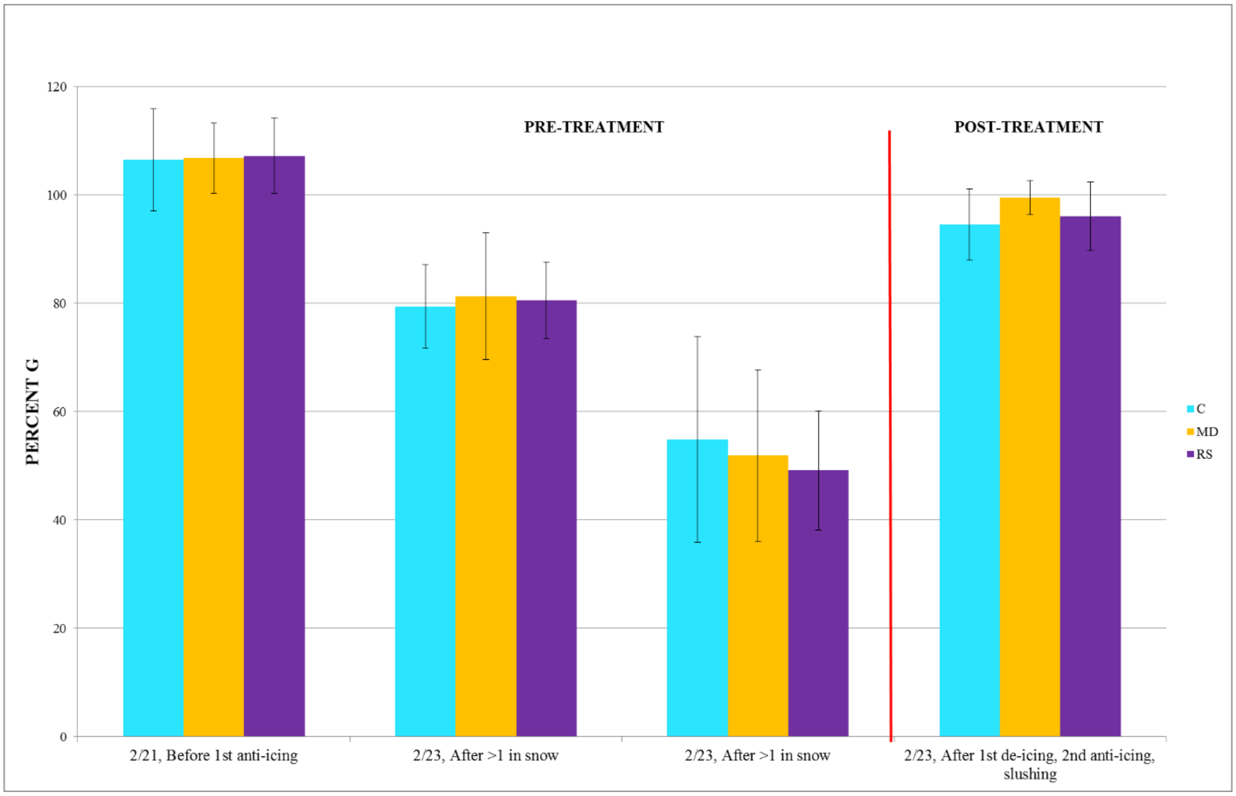


Figure 6.10 Analyses of De-icing Section Decelerometer Data, Storm 3-4

6.4.2 Storm 3-5 Decelerometer

Four sets of decelerometer tests were performed in the de-icing sections in Storm 3-5. The first round of tests began at 7:32 a.m. on February 27, after the first plow run. The second set of tests began at 10:22 a.m. on February 27, after the second anti-icing applications and slushing. The third test set started at 11:53 a.m. on February 27, after the second plow run. The final set of tests began at 2:19 p.m. on February 27, after the third plow run.

The results of the quantitative decelerometer data analyses for Storm 3-5 are presented in Figure 6.11 in the same manner as used with the photo data analyses.

Summary observations from Storm 3-5 are as follows.

1. The first de-icing DSA data set was collected after the first plowing before application of de-icing chemicals. No significant differences were seen across the three treatments.
2. De-icing DSA data set 2 was collected after application of the de-icing chemicals and slushing. The control sections were significantly slicker than the MD sections.
3. There was no significant difference between MD and RS sections, nor was there a significant difference between RS and control sections.

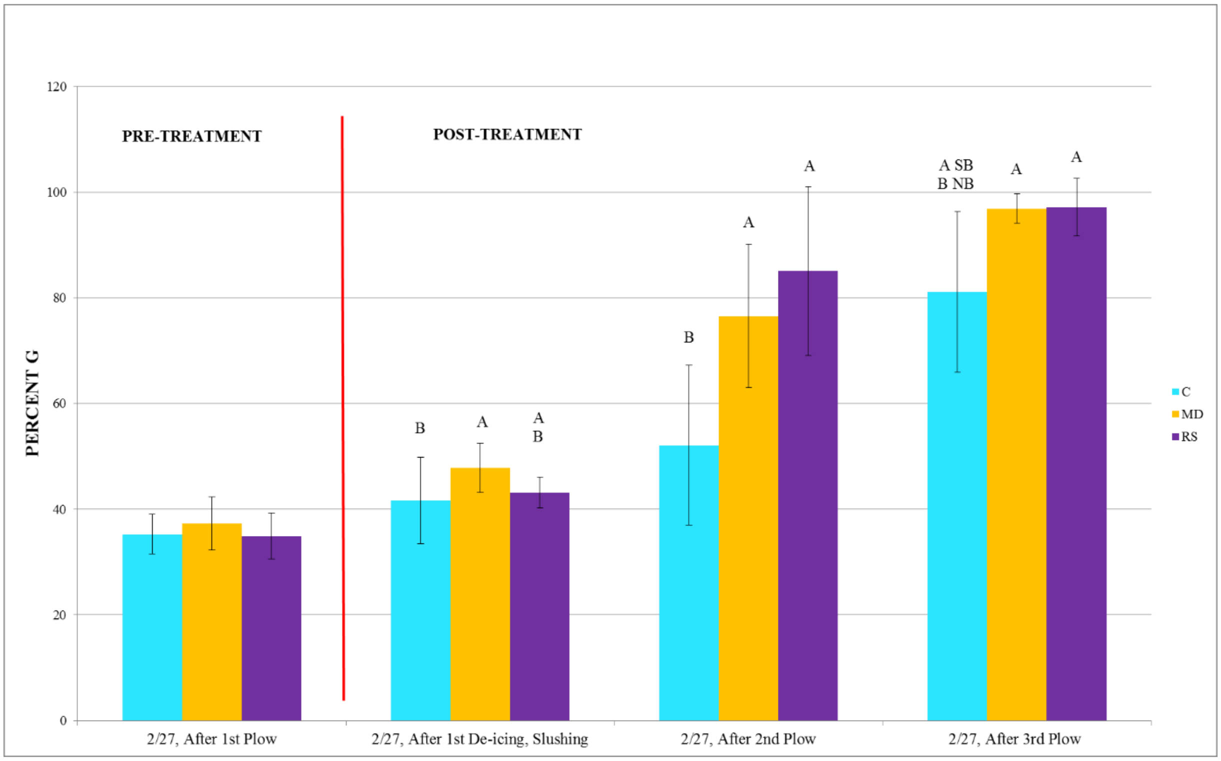


Figure 6.11. Analyses of De-icing Section Decelerometer Data, Storm 3-5

4. De-icing data set 3 was collected after the plowing that preceded the second de-icing chemical applications. The control sections were significantly slicker than the MD and RS sections, but there was no significant difference between the MD and RS sections.
5. The final de-icing DSA data set was collected after the final plowing after the second de-icing chemical applications and slushing. The NB control sections were significantly slicker than all of the other treatment and land combinations. There was no significant difference between the MD and RS sections.

6.5 Summary of Findings for De-Icing Treatment

6.5.1 Comparison of RS and MD

The effectiveness of RS and MD granular chemicals for de-icing applications were observed in three storm events that generally met our criterion of 1 to 3 in of snow accumulation on the pavement in the test sections. Table 6.1 summarizes the comparisons of performance of the chemicals (RS vs. MD) for each of the three data types for Storm 2-3, Storm 3-4 and Storm 3-5. For the photo and video data, the numerical values represent the percentage of visible or bare pavement for the test sections. For the decelerometer data, the numerical values are deceleration as a percentage of the acceleration of gravity.

Four of the seven post-treatment photo datasets indicated a statistically-significant improvement in performance for sections treated with RS de-icing chemical vs. sections treated with MD de-icing chemical. These RS-treated test sections were 10 to 22 percent more clear than the MD-treated test sections. Three of the seven post-treatment photo datasets showed no statistically-significant difference in performance for RS-treated vs. MD-treated sections.

Table 6.1 Summary of Statistical Comparisons of RS vs. MD for De-icing Test Sections

Field Test Condition	Storm 3 (3/1-3/14)			Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●	●		●		●			
Applied anti-icing chemicals					√			√	
After 1st anti-icing, slushing				●				●	
After first snowfall		●		●	●			●	
After more snow	●	●							
After >1 in snow				●	●	●	●	●	
After 1st plow	●				●	●	●	●	●
Applied de-icing chemicals	√	√			√			√	
Applied anti-icing chemicals again					√			√	
After 1st de-icing, 2nd anti-icing, slushing	▲(10)	●		●	●	●	●	●	●
After 2nd plow	▲(12)	●			●				●
Applied de-icing chemicals again	√	√						√	
After 2nd de-icing, slushing	▲(22)	▲(20)						●	
After 2nd de-icing, slushing, 3rd plow	▲(15)	●					●	●	●

●	RS=MD
▲	RS>MD with percentage difference
■	MD>RS with percentage difference
√	Chemical application

The video datasets typically displayed no statistically-significant difference between the performances of sections treated with RS de-icing chemical vs. sections treated with MD. Eight of nine post-treatment datasets showed this response. One dataset indicated that RS-treated sections performed better than MD-treated sections.

Our post-de-icing treatment observations exhibited no statistically-significant difference between sections for four of four decelerometer datasets.

6.5.2 Comparison of RS vs. Control

The effectiveness of RS and MD de-icing treatments were not only compared to each other but were also observed relative to untreated field test sections (control). Table 6.2 summarizes the comparison of performance of RS vs. control for each of the three data types for Storm 2-3, Storm 3-4 and Storm 3-5. For the photo and video data, the numerical values represent the percentage of visible or bare pavement for the test section. For the decelerometer data, the numerical values are deceleration as a percentage of the acceleration of gravity.

Table 6.2 Summary of Statistical Comparisons of RS vs. C for De-icing Test Sections

Field Test Condition	Storm 3 (3/1-3/14)			Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●	●		●		●			
Applied anti-icing chemicals					√			√	
After 1st anti-icing, slushing				●				●	
After first snowfall		●		●	●			●	
After more snow		●							
After >1 in snow	●			●	●	●	●	●	
After 1st plow	●				●	●	■(10)	●	●
Applied de-icing chemicals	√	√			√			√	
Applied anti-icing chemicals again					√			√	
After 1st de-icing, 2nd anti-icing, slushing	▲(26)	●		●	●	●	●	●	●
After 2nd plow	▲(26)	●			●				▲(33)
Applied de-icing chemicals again	√	√						√	
After 2nd de-icing, slushing	▲(15)	▲(29)						●	
After 2nd de-icing, slushing, 3rd plow	▲(7)	●					●	●	▲(16)

●	RS=C
▲	RS>C with percentage difference
■	C>RS with percentage difference
√	Chemical application

Four of the seven post-treatment photo datasets showed a statistically-significant improvement in performances for sections treated with RS de-icing chemical vs. untreated control sections. These RS-treated test sections were 7 to 26 percent more clear than the untreated test sections. Three of the seven post-treatment photo datasets showed no statistically-significant difference in performances for RS-treated vs. untreated sections.

The video datasets also typically indicated no statistically-significant difference between the performances of sections treated with RS de-icing chemical vs. untreated (control) sections. Eight of nine post-treatment datasets showed this response. One dataset indicated that RS-treated sections performed better than untreated (control) sections.

In contrast to the photo and video data, two of four decelerometer datasets showed a statistically-significant improvement for sections treated with RS de-icing chemical vs. untreated (control) sections. That is, the RS application yielded a pavement surface less slick than untreated pavement for these sections. Two decelerometer datasets showed no statistically-significant difference between RS-treated sections vs. untreated (control) sections.

6.5.3 Comparison of MD vs. Control

Table 6.3 summarizes the comparison of performance of MD vs. control for each of the three data types for Storm 2-3, Storm 3-4 and Storm 3-5. For the photo and video data, the numerical values represent the percentage of visible or bare pavement for the test section. For the decelerometer data, the numerical values are deceleration as a percentage of the acceleration of gravity.

Table 6.3 Summary of Statistical Comparisons of MD vs. C for De-icing Test Sections

Field Test Condition	Storm 3 (3/1-3/14)			Storm 4 (2/21-23)			Storm 5 (2/25-27)		
	Photo	Video	Decel	Photo	Video	Decel	Photo	Video	Decel
Before 1st anti-icing	●	●		●		●			
Applied anti-icing chemicals					√			√	
After 1st anti-icing, slushing				●				●	
After first snowfall		●		●	●			●	
After more snow		●							
After >1 in snow	●			●	●	●	●	●	
After 1st plow	●				●	●	■(10)	●	●
Applied de-icing chemicals	√	√			√			√	
Applied anti-icing chemicals again					√			√	
After 1st de-icing, 2nd anti-icing, slushing	●	●		●	●	●	●	●	▲(6)
After 2nd plow	●	●			●				▲(25)
Applied de-icing chemicals again	√	√						√	
After 2nd de-icing, slushing	●	●						●	
After 2nd de-icing, slushing, 3rd plow	●	●					●	▲(18)	▲(16)

●	MD=C
▲	MD>C with percentage difference
■	C>MD with percentage difference
√	Chemical application

The photo datasets exhibited no statistically-significant difference between the performances of sections treated with MD de-icing chemical vs. untreated (control) sections. Seven of seven post-treatment datasets showed this response.

The video datasets typically indicated no statistically-significant difference between the performances of sections treated with MD de-icing chemical vs. untreated (control) sections. Eight of nine post-treatment datasets showed this response. One dataset showed a statistically-significant improvement for MD-treated sections compared to untreated (control) sections.

Three of four decelerometer datasets displayed a statistically-significant improvement for sections treated with MD de-icing chemical vs. untreated (control) sections, such that the MD application yielded a pavement surface less slick than untreated pavement for these sections. One decelerometer dataset showed no statistically-significant difference between MD-treated sections vs. untreated control sections.

6.5.4 Overall Comparison of RS and MD for De-icing Applications

Photo and video data obtained during field trials associated with three storm events were used to evaluate the effectiveness of de-icing applications. These data provided mixed results but generally showed sections treated with RS (at the TxDOT rate of 300 lb/lane mile) yielded the same or more visible bare pavement vs. sections treated with MD de-icing chemical (at the TxDOT rate of 150 lb/lane mile). Decelerometer tests indicated no statistically-significant difference in pavement friction between sections treated with RS vs. sections treated with MD.

How does the performance of these de-icing chemical applications compare to pavement sections that received “no treatment”? These data provided mixed results but generally showed sections treated with RS (at the TxDOT rate of 300 lb/lane mile) yielded the same or more visible bare pavement compared to untreated control sections. Sections treated with MD de-icing chemical (at the TxDOT rate of 150 lb/lane mile) typically showed no statistically-significant difference in the amount of visible bare pavement compared to untreated control sections. Decelerometer tests suggested that both MD-treated test sections and RS-treated sections are less slippery (better deceleration) than untreated sections.

CHAPTER 7
LABORATORY TEST RESULTS

7.1 Introduction

This chapter presents findings from a laboratory test program designed to evaluate particular impacts of de-icing chemical solutions and solids. The researchers tested snow and ice control chemicals using available published methods in a laboratory setting. The testing was not meant to directly mimic field conditions, field test methods or other aspects of field operations. Rather, this testing was specifically designed to evaluate the ability of Salt Brine, MeltDown 20® and MeltDown Apex™ to melt ice, as well as to evaluate the impact of these chemicals on the dynamic friction characteristics of a standard surface. The laboratory test program provided a way to expand the parameter space associated with the field trials which were of necessity limited to two types of anti-icing and de-icing chemicals, standard application rates, and site environmental conditions.

The laboratory test program included four types of tests: (1) modified ice melting, (2) modified ice undercutting, (3) ice/snow disbondment, and (4) modified friction. All products were applied as solutions as per test specifications (Chappelow, et al. 1992). Salt brine and MeltDown 20® brine were made by dissolving the granular products, while MeltDown Apex™ was used as received.

The modified ice melting test (Test Method H-205.2) was selected to evaluate the ability of Salt Brine, a solution of MeltDown 20®, and MeltDown Apex™ to melt ice over time with respect to temperature and volume of solution applied. The modified ice undercutting (Test Method H-205.6) evaluated the ability of these chemicals to undercut ice bonded to mortar with respect to temperature and time. The ice/snow disbondment testing evaluated the ability of these chemicals to break the bond between ice or snow frozen on mortar. The modified friction test (SHRP H-205.10) measured the influence of these chemicals on surface friction for a standard surface with respect to temperature.

7.2 Methods

7.2.1 Modified Ice Melting

The purpose of the ice melting test was to determine the rate and degree of ice melting produced by salt solutions. The goal of this test was to compare the melting abilities of liquid salt solutions as a function of volume applied, time of contact, and temperature. The test method for ice melting includes application of deicing solutions to a uniform ice mold at a specified temperature. In general, differing volumes of liquid deicer are added to the surface of ice in molds and the volume of melted liquid is measured over a set time period. The brine/melt solution is re-applied after each measurement.

Sample preparation was adopted from the *Handbook of Test Methods for Evaluating Chemical Deicers* SHRP H-205.2. A flat acrylic dish (Figure 7.1) was created with a circular opening of approximately 9 in diameter and ½ in deep. A volume of 103 ml of distilled water (corresponding to an ice thickness of ⅛ in) was poured into the acrylic dish to create the samples (Figure 7.1). The samples were placed inside a walk-in cold box at the appropriate testing temperature and allowed to freeze overnight. The surface ice was then melted with a circular ½ in aluminum plate and allowed to refreeze in order to create a smooth surface.

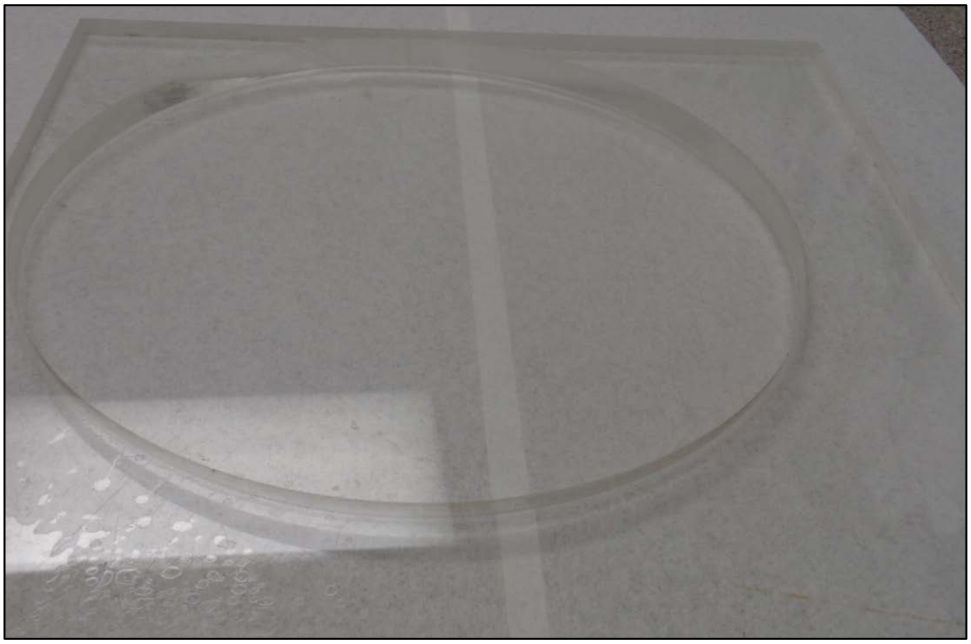


Figure 7.1 Circular acrylic dish used for ice melting.

Testing was conducted by adding known volumes (Table 7.1) of MeltDown Apex™, MeltDown 20®, and Salt Brine with a syringe in a spiral manner to the surface of the ice samples. Volumes of de-icing solution ranging from 1.9 mL to15.2 mL were applied based on the benchmark recommended value (3.8ml) which equates to a loading rate of (9 µl/cm^2). Typical field application rates would equate to 4.0, 5.0, and 1.3 µl/cm^2 for Salt Brine, MeltDown 20®, and MeltDown Apex™, respectively.

Table 7.1 Testing parameters used for Ice Melting Tests

De-Icing Solution	30°F (-1°C)	15°F (-10°C)	0°F (-18°C)
	Volumes of Solution Applied (ml)		
Salt Brine	1.9, 3.8, 5.7	1.9, 3.8, 5.7, 7.6, 15.2	1.9, 3.8, 5.7, 7.6, 15.2
MeltDown 20®	1.9, 3.8, 5.7	1.9, 3.8, 5.7, 7.6, 15.2	1.9, 3.8, 5.7, 7.6, 15.2
MeltDown Apex™	1.9, 3.8, 5.7	1.9, 3.8, 5.7	1.9, 3.8, 5.7

Deicing solutions were placed into the walk-in cold room overnight along with the ice. Concentrations of MeltDown 20® and Salt Brine corresponded to ~26% and ~23% by weight, while MeltDown Apex™ was used as received. After each time interval (10, 20, 30, 45, and 60 min), ice samples were tilted at a ~45º angle and melted liquid was pulled from the side of the ice sample by syringe and the volume of melt water recorded. Melted solutions were then re-applied to the ice samples and allowed to sit for the next allotted time and the process repeated until the time period expired. Two separate temperature measurements were also recorded to ensure accuracy of the temperature reading. Ice melting experiments were conducted in triplicate. Salt Brine and Meltdown 20 were tested at two higher volumetric application rates for the lower two temperatures to explore whether increased application could increase the effectiveness.

7.2.2 Modified Ice Undercutting

The purpose of the ice undercutting test was to evaluate the degree and rate of ice undercutting achieved by application of salt solutions on ice bonded to mortar specimens under relevant temperatures. The undercutting test method involved adding known volumes of salt solutions (Salt Brine, MeltDown 20®, and Apex™) into small (4mm diameter) cylindrical cavities in ice bonded to mortar. Photographs were taken at increasing time intervals to document the undercutting progression. The photographs were then analyzed to determine the area of ice that was dis-bonded from the mortar by measuring the lateral spread of a dye added to the deicing solutions.

Mortar specimens were made to the specifications in the *Handbook of Test Methods for Evaluating Chemical Deicers* SHRP H-205.5 with locally available materials. The concrete mortar samples were created by mixing QUIKRETE® Portland cement Type I/II and QUIKRETE® Multipurpose sand, sieved to remove particles greater than a mesh size of 16 (Table 7.2). The mortar mix contained 2.60 parts sand, 0.485 parts water and 1.0 part cement.

Table 7.2 Sieve analysis of sand used to create mortar specimens.

Mesh Size	Ideal Percent Passing	Actual % Passing
16	99	80
30	45	55
40	30	24
50	15	11
60	6	8
100	1	1

Mortar specimens were made by placing the final mixture into a mold containing nine individual specimens made out of 2 in x 4 in lumber. The mold was lined on the bottom with textured fiberglass board in order to achieve a textured surface for promoting ice bonding. The trays were shaken periodically to remove excess air bubbles and to ensure a level surface. Specimens were cured overnight at ambient temperatures and humidity. Specimens were then removed from the tray and cured in a saturated lime solution for a minimum of 7 and a maximum of 14 days. To retain water on the mortar specimens, an edge (¼ in to ½ in) was constructed of either acrylic strips or duct tape lined with latex caulk.

Ice was formed on the specimens from the bottom up by using a freezing box (Figure 7.2). The freezing box was constructed out of styrofoam insulation. Inside the Styrofoam box is a plywood box that is fitted with a metal plate on the bottom of the box and two loose-fitting removable plywood lids. The air in the box is kept at an approximate 33° to 35° (1° to 2° C) temperature using a 100 W incandescent halogen bulb connected to a thermostat, regulating the temperature inside the box.

Figure 7.2 Photograph of freezing box inside cold box.

Specimens were pre-cooled in a freezer at approximately 15°F (-10°C) overnight. Specimens were then placed in a freezing box with 96 to 98 mL of distilled water ~33°F added to the top of the mortar specimen and allowed to freeze overnight. After specimens had completely frozen, specimens were placed on a work bench inside the walk-in cold box and allowed to acclimate to the testing temperature overnight. Following acclimation, cavities (~⅛ in deep) were made in the ice using heated aluminum rods (~0.16 in diameter) and removal of melted water. For each specimen, 15 cavities (3 rows and 5 columns) were made with ~ 4 cm spacing. Cavities were made inside the walk-in cold box to prevent further melting from changing temperatures.

The ice undercutting test was conducted by adding 30 μL of pre-cooled salt solution into each cavity. We added 20 μL of dye per 5 mL of each salt solution. The de-icing solutions tested included manufactured Salt Brine (~23% by weight), MeltDown 20® (26% by weight), and MeltDown Apex™ (used as received). Photographs of the specimens were made after 5, 10, 15, 20, 30, 45, and 60 min (Figure 7.3).

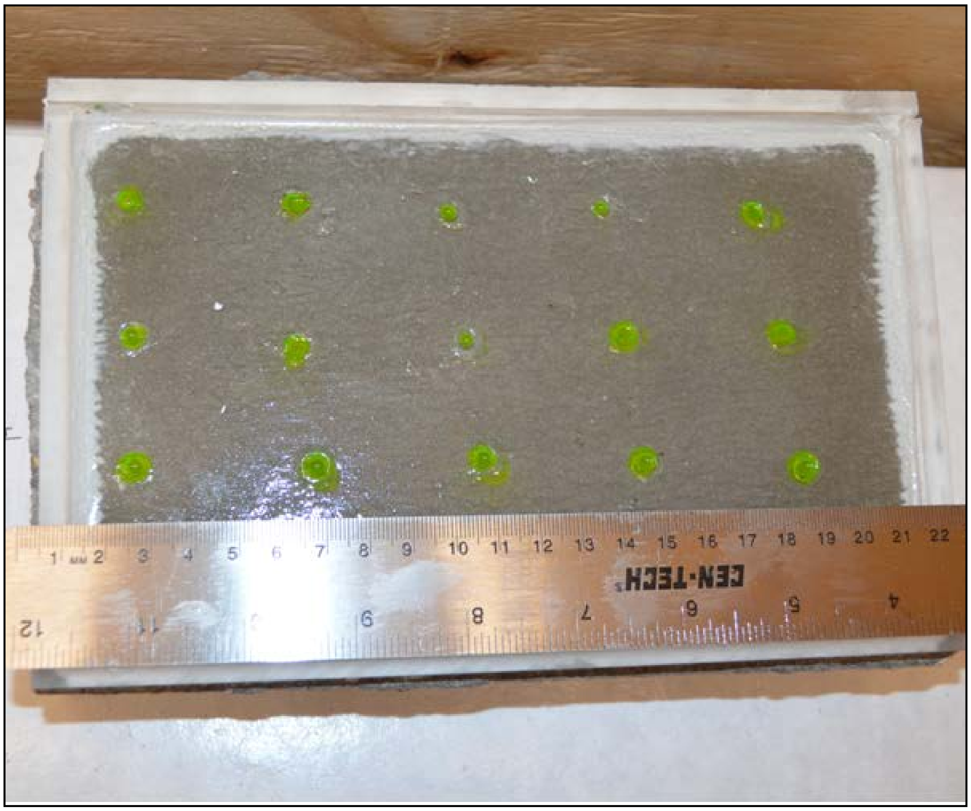


Figure 7.3 Photograph of mortar specimen immediately after addition of salt solution.

Each solution was tested at 30°F (-1°C), 15°F, (-10°C), and 0°F, (-18°C) in triplicate with each replicate comprised of the average of 15 individual test points. Areas for each undercutting area were determined by measuring the dyed areas surrounding the 15 ice cavities in the specimens. Area calculations were completed by uploading digital photographs into ImageJ, an area measuring tool. Test procedures were adopted from the *Handbook of Test Methods for Evaluating Chemical Deicers* SHRP H-205.5 and H-205.6.

7.23 Disbondment Testing

A standardized test does not exist for measuring the capability of deicing chemicals to break the bond between ice/snow and pavement substrates. The *Handbook of Test Methods for Evaluating Chemical Deicers* states that the undercutting test provides a simpler approach and provides similar, if not the same type of information. Nonetheless, several studies have attempted to quantify the bond strength between ice/snow and substrate. The two most commonly used disbondment procedures are either placing a ring around an ice/snow specimen and applying a shear force to disrupt the bond or using a blade to scrape the ice/snow, roughly analogous to how a snow plow functions. For our testing procedure, the former was selected. In general, we added salt solutions to cavities created in ice or snow that had been frozen on to mortar speciemes after which the force required to remove the snow or ice was evaluated.

Mortar specimen preparation for the disbondment testing was identical to that of the undercutting test with the exception of the mold. Readily available QUIKRETE® Portland Cement TypeI/II, as well as QUIKRETE® Multipurpose sand was used. Prior to mixing, the sand was sieved to remove any particles greater than a sieve size of 16. The mix ratio was 1.0 part cement, 0.485 parts water, and 2.60 parts sand. Molds were made from 4 in diameter PVC piping cut at 1.5 in intervals and place on a textured fiberglass board (Figure 7.4). Molds were filled and shaken to help remove air and level the mix. Curing occurred overnight at ambient temperature and humidity prior to be being placed in a saturated lime bath for a cure time of roughly one week.

Figure 7.4 Photograph of mortar specicemen for disbondment testing, with and without ice.

Specimens were frozen via the bottom-up freezing method used in the undercutting tests. Water/snow retention was achieved by placing a neoprene band at the required height around a speciment with a wormscrew clamp. Rubber bands were used as a sealing gasket between the specimen and the neoprene to create a watertight seal. For the ice disbondment tests, enough water was used to to form a ¼ in layer of ice (52 mL), while snow disbondment testing used approximately 1-1½ in of manufactured snow (shaved ice) which was lightly compacted to form a ½ in layer of snow on the mortar specimen. Manufactured snow was produced by a Hatsuyuki HF-500E block ice shaver, set to the minimal blade height capable of producing a constant stream of shaved ice. Freezing was accomplished using a special box designed to allow freezing from the bottom up, as previoulsy described. Freezing was achieved by setting the cold room to 15°F and allowing the specimens to freeze overnight.

The chemical salt solutions (Salt Brine (~23% by weight), MeltDown 20® (26% by weight), and MeltDown Apex™) including dye were added to cavities made in the snow or ice. Specimens were pre-equilibrated at the appropriate temperature (30°F and 15°F) for 12 hours. Cavities in the ice/snow were made using a 4mm steel rod heated in a water bath with excess melt water removed by sryinge. We tested both 30 and 60 µL of each de-icing solution. Due to the size of the specimens, only 4 cavities per specimen were possible, larger speciemens were not possible due to force limitations of the testing apparatus (Figure 7.5). Spacing of cavities was kept at 4cm on center per the undercutting procedures.

Figure 7.5 Mecmesin MultiTest 1-d motorized test stand used for disbondment testing.

One hour after the de-icing solutions were added to each specimen the ice/snow was sheared off. We used a modified Mecmesin MultiTest 1-d motorized test stand, rated at 1kN (220 lbf) to apply the shear force. Force measurements were recorded via a Quantrol AFG 500N (110 lbf) force gauge connected to a computer running DataPlotX software (Figure 7.4). Three specimens per solution were tested at two temperatures, giving a total of 72 samples. Images were taken both before and after the ice or snow was sheared from the specimens.

7.2.4 Modified Friction Testing

The friction test determines the frictional characteristics of de-icer materials using the British Pendulum Skid Resistance Tester (BPT) (Figure 7.6). This test is commonly used for the measurement of skid resistance of pavement surfaces. The British Pendulum Tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface. It is extremely versatile in its applications to many test situations and has received acceptance worldwide. The test device measures low-speed friction (about 10 km/h) and is commonly used to assess the microtexture of pavement surfaces. The test yields a British Pendulum (Tester) Number expressed as BPN. For flat surfaces, the BPN represents the frictional properties obtained with the apparatus.

Figure 7.6 British Pendulum Skid Resistance Tester used for friction testing.

We measured the impact of the three salt solutions (MeltDown 20®, MeltDown Apex™, and Salt Brine) on surface friction characteristics using the Portable Skid Resistance Tester (Stanley London), generally following SHRP H-205.10, Test Method for Evaluation of Frictional Characteristics of Deicer Chemicals. The tests were conducted on media-blasted glass (3.5 in x 6 in) with peak valley profiles between 1.0 and 1.5 mils. The solutions to be tested and the glass plate were both pre-conditioned at the temperature to be tested for 1 hour. All tests were performed in a walk-in temperature controlled room. Each solution was tested 5 times at -12°C (-10°F) and at -4°C (25°F). The magnitude of each measurement was measured as BPN, accurate to within ±1 BPN.

7.3 Results

7.3.1 Modified Ice melting

Results from the modified ice melting test are presented in Figure 7.7 through Figure 7.10. These results show that the amount of ice melting induced by the three salt solutions was highly dependent on the temperature evaluated and volume of solution applied. The data have been transformed and expressed as the percent change in applied volume to normalize for the varying applied volumes.

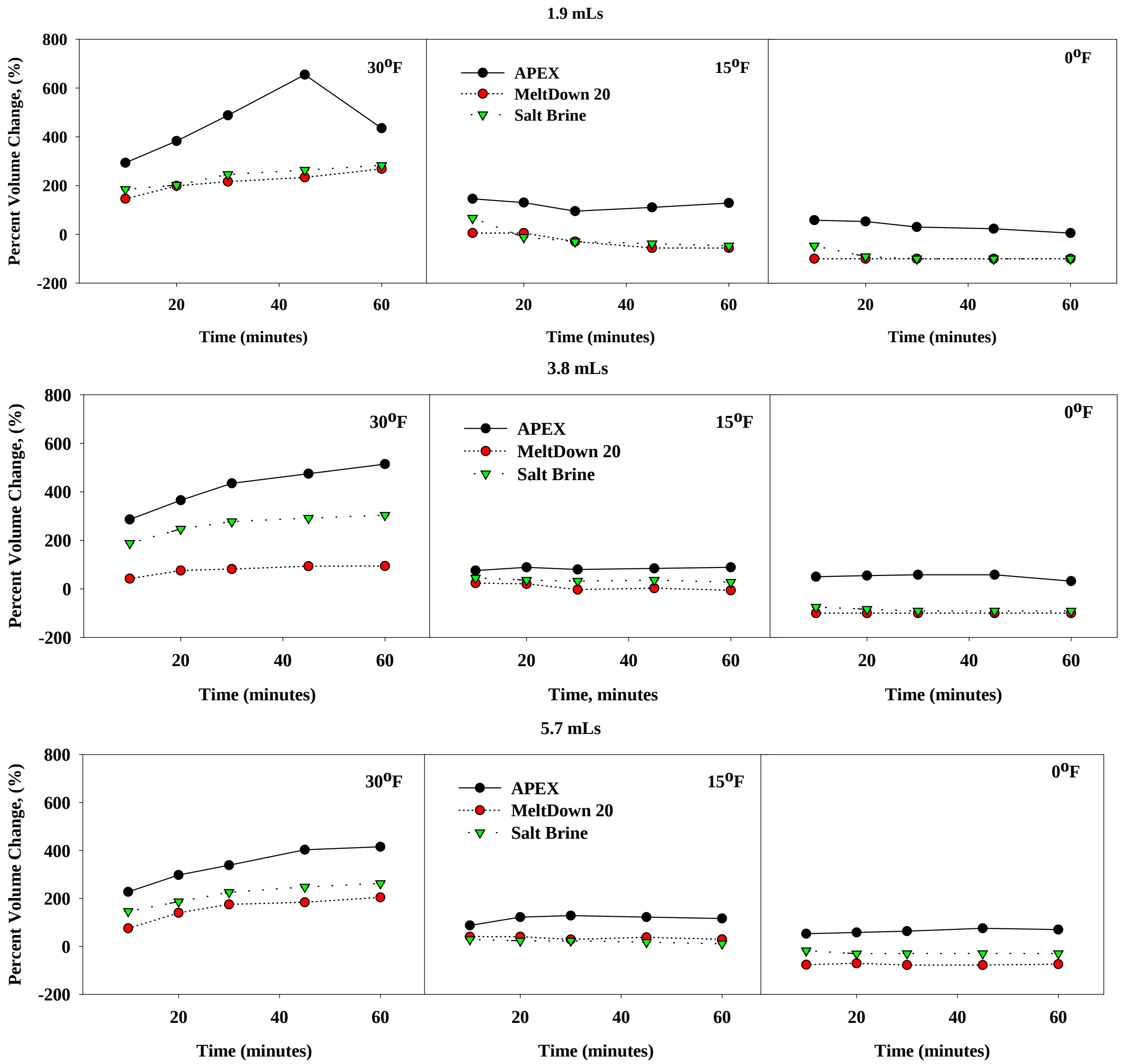


Figure 7.7 The impact of deicing solutions on ice melting over time normalized to the applied volume. Note that standard error bars are smaller than symbols size.

Figure 7.7 displays the change of percent volume with time for each solution and for applied volumes of 1.9, 3.8, and 5.7 mls. We also simultaneously plotted the percent volume change with temperature and volume applied to aid in the overall comparison for both the initial time point and final time point assuming the final time point reflects the best measure of the final volume change (Figure 7.8 and 7.9). We also tested higher applied volumes (7.6 and 15.2 ml) of Salt Brine and MeltDown 20® to evaluate if higher applied volumes would be more effective at lower temperatures (Figure 7.10).

At 30°C, all three de-icing solutions produced ice melting defined as a positive increase in the percent volume change. MeltDown Apex™ produced the greatest amount of melting at 30°F for 1.9, 3.8, and 5.7ml of applied solution. The amount of melting produced by MeltDown 20® and Salt Brine was generally comparable, but in all cases Salt Brine produced more melting and in one case (*e.g*., 3.8ml of applied solution) the difference was substantial (Figure 7.8 and 7.9). For all solutions the volume of melt solution increased with time and generally approached a maximum volume by 60 minutes (Figure 7.7). This is not unexpected as the melting ice will dilute the deicing solutions. As the deicing solutions become increasingly dilute they will approach the freezing point of the salt solution and reach steady state. The much higher (~2X) volume of melt solution produced by MeltDown Apex™ was not unexpected given the much lower freezing point of Mg^{+2} based solutions. This percent volume change does not vary with applied volume even though the absolute volume increases with applied volume.

At 15°F, all three de-icing solutions produced melting initially, but at the final time point, the lowest volumes of salt brine and MeltDown 20® applied lost volume (negative percent change). There was little if any change in percent volume with time except at the two lowest volumes applied for both Salt Brine and MeltDown 20® but not for MeltDown Apex™. Further, at the final time point there was an increase in the percent volume change with applied volume for both Salt Brine and MeltDown 20® but not MeltDown Apex™. The percent change in volume (e.g. amount of melting) was much higher (>2X) for MeltDown Apex™ than for Salt Brine or MeltDown 20® which were of similar magnitude. Most solutions reached their maximum change in volume within 20 minutes and did not substantially change after that time point. At the final time point, the final percent volume change was ~50% for both the Salt Brine and MeltDown 20® effectively reducing the salt concentration by 50%. At this salt concentration (~12.5%), the freezing point is near 15F°.

At 0°F only MeltDown Apex™ produced significant positive melting, noting that MeltDown Apex™ produced much lower percent volume changes (50%) compared to results at 30°F or 15°F (Figure 7.8 and 7.9). There was little consistent change with time for any applied solution. Both Salt Brine and MeltDown 20® lost volume at all applied volumes at the final time point, suggesting that the solutions were freezing. This was not unexpected given that the freezing point for saturated NaCl brines is just under 0°F.

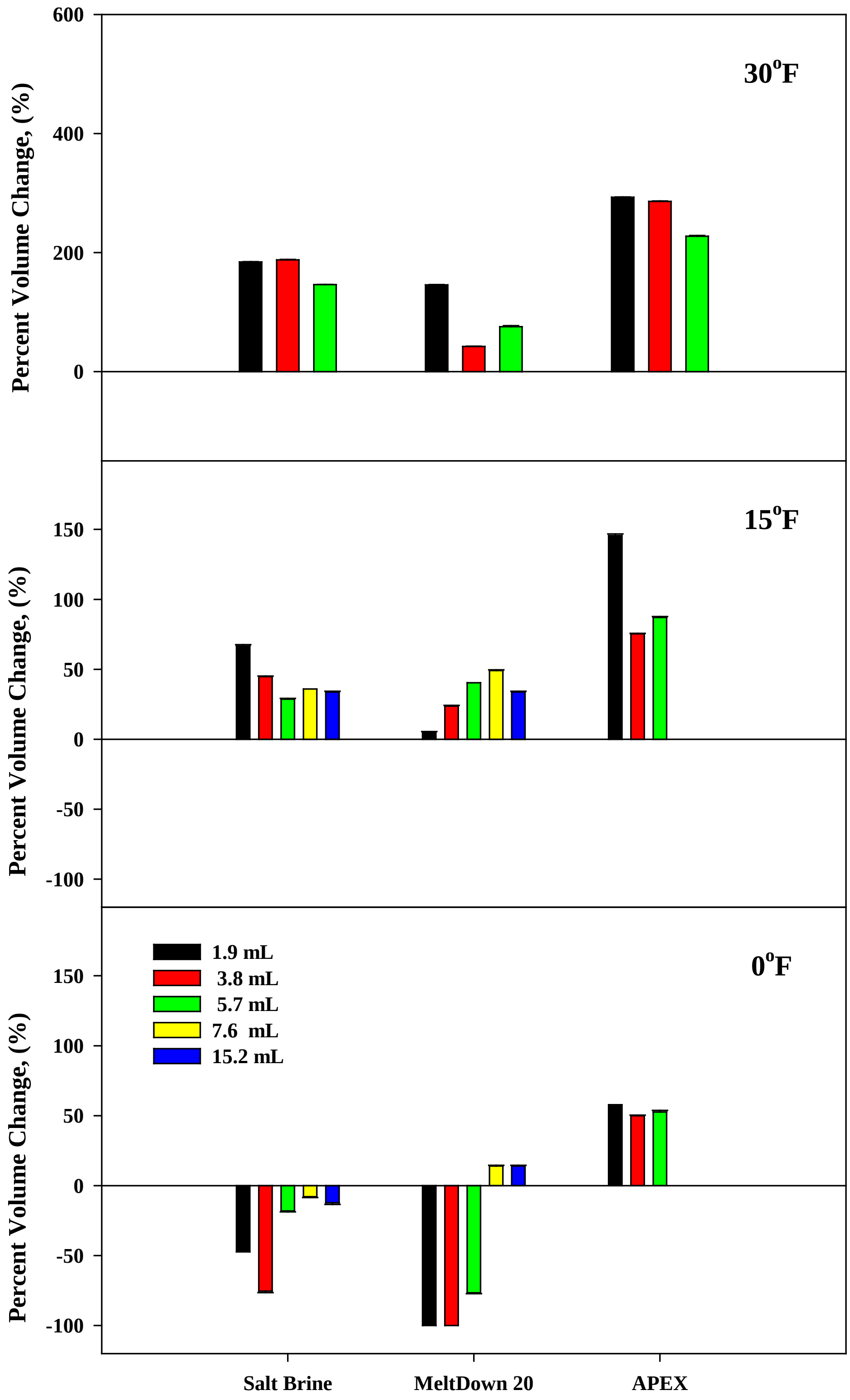


Figure 7.8 Initial percent volume changes produced by application of varying volumes of de-icing solutions at 30, 15, and 0°F. Standard error bars are smaller than symbols size.

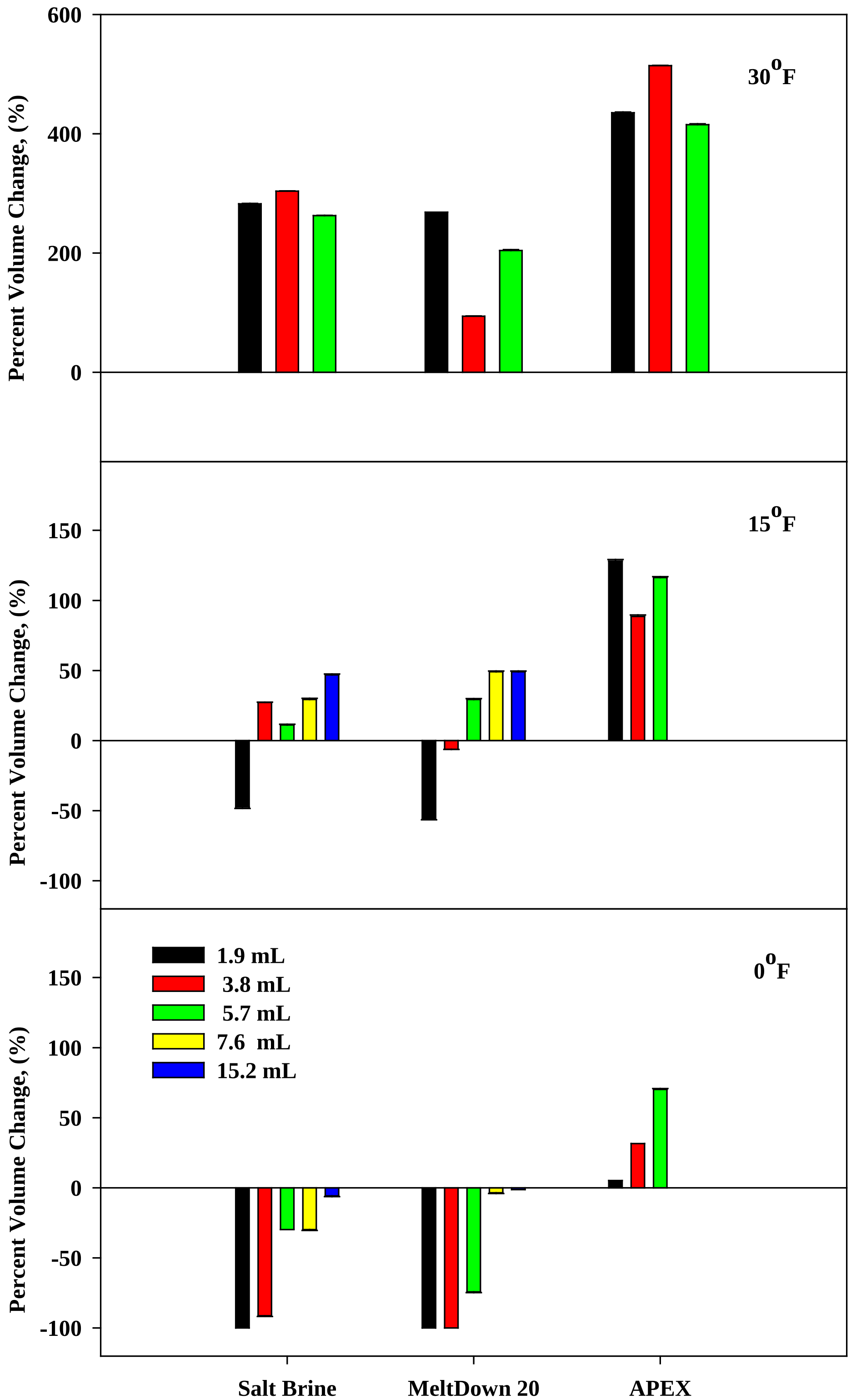


Figure 7.9 Final percent volume changes produced by application of varying volumes of de-icing solutions at 30, 15, and 0°F. Standard error bars are smaller than symbols size.

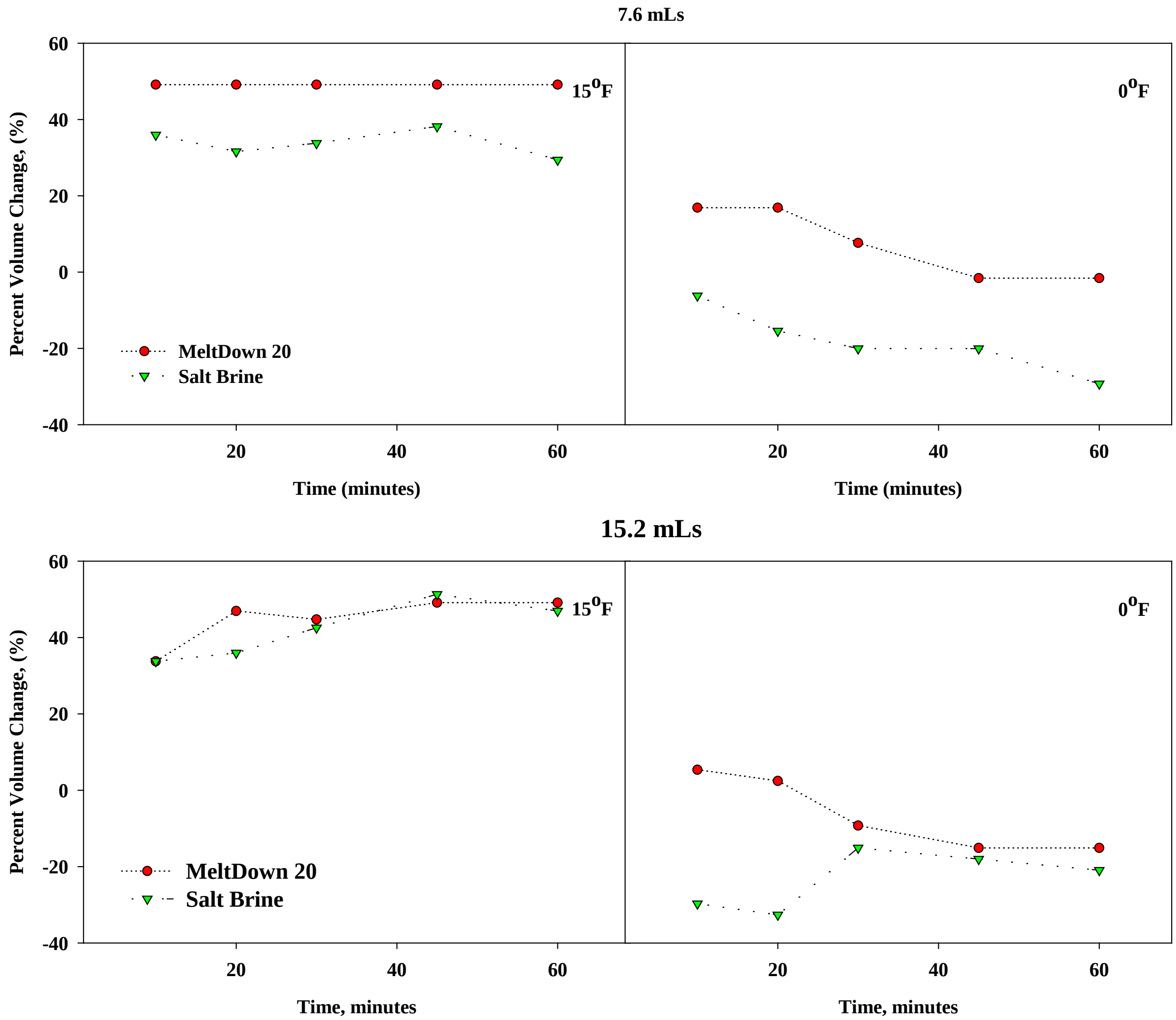


Figure 7.10 The impact of application of Meltdown 20 and Salt Brine on ice melting over time normalized to the applied volume. Standard error bars are smaller than symbols size.

Overall, MeltDown Apex™ was much more effective (more melting per applied volume) at producing melting over the entire temperature range and was the least sensitive to the volume applied except at the lowest temperature evaluated. Salt Brine and MeltDown 20® were overall comparable with very similar performance over the entire range of test variables. One important issue that the testing illuminates is the impact of dilution at cold temperatures (i.e., pavement temperatures below 20°F). The lowest chemical application rates for the ice melting tests are similar to or lower than typical field application rates. The data suggest that at cold temperatures, even a small amount of melting will quickly reduce the applied salt's ability to melt ice further. At pavement temperatures below 15°F, only MeltDown Apex™, is likely to be effective.

7.3.2 Ice Undercutting

The ability of salt solutions to undercut ice was evaluated by applying salt solutions to small holes in ice which had been bonded to mortar. Undercutting was measured by quantifying the spread of a dye in the salt solution with time. Characteristic images of mortar specimens for ice undercutting at time *t* =0 and at time *t* >1 hr are presented in Figure 7.3 and Figure 7.11, respectively. In general the results from the ice undercutting tests were rather variable. There were moderate increases in area with time for some treatments (*e.g.*, MeltDown 20® and MeltDown Apex™ at 15°F) but given the large variation at each time point there are not generally substantial differences with time. This is consistent with the results of the ice melting experiment and likely due to the dilution of the salt brine as it spreads.

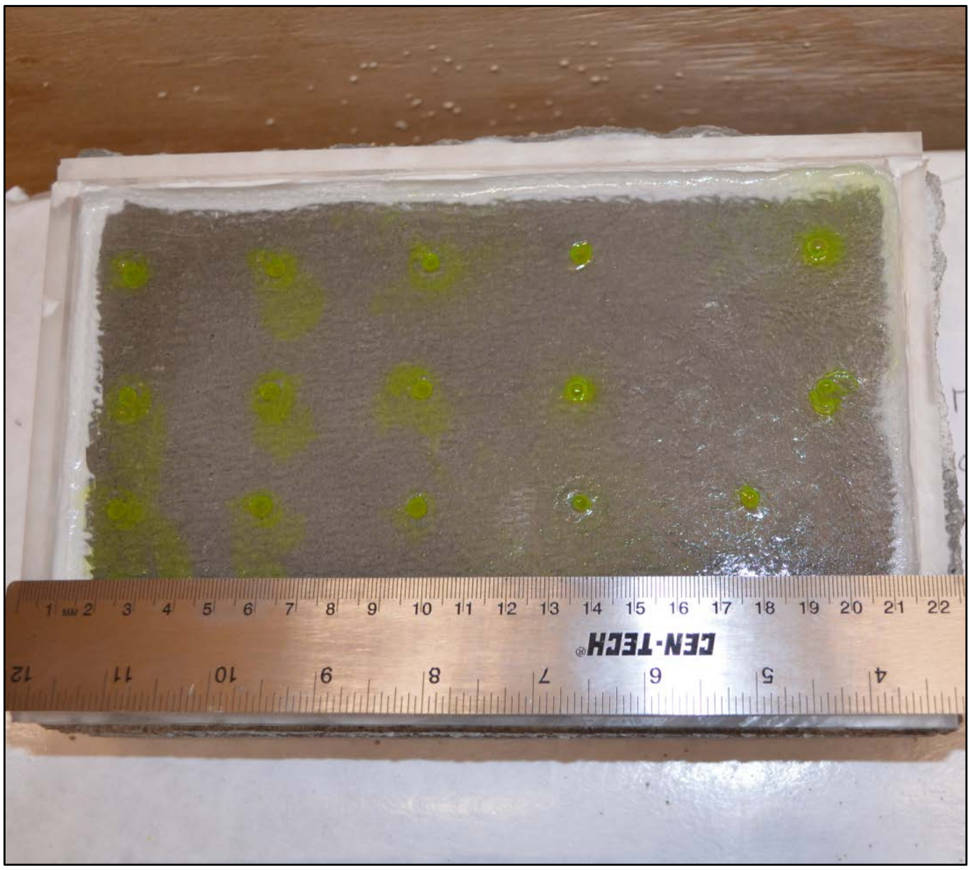


Figure 7.11 Ice undercutting of mortar specimen 1 hour after addition of salt solution.

Assuming the final time point represents the best measure of the maximum undercutting extent, we compared data for the three de-icing solutions at three temperatures (Figure 7.12). Results for MeltDown Apex™ and Salt Brine were consistent with known temperature effects in that undercutting area decreased with decreasing temperature. Results for MeltDown 20® were more variable with the undercutting area greater at 15°F than at 30°F, which is not consistent with known temperature effects and thus the results of the test for MeltDown 20® may be unreliable.

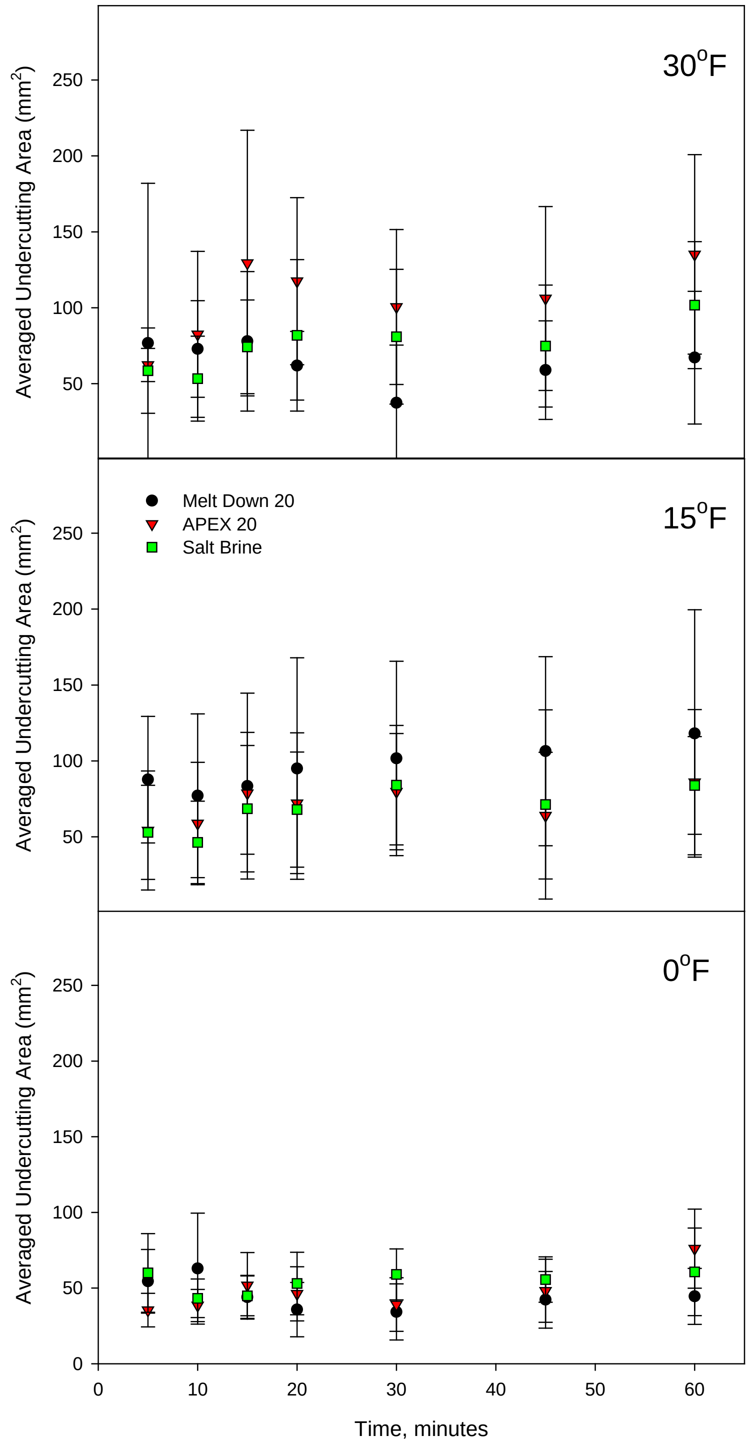


Figure 7.12 Measured undercutting areas for the three de-icing solutions at three test temperatures. Points represent an average for 3 replicates at sequential differing contact times between the de-icing solution and ice cavities.

In general there were only small differences between MeltDown chemicals (Figure 7.13). MeltDown Apex™ did have the greatest undercutting area at all temperatures with the exception of 15°F for MeltDown 20®.

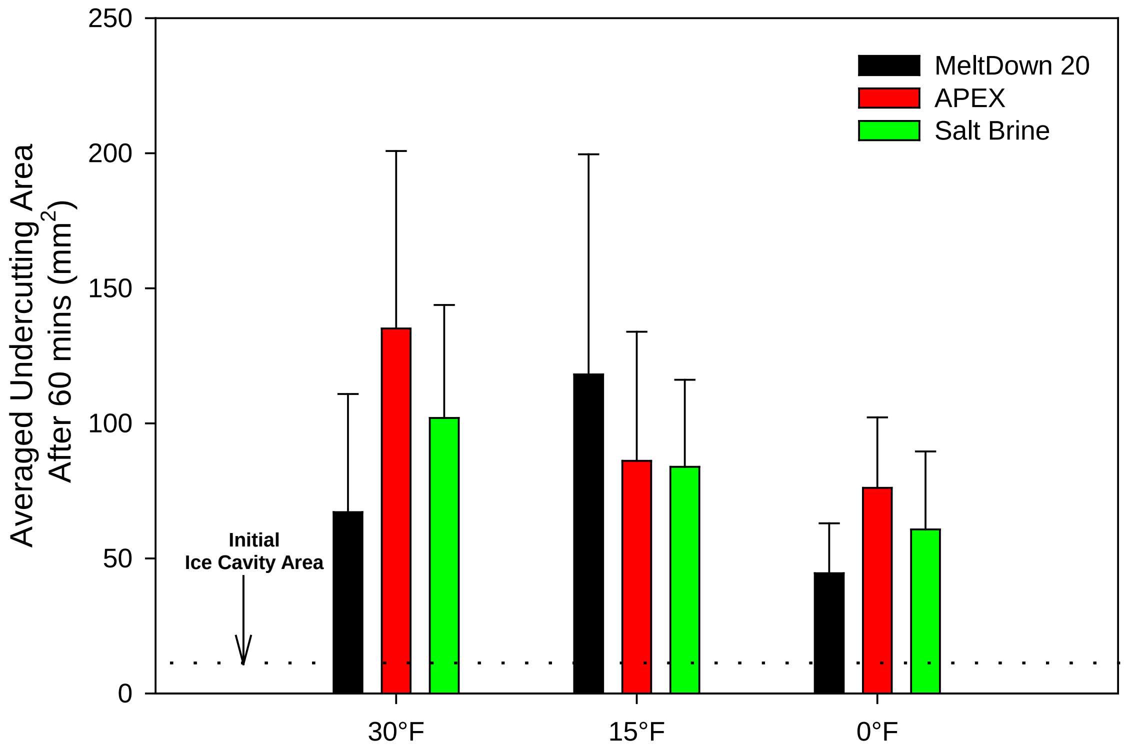


Figure 7.13 Averaged undercutting areas after 60 minutes of de-icing solution being in contact with ice cavities. Values are averaged between 3 replicates for each different deicing solution at each corresponding testing temperature

7.3.3 Disbondment Testing

The disbondment test evaluated how the de-icing salt solutions impacted the strength of bond between ice/ snow and mortar specimens. Tests were performed for all three salt solutions at two loadings and at temperatures of 15°F and 30°F (see Table 7.3 and Table 7.4).

Results from the disbondment tests provided limited data for further analysis due to significant operational issues. After data collection, only runs that provided a clear distinct point of separation were quantitated. Ice samples at 15°F were not considered since the ice was not sheared from the mortar, but rather crushed or scraped on the surface. This type of (non-successful) test left a remaining layer of ice bonded to the mortar with only small cavities (where deicing solution was applied) devoid of ice.

The most complete set of data was for ice specimens at 30°F where complete shearing was achieved consistently. The values all fall within the same range and do not show a clear difference between chemicals or application rates (Figure 7.14). Samples for both snow and ice at other temperatures failed to yield sufficient data for comparison. Snow specimens tended to freeze only at the interface, and on the surface, leaving the center insulated. This allowed for easier removal of the snow from the specimen, but the test tended to break up the snow rather than shear it off.

Table 7.3 Disbondment results for ice specimens.

De-icing Solution	Ice Specimens 30µl of De-icing Solution				
	Temperature 30°F				
	Sample #	Area Undercut (in^2)	Separation	Force (lb)	Comments
Salt Brine	1	1.083	Yes	485.72	
	2	0.899	Yes	441.96	
	3	0.99	Yes	460.08	
MeltDown 20®	1	0.767	Yes	486.64	
	2	0.722	Yes	490.64	
	3	0.495	Yes	451.68	
MeltDown Apex™	1	0.786	Yes	461.88	
	2	0.988	Yes	433.96	
	3	1.022	Yes	487.52	
	Temperature 15°F				
Salt Brine	1	0.598	no	n/a	ice scraped, doesn't separate
	2	0.604	no	n/a	ice scraped, doesn't separate
	3	0.678	no	n/a	ice scraped, doesn't separate
MeltDown 20®	1	0.97	no	n/a	Test failed
	2	0.611	no	n/a	ice scraped, doesn't separate
	3	0.644	no	n/a	Test failed
MeltDown Apex™	1	0.59	no	n/a	ice scraped, doesn't separate
	2	0.637	no	n/a	ice scraped, doesn't separate
	3	0.535	no	n/a	ice scraped, doesn't separate
	Ice Specimens 60µl of De-icing Solution				
	Temperature 30°F				
Salt Brine	1	1.124	yes	494.28	Stair step chart
	2	1.054	yes	312.04	
	3	1.104	yes	488.96	Stair step chart
MeltDown 20®	1	0.92	yes	462.84	Stair step chart
	2	0.926	yes	472.96	
	3	0.847	yes	422.6	
MeltDown Apex™	1	1.422	yes	n/a	Data failed to record
	2	1.532	yes	472.96	
	3	1.534	yes	422.6	
	Temperature 15°F				
Salt Brine	1	n/a	no	n/a	ice scraped, doesn’t separate
	2	n/a	no	n/a	ice scraped, doesn’t separate
	3	n/a	no	n/a	ice scraped, doesn’t separate
MeltDown 20®	1	n/a	no	n/a	ice scraped, doesn’t separate
	2	n/a	no	n/a	ice scraped, doesn’t separate
	3	n/a	no	n/a	ice scraped, doesn’t separate
MeltDown Apex™	1	n/a	no	n/a	ice scraped, doesn’t separate
	2	n/a	no	n/a	ice scraped, doesn’t separate
	3	n/a	no	n/a	ice scraped, doesn’t separate

Table 7.4 Disbondment results for snow specimens.

De-icing Solution	Snow Specimens 30µl of De-icing Solution				
	Temperature 30°F				
	Sample #	Area Undercut (in^2)	Separation	Force (lb)	Comments
Salt Brine	1	n/a	Yes	n/a	no distinct point of separation
	2	n/a	Yes	n/a	no distinct point of separation
	3	n/a	Yes	60.32	
MeltDown 20®	1	n/a	Yes	20.92	
	2	n/a	Yes	19.68	
	3	n/a	Yes	n/a	no distinct point of separation
MeltDown Apex™	1	n/a	Yes	47.16	
	2	n/a	Yes	51.8	
	3	n/a	no	n/a	no distinct point of separation
	Temperature 15°F				
Salt Brine	1	n/a	yes	16.4	
	2	n/a	yes	18.24	
	3	n/a	yes	50.04	
MeltDown 20®	1	n/a	no	n/a	
	2	n/a	no	n/a	
	3	n/a	yes	63.44	
MeltDown Apex™	1	n/a	no	n/a	
	2	n/a	no	n/a	
	3	n/a	yes	14.72	
	Snow Specimens 60µl of De-icing Solution				
	Temperature 30°F				
Salt Brine	1	n/a	yes	20.04	n/a
	2	n/a	yes	34.52	n/a
	3	n/a	yes	45.92	n/a
MeltDown 20®	1	n/a	yes	n/a	came off normal handling
	2	n/a	yes	54.6	
	3	n/a	no	n/a	no distinct point of separation
MeltDown Apex™	1	n/a	yes	39.48	
	2	n/a	yes	16.64	
	3	n/a	no	n/a	no distinct point of separation
	Temperature 15°F				
Salt Brine	1	n/a	yes	n/a	no distinct point of separation
	2	n/a	yes	25.84	
	3	n/a	yes	32.84	
MeltDown 20®	1	n/a	no	n/a	bad data collection
	2	n/a	no	n/a	no distinct point of separation
	3	n/a	no	84.48	two distinct points of separation
MeltDown Apex™	1	n/a	no	n/a	no distinct point of separation
	2	n/a	no	16.96	only partial separation
	3	n/a	yes	n/a	grabbed mortar edge

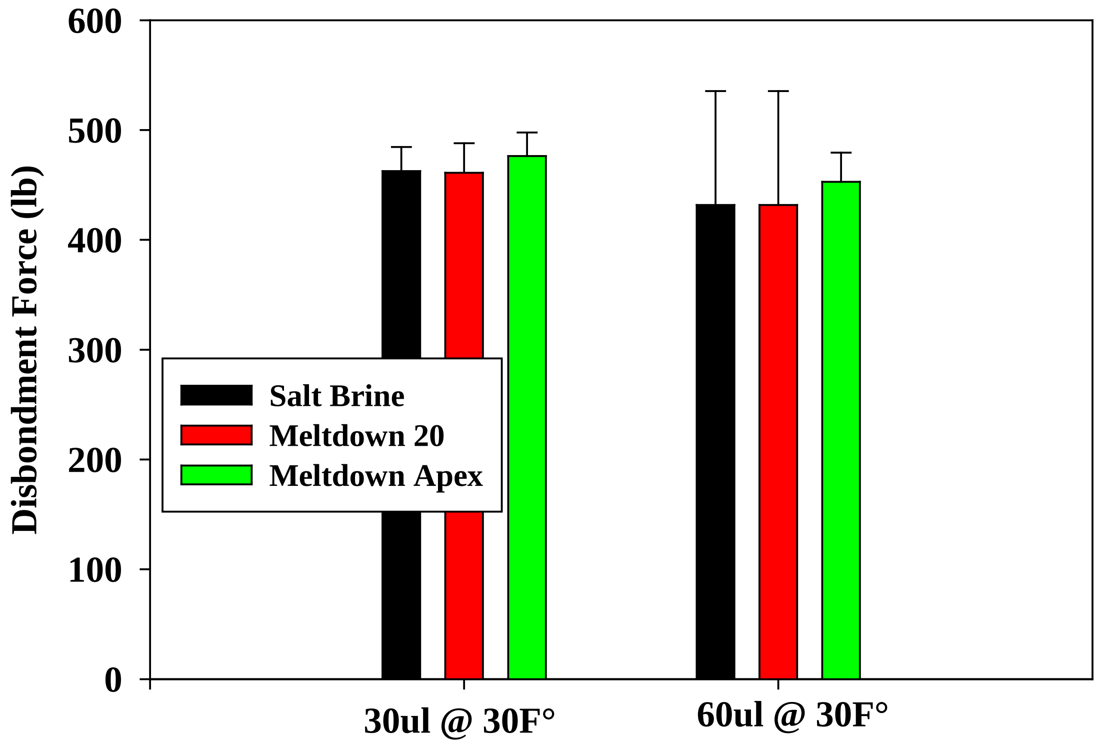


Figure 7.14 Average force required to produce ice disbondment from mortar specimen at 30°F for two loadings.

Although the disbondment test shows promise, it was not ideal and was unable to provide sufficient data for analysis. Testing at 30°F on ice appeared to give the best results, but a larger sample size is needed to illuminate whether a measureable difference in bond-breaking strength exists between the chemicals. Snow samples were more difficult to work with since they are difficult to make consistently. The inability to measure the disbondment area of the specimen prior to testing was another issue with snow, as well as the chemical being absorbed into the snow rather than pooling at the interface.

7.3.4 Modified Friction Testing

The modified friction test was performed to measure the influence of de-icing chemicals on the frictional characteristics of a test surface (media blasted glass) applied over a range of temperatures.

Test results (Table 7.5) indicate that Salt Brine and MeltDown20® have comparable impacts on the friction characteristics, while MeltDown Apex™ clearly decreases the skid resistance (lower BPN) for all temperatures. BPN values for Salt Brine and MeltDown20® compare similarly to distilled water at standard temperature. In general, the skid resistance increased (higher BPN) at lower temperatures. These results are generally in agreement with field test results of anti-icing chemicals evaluated on pavement prior to storm onsets.

Table 7.5. Friction Characteristics of Common Snow and Ice Chemicals at varying temperature using the British Pendulum Skid Resistance Test.

Temperature of Test	British Pendulum Number (BPN)			
	Distilled Water	Salt Brine	MeltDown 20®	MeltDown Apex™
20°C (68°F)	53 ±0.4	50 ± 1	48 ± 1	37 ± 0.5
-4°C (25°F)	-	60 ±0.5	63±0.7	46±0.5
-12°C (10°F)	-	64±0.4	63±0.7	53±0.5

7.4 Laboratory Test Program Summary

The laboratory test program was designed to evaluate particular impacts of de-icing snow and ice control chemicals using available published methods in a controlled laboratory setting. The testing was not meant to directly mimic field conditions, methods or other aspects of field operations.

Overall results suggest that MeltDown20® and Salt Brine de-icing solutions are comparable with regard to their ability to melt ice or undercut ice under laboratory conditions at temperatures above 15°F. Neither Salt Brine nor MeltDown20® were was particularly effective at 0°F (which is near the freezing temperature of a 23% salt mixture). MeltDown Apex™ was substantially more effective at ice melting, even at 0°F, and was generally more effective at undercutting although this effect was much more variable and variation in the data precludes any strong assertions regarding comparisons between the products. Data indicate that the melting process rapidly dilutes the salt solutions, reducing their effectiveness.

On surface glass with no snow or ice, MeltDown Apex™ was much “slicker” than either MeltDown20® or Salt Brine. Friction data for MeltDown20® and Salt Brine at standard temperature are roughly similar to distilled water. In general, the skid resistance increased (higher BPN) at lower temperatures. The impacts on friction are similar to those observed for the roadway at the field site after anti-icing, prior to snow or ice events.

CHAPTER 8
PROJECT SUMMARY AND CONCLUSIONS

8.1 Research Summary

In January 2012, TxDOT sponsored 0-6793, "Snow and Ice Chemicals for Texas Roads," which is the research study described in this report. The work plan included seven functional tasks. Collectively, this work serves to quantify and qualify the relative merits of common snow and ice materials used in TxDOT's winter maintenance operations.

Task 1. Characterize the application and effectiveness of snow and ice control chemicals. The objective of Task 1 was to identify and classify the types of snow and ice control chemicals that can be used for Texas roads and winter weather conditions. This assessment included the effectiveness, as a function of application, of the major snow and ice chemicals currently used by TxDOT (e.g. NaCl, $MgCl_2$, and $MgCl_2$ with additives) as well as natural brines. This task also included limited evaluation of abrasives to provide a basis for comparison.

Task 2. Determine the availability, storage requirements, and transport issues related to natural brines. Task 2 characterized natural brines as a potential snow and ice control chemical for Texas roads. This work required evaluation of the availability of natural brine suppliers or potential suppliers for the state of Texas, review of storage requirements for these products, and consideration of transport issues including mode of transport, time of transport, and cost. Corrosivity concerns, potential environmental impacts, and regulatory issues associated with the use of these brines were also addressed.

Task 3. Evaluation of infrastructure durability impacts due to anti-icing and de-icing operations. The primary objective of Task 3 was to evaluate possible adverse impacts to the durability of highway infrastructure caused by de-icing and anti-icing operations on Texas roads. These durability concerns included corrosion of steel reinforcement and scaling of surfaces of concrete structures, as well as corrosion of infrastructure exposed to these chemicals such as steel bridge girders, expansion joints and supports, and snow and ice control equipment.

Task 4. Evaluate the environmental impacts and regulations with relation to the current and future use of salts and brines to control snow and ice on Texas roads. Task 4 consisted of a comprehensive review of the relative environmental impacts of anti-icing and de-icing salts including natural brines. Research also evaluated the current state and future direction of environmental regulations covering the use of these salts and brines in Texas. In addition, this task evaluated environmental impacts associated with selected, commonly-used abrasives.

Task 5. Field trial to compare effectiveness of snow and ice control chemicals. The objective of Task 5 was to obtain a comparative "side-by-side" determination of how selected snow and ice control chemicals perform on Texas roads under representative winter weather conditions. This task was extended for two additional years, and a laboratory test program was added in the third year to explore the influences of certain variables which could not be addressed in the field trials.

Task 6. Perform a comprehensive cost analysis of the use of snow and ice control materials. Task 6 consisted of an analysis of the life-cycle costs of selected snow and ice control materials used in Texas. This analysis considered both the short-term cost factors (e.g., purchasing, processing, storage, transport, and application) and long-term factors (e.g., potential damage to equipment and roadways) of these materials.

Task 7. Production of deliverables. The objective of Task 7 was to produce the deliverables associated with the project including the research report and products.

8.2 Conclusions

Project 0-6793 considered all major aspects of TxDOT's typical snow and ice control materials including their effectiveness, availability, impact on infrastructure durability (corrosion), environmental concerns and regulations, field performance, and cost. The reader is directed to the individual report chapters for details. The following statements are the key conclusions from this study, presented by research task.

<u>Task 1</u>. Review of technical literature on snow and ice control materials used in the United States and in Texas, including the effectiveness of these materials in relation to type of application, shows the following:

1.1. Texas snow and ice control material historical usage has relied heavily on Meltdown® products (51% granular, 8% liquid), but national usage focuses even more strongly on road salt and road salt brine.

1.2. A widespread belief exists among TxDOT personnel that MeltDown® products are comprised of magnesium chloride. Liquid MeltDown Apex™ is truly $MgCl_2$ in water, but granular MeltDown 20® is almost pure <u>sodium</u> chloride. *Manufacturer's* data for MeltDown 20® shows this product consists of 90 to 98% NaCl (road salt) and 0.06 to 0.2% $MgCl_2$ plus other elements and a proprietary corrosion inhibitor.

1.3. Texas ranks 30th nationally in terms of snow and ice control expenditures, and 42nd nationally in terms of percent maintenance effort *and* cost of treatment per lane mile.

1.4. Texas winter weather is very challenging for snow and ice control in that it is unpredictable (varying number and frequency of storms), diverse (both snow *and* ice), and presents with a wide range of severity (from climate normals to extreme winter storm events).

1.5. Weather directly influences winter roadway maintenance strategy and operational issues including the type, application, quantity, and effectiveness of snow and ice control materials, as well as equipment selection and personnel training.

Task 2. Review of technical literature and other data on the usability of brines for snow and ice control shows the following findings.

2.1. Texas historical usage of brines includes Meltdown Apex™ and more recently, homemade salt brine in the Childress District.

2.2. Many pre-approved brine products with known properties are available for purchase.

2.3. Three types of “geologic” brines are available for consideration in snow and ice control: natural brine, manufactured brine, and oilfield brine (produced water).

2.4. All of the geologic brines should be tested and approved prior to widespread use; concentrations of trace metals could be highly variable.

Task 3. Review of technical literature and a limited experimental program on durability impacts of snow and ice chemicals on infrastructure show the following facts.

3.1. TxDOT’s historical usage of chemicals includes both inhibited chlorides (Meltdown Apex™, Meltdown 20®) and uninhibited chlorides (road salt, salt brine).

3.2. These are all chloride salts and all chloride salts are highly corrosive.

3.3. Atmospheric corrosion tests indicate

- No difference in corrosion rate observed between sodium chloride products, and
- Inhibited chlorides are 36% to 55% less corrosive than uninhibited road salt.

3.4. Chloride diffusion tests indicate

- Magnesium chloride achieves the highest chloride concentrations during diffusion, and
- No chemicals diffused beyond Level 2 (0.75” to 1.25”).

3.5. The literature demonstrates that studies that have tried to compare specific snow and ice control chemicals show a wide range of conclusions, and sometimes contradict one another.

3.6. Laboratory corrosion results often differ from observed field impacts.

3.7. Texas’ annual chemical applications are generally an order of magnitude lower than applications in northern states.

Task 4. Review of literature on environmental impacts and regulations associated with application of snow and ice chemicals, nationally and in Texas, shows the following results.

4.1. Overall, the literature suggests there is minimal added risk to the environment when using Na, Mg, Ca, and Cl salts for snow and ice control.

4.2. Any product (solids or brines) should be tested for constituents and toxicity prior to use, with particular attention to geologic brines that can be spatially and temporally variable.

4.3. De-icing chemicals commonly used in Texas include road salt (both liquid and granular), liquid MeltDown Apex™, and granular MeltDown 20®, all of which are approved products on the PNS Qualified Products List.

4.4. Dilution by snowmelt greatly decreases potential impacts (~500X).

4.5. The coldest and snowiest portions of Texas have less severe winters than northern states with more active, chemical-based winter roadway maintenance programs.

Task 5 (field trials). The field trials performed in Winter 2012/13, Winter 2013/14, and Winter 2014/15 showed the following findings.

5.1. Photo and video datasets for anti-icing applications typically showed

- No statistically-significant difference in the amount of visible bare pavement for sections treated with Salt Brine vs. sections treated with MeltDown Apex™, and
- No statistically-significant difference in the amount of visible bare pavement for sections treated with Salt Brine or MeltDown Apex™ compared to untreated control sections.

5.2. Decelerometer tests for anti-icing applications indicated

- MeltDown Apex™ -treated sections could be 10 to 20 percent slicker (lower deceleration) than the Salt Brine-treated sections, and
- MeltDown Apex™ -treated test sections could be slicker (lower deceleration) than untreated sections.

5.3. Photo and video datasets for de-icing applications typically showed

- A statistically-significant improvement in the amount of visible bare pavement for sections treated with road salt (at the TxDOT rate of 300 lb/lane mile) vs. sections treated with MeltDown 20® (at the TxDOT rate of 150 lb/lane mile), and
- No statistically-significant difference in the amount of visible bare pavement for sections treated with road salt or MeltDown 20® de-icing chemical compared to untreated control sections.

5.4. Decelerometer tests for de-icing applications indicated

- No statistically-significant difference in pavement friction between sections treated with road salt vs. sections treated with MeltDown 20®, and
- Both MeltDown 20®-treated test sections and road salt -treated sections were less slippery (better deceleration) than untreated sections.

Task 5 (laboratory testing). The laboratory testing program shows the following:

5.5. With respect to ice melting and undercutting

- MeltDown 20® and Salt Brine de-icing solutions are comparable with regard to their ability to melt ice or undercut ice under laboratory conditions at temperatures above 15°F,
- Neither Salt Brine nor MeltDown 20® was particularly effective at 0°F (which is near the freezing temperature of a 23% salt mixture),
- MeltDown Apex™ was substantially more effective at ice melting, even at 0°F, and was generally more effective at undercutting although this effect was much more variable, and
- The melting process rapidly dilutes the salt solutions, reducing their effectiveness.

5.6. With respect to surface friction

- MeltDown Apex™ was much "slicker" than either MeltDown 20® or Salt Brine, and
- Friction data for MeltDown 20® and Salt Brine were similar to distilled water.

Task 6. Detailed cost analyses established the baseline of TxDOT's snow and ice control expenditures and show the following results.

6.1. Opportunities to improve efficiency in snow and ice material procurement include

- Standardize selection of materials,
- Develop a uniform standard for selecting snow and ice control materials, and
- Leverage TxDOT's purchasing power to lower prices.

6.2. Opportunities to improve efficiency of winter maintenance operations include

- Reduce Operation to Material (O-M) ratios,
- Capture data on cleanup and anti-icing maintenance functions, and
- Manage risk for low-frequency, high-impact events.

6.3. Opportunities to improve efficiency of winter maintenance policy include

- Apply performance-based models for snow and ice control,
- The current cost analysis focuses on input factors, and

- A significant question remains unanswered, namely: “Is the current level of winter maintenance spending adequate in maintaining snow and ice free roadways in Texas?”

Task 7. Deliverables for this study are

7.1. Research Report VOL 1, Literature and Best Practices Review,

7.2. Research Report VOL 2, Field Trials and Laboratory Testing,

7.3. Project Summary Report,

7.4. Product P1, Guidelines on Selection and Use of Snow and Ice Control Materials, and

7.5. Product P2, Guidelines to Facilitate the Evaluation of Brines for Winter Roadway Maintenance Operations.

8.3 Recommendations

The findings of this research study support several recommendations relative to snow and ice control material policy, procurement and practice.

Recommendation 1. Operational Strategy.

Because weather directly influences winter roadway maintenance, it is recommended that TxDOT tailor its winter weather operational strategy for snow and ice control, including material selection, to different weather zones in the State. Implications include the following.

1. Planning should address both climate normals and extreme weather events.
   a. Create operational winter maintenance plans based on historic experience, focusing on climate normals for different regions (zones) in Texas.
   b. Concurrently, with consideration to the probability of extreme weather events and their mobility impacts, create regional maintenance plans for extreme winter weather events focused on priority routes.
2. Differentiate maintenance operational strategy for snow removal from strategy for ice removal.
   a. Winter storms in the Texas Panhandle and northern part of the State are typically characterized by snow, whereas winter storms along IH20 are typically characterized by ice and snow.
   b. Maintenance strategy for these different areas should reflect the different types of storms; i.e., snow plows have limited effectiveness on ice.

3. Take advantage of Texas' relatively mild winter weather.
   a. Chemicals such as calcium chloride or magnesium chloride that are suitable for application at *very cold* temperatures are rarely justified by the winter weather and temperatures characteristic of most parts of Texas.
   b. Abrasives (chemically inert) have a place in TxDOT's winter maintenance strategy for areas of the State with particularly mild winters, especially the southern Districts.

<u>Recommendation 2</u>. Usage of Brines.

TxDOT has historically relied on pre-approved brine products such as MeltDown Apex™ and to a lesser extent, salt brine, for anti-icing operations associated with snow and ice control. Geologic brines such as natural brine (unrelated to oil or gas plays), manufactured brine (created by circulating fresher water in naturally-occurring below-ground salt deposits), and oilfield brine (produced water related to oilfield operations for oil and gas production) have been identified as potential alternative brines for winter roadway maintenance applications, especially during times when customary sources of brine are either unavailable or prohibitively expensive. Recommendations include the following.

1. One benefit of using pre-approved brines (and granular chemicals) is that these products have been tested and cleared for use by the Pacific Northwest Snowfighters (PNS) "Snow and Ice Control Chemicals Products Specifications and Test Protocols." Chemical constituents and impacts are known.

2. TxDOT has initiated steps to manufacture their own homemade salt brine on site (in the maintenance yard) using pre-approved brining quality salt. This approach can be very economical and makes sense for areas of the State where brine usage is significant.

3. Analytical results suggest that concentrations of trace metals and other constituents could be highly variable among different brine sources. Therefore, any geologic brine (natural, manufactured, or oilfield) should be tested and approved prior to widespread application on Texas roads. The PNS product specification and test protocols identified herein are appropriate for such evaluation.

<u>Recommendation 3</u>. Usage of Inhibited and Non-inhibited Chemicals.

Typical snow and ice control chemicals used in Texas are chloride salts, and all chloride salts are highly corrosive. Historically TxDOT has used both inhibited chlorides (Meltdown Apex™, Meltdown 20®) and uninhibited chlorides (road salt, salt brine). Both laboratory test results and findings published in the literature on durability impacts are mixed. These recommendations are encouraged.

1. The use of inhibited chlorides provides some added protection against atmospheric corrosion.
    a. Approved snow and ice control chemicals containing corrosion inhibitors can be purchased directly.
    b. Approved corrosion inhibitors can be purchased and applied to homemade salt brine and other chemicals.
2. TxDOT should proceed with caution when using non-inhibited chemicals.
    a. Concrete infrastructure (both pavements and bridges) that is not designed for low permeability or with epoxy-coated reinforcing will be more susceptible to corrosion impacts.
    b. Metal infrastructure (bridges), especially with partially-coated or non-coated steel, will be more susceptible to corrosion impacts.
    c. Routine maintenance inspections of treated infrastructure should include observation, monitoring, and evaluation for any signs of increased corrosion impact.
3. The usage of any snow and ice control chemical – either inhibited or non-inhibited – should be done within the context of maintenance practices that minimize corrosion impacts.
    a. Roadway maintenance following the winter season should include cleaning of infrastructure to remove, dilute, or otherwise normalize the effects of chloride salts with special attention to expansion joints and other metal elements directly exposed to the chemical.
    b. Equipment maintenance should include cleaning of equipment to remove, dilute, or otherwise normalize the effects of chloride salts with special attention to electrical wiring, gears, and any other uncoated metal elements directly exposed to the chemicals.

<u>Recommendation 4</u>. Environmentally-friendly Winter Maintenance Practices.

The Texas Commission on Environmental Quality (TCEQ) has no implicit rules about snow and ice control on their website or in the Texas Administrative Code. Overall, the literature suggests there is minimal added risk to the environment when using Na, Mg, Ca, and Cl salts for snow and ice control. Recommendations include the following.

1. TxDOT winter roadway maintenance should continue to employ best practices for snow and ice control operations with a view to minimizing environmental impacts.
    a. Annually calibrate both granular and liquid chemical application equipment.
    b. Train maintenance personnel in proper application of snow and ice control chemicals.

   c. Employ anti-icing strategies to minimize the amount of chemical needed for snow and ice operations.
   d. Use chemical application strategies such as pre-wetting to achieve less bounce and scatter (material loss) and more effective melting action.

2. Any snow and ice control chemical product should be tested and approved prior to widespread application on Texas roads.
   a. Pay particular attention to geologic brines that can be spatially and temporally variable.
   b. The PNS product specification and test protocols identified herein are appropriate for such evaluation.

3. Consider chemically-inert abrasives for areas of the State with particularly mild winters, especially the southern Districts.

Recommendation 5. Selectively Migrate from Meltdown® Products to Road Salt.

The field trials performed for this study suggest that, when applied at TxDOT-recommended application rates, granular road salt and salt brine are equally or more effective at clearing snow from an asphalt pavement surface compared to the corresponding granular and liquid MeltDown® products. Laboratory tests indicate MeltDown Apex™ is more effective than salt brine at colder temperatures (below 15°F), but such temperatures rarely prevail for any extended period in most parts of Texas. MeltDown Apex™ also yields a slicker pavement surface at temperatures above freezing. Given that MeltDown® products perform similarly but are purchased at unit costs roughly 5 to 10 times more than their road salt counterparts, the continued usage of MeltDown® products on the basis of snow clearing *cost effectiveness* is not supported. These recommendations are encouraged.

1. Districts in the southern and central regions of the State that historically have used MeltDown® products for snow and ice control will likely be able to replicate the snow clearing experience using road salt products applied at the manufacturer's recommended rates.
   a. Existing inventories of MeltDown® products should be used. Care should be used when anti-icing with MeltDown Apex™ at temperatures above freezing in order to avoid creating a slippery pavement surface.
   b. Material supply, handling, and storage for replacement road salt products should be pursued.

2. Districts in the northern regions of the State should evaluate climate data for their area to determine whether winter temperatures reasonably justify the use of MeltDown Apex™.

a. Existing inventories of MeltDown® products should be used. Care should be used when anti-icing with MeltDown Apex™ at temperatures above freezing in order to avoid creating a slippery pavement surface.
b. Material supply, handling, and storage for replacement road salt products should be pursued as appropriate.

3. Districts in all regions of the State that are considering a change from MeltDown® products (inhibited) to road salt products (non-inhibited) should evaluate their equipment and infrastructure for susceptibility to potential corrosion impacts.
   a. Consider using approved corrosion inhibitors to modify non-inhibited road salt products.
   b. Identify and assess snow and ice control plans to identify older infrastructure that was not designed or constructed for corrosion-resistance, such as using epoxy-coated reinforcing, and which will be more susceptible to corrosion.
   c. Identify and assess snow and ice maintenance equipment relative to corrosion impacts.
   d. Implement routine maintenance practices for cleaning both infrastructure and equipment to remove, dilute, or otherwise normalize the effects of chloride salts with special attention to metal elements directly exposed to the chemical.

<u>Recommendation 6</u>. Cost-Saving Strategies for Winter Maintenance Operations.

The cost analyses for this study explored opportunities to improve efficiency and outcomes for snow and ice control materials. Recommendations include the following.

1. Standardize the selection of snow and ice control materials.
   a. Develop a uniform standard for selecting snow and ice control materials.
   b. Leverage TxDOT's purchasing power to lower prices.

2. Improve efficiency of snow and ice control activities.
   a. Reduce snow and ice Operation to Material (O-M) ratios.
   b. Capture data on post-storm cleanup and anti-icing operations.
   c. Explore options to manage risk for low-frequency, high-impact events.

3. Apply performance-based models for snow and ice control.
   a. Existing cost analyses focus on input factors.
   b. Consider transitioning from an input-based level of service (LOS) model to a performance-based LOS model.

8.4 Limitations/ Topics for Further Study

The research described herein was conducted during the period, January 2012 through August 2015. The research methods, practices, and procedures associated with the various tasks are described, and limitations are identified.

With the exception of the field trials and associated laboratory test program, most research tasks were performed in 2012-13. Principal authors for the various tasks were

- Lawson - Task 1… chemical application and effectiveness,
- Rainwater - Task 2… natural brines,
- Senadheera - Task 3… infrastructure durability impacts,
- Morse, Yan - Task 4… environmental impact and regulations,
- Rainwater, Lawson, Surles, Jackson - Task 5… field trials and laboratory testing,
- Liang - Task 6… comprehensive cost analysis, and
- Jackson and Team - Task 7… production of deliverables.

It is recognized that all of the several topics comprising this study could be explored in further detail, more tests could be run, more data could be obtained, and more analyses could be performed. However, given our understanding of TxDOT's need and motivation for the study, the present effort appears to have reasonably addressed most of their research questions.

The one topic that remains "open" is infrastructure durability impacts. While this study did evaluate atmospheric corrosion and chloride diffusion for selected chemicals, and we did survey the literature on durability impacts, the findings were mixed. Further, it was outside the scope of this study to delve into corrosion inhibitors. Given that one of the findings of the study supports migration toward increased usage of historically non-inhibited chemicals (road salt) for TxDOT applications, the need for further study on corrosion inhibitors relative to winter roadway maintenance has become more salient.

REFERENCES

1. AASHTO. (2003). "Anti-Icing/Road Weather Information Systems Computer Based Training." Washington DC: American Association of State Highway and Transportation Officials. AASHTO Snow and Ice Pooled Fund Cooperative Program (SICOP).

2. Blackburn, R.R., K.M. Bauer, D.E. Amsler, S.E. Boselly, A.D. McElroy, (2004). *NCHRP Report 526, Snow and Ice Control: Guidelines for Materials and Methods.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

3. Chappelow, Cecil C., et al. *Handbook of test methods for evaluating chemical deicers.* No. PB-93-132538/XAB. Midwest Research Inst., Kansas City, MO (United States), 1992.

4. National Climatic Data Center (2015). National Centers for Environmental Information. National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/

5. Rowe, G. and Wright G. (2001). “Expert Opinions in Forecasting: The Role of the Delphi Technique”. In J. Armstrong (Ed.) *Principles of Forecasting (*pp. 125-144). Boston: Kluwer Academic.

APPENDIX A

Winter 2013/14

Storm 2-3

03-02-2014

APPENDIX A

Storm 2-3

WEATHER DATA

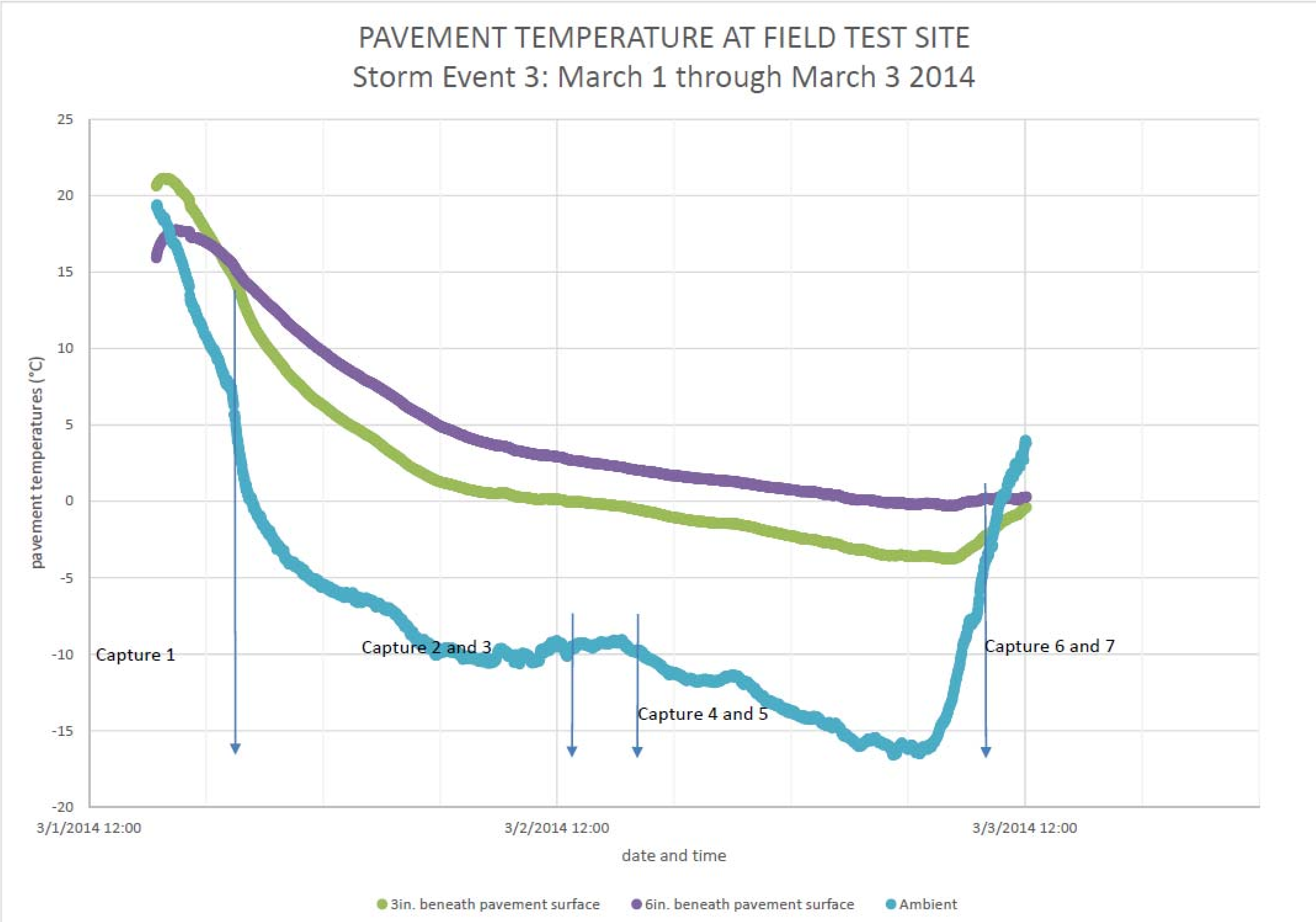


Figure A.1. Pavement Temperature at Field Test Site, Storm Event 2-3, March 1-3, 2014

Table A.1 Storm 2-3, Hourly Observations, 1 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01	0053	11	CLR	10.00		44	6.7	36	2.4	26	-3.3	49	13	130		26.20			29.80	AA		29.89
01	0153	11	CLR	10.00		43	6.1	36	2.3	27	-2.8	53	13	130		26.20			29.81	AA		29.90
01	0253	11	CLR	10.00		41	5.0	36	2.1	29	-1.7	62	11	120		26.21			29.83	AA		29.91
01	0353	11	CLR	10.00		39	3.9	36	1.9	31	-0.6	73	13	100		26.21			29.83	AA		29.91
01	0453	11	CLR	10.00		35	1.7	33	0.5	30	-1.1	82	11	100		26.21			29.84	AA		29.91
01	0553	11	CLR	5.00	BR	32	0.0	31	-0.4	30	-1.1	92	8	060		26.22			29.86	AA		29.92
01	0600	11	FEW002	4.00	BR	32	0.0	31	-0.4	30	-1.1	92	8	070		26.23			M	SP		29.93
01	0609	11	BKN002	0.25	BR	32	0.0	32	-0.2	31	-0.6	96	9	070		26.23			M	SP		29.93
01	0638	11	VV002	0.25	FG	32	0.0	32	0.0	32	0.0	100	8	110		26.24			M	SP		29.94
01	0653	11	VV002	0.25	FG	32	0.0	32	0.0	32	0.0	100	9	100		26.23			29.89	AA		29.93
01	0753	11	VV002	0.00	FG	32	0.0	32	0.0	32	0.0	100	8	120		26.24			29.91	AA		29.94
01	0853	11	VV002	0.00	FG	35	1.7	35	1.6	35	1.7	100	14	120		26.27			29.94	AA		29.97
01	0925	11	VV002	0.00	FG	37	2.8	37	2.5	36	2.2	96	13	110		26.27			M	SP		29.97
01	0953	11	OVC002	0.50	BR	38	3.3	38	3.0	37	2.8	96	17	140		26.25			29.92	AA		29.95
01	1005	11	OVC002	0.75	BR	38	3.3	38	3.0	37	2.8	96	16	130		26.24			M	SP		29.94
01	1015	11	OVC002	1.50	BR	38	3.3	38	3.0	37	2.8	96	15	140		26.24			M	SP		29.94
01	1018	11	OVC003	1.50	BR	39	3.9	38	3.3	37	2.8	93	15	130		26.24			M	SP		29.94
01	1034	11	BKN003	5.00	BR	41	5.0	39	3.9	37	2.8	86	14	120		26.24			M	SP		29.94
01	1041	11	SCT004	5.00	BR	42	5.6	40	4.5	38	3.3	86	14	140		26.24			M	SP		29.94
01	1053	11	CLR	6.00	HZ	47	8.3	42	5.6	37	2.8	68	16	140		26.24			29.90	AA		29.94
01	1153	11	CLR	10.00		55	12.8	46	7.6	36	2.2	49	10	160		26.23			29.87	AA		29.93
01	1253	11	CLR	10.00		58	14.4	47	8.1	35	1.7	42	7	180		26.22			29.86	AA		29.92
01	1353	11	CLR	10.00		59	15.0	48	8.6	36	2.2	42	15	120		26.16			29.79	AA		29.85
01	1453	11	CLR	10.00		59	15.0	48	8.8	37	2.8	44	15	110		26.15			29.78	AA		29.84
01	1553	11	CLR	9.00		55	12.8	46	7.8	37	2.8	51	20	100		26.15			29.80	AA		29.84
01	1653	11	CLR	7.00		49	9.4	43	6.0	36	2.2	61	20	060		26.19			29.86	AA		29.88
01	1753	11	FEW120	9.00		38	3.3	33	0.6	26	-3.3	62	20	050		26.21			29.93	AA		29.91
01	1843	11	SCT008 OVC110	5.00	UP BR	28	-2.2	27	-3.0	24	-4.4	85	23	020	31	26.30			M	SP		30.01
01	1850	11	BKN006 OVC110	1.00	BR	27	-3.0	26	-3.5	23	-5.0	85	26	020	33	26.30			M	SP		30.01
01	1851	11	FEW003 BKN006 OVC110	1.00	BR	26	-3.3	25	-3.9	23	-5.0	88	25	020	33	26.31			30.06	AA	T	30.02
01	1856	11	BKN004 OVC110	0.25	BR	26	-3.3	25	-3.9	23	-5.0	88	26	020	33	26.31			M	SP		30.02
01	1909	11	BKN002 OVC007	0.50	BR	24	-4.4	24	-4.6	23	-5.0	96	23	020		26.31			M	SP		30.02
01	1936	11	OVC002	0.75	BR	23	-5.0	22	-5.3	21	-6.1	92	25	010	31	26.33			M	SP		30.04
01	1951	11	OVC002	2.50	BR	21	-6.0	20	-6.4	19	-7.0	92	22	010		26.33			M	SP		30.04
01	1953	11	OVC002	2.00	BR	22	-5.6	21	-5.9	20	-6.7	92	22	010		26.33			30.10	AA		30.04
01	2000	11	OVC002	1.50	BR	22	-5.6	21	-5.9	20	-6.7	92	23	020		26.33			M	SP		30.04
01	2010	11	OVC002	0.50	BR	21	-6.1	21	-6.2	20	-6.7	96	23	020		26.34			M	SP		30.05
01	2034	11	VV002	0.75	BR	20	-6.7	20	-6.8	19	-7.2	96	21	010		26.33			M	SP		30.04
01	2053	11	OVC002	0.75	BR	20	-6.7	19	-7.0	18	-7.8	92	20	360		26.37			30.14	AA		30.08
01	2106	11	OVC002	1.00	BR	19	-7.2	18	-7.5	17	-8.3	92	21	030		26.34			M	SP		30.05

Table A.1 Storm 2-3, Hourly Observations, 1 MAR 2014, National Climatic Data Center, continued

01	2129	11	OVC002	2.00	BR	19	-7.2	18	-7.5	17	-8.3	92	18	020		26.37			M	SP		30.08
01	2151	11	OVC003	1.00	BR	18	-8.0	17	-8.1	16	-9.0	92	18	020		26.37			M	SP		30.08
01	2153	11	OVC003	2.00	BR	18	-7.8	17	-8.1	16	-8.9	92	21	020		26.37			30.13	AA		30.08
01	2224	11	OVC003	7.00		17	-8.3	16	-8.6	15	-9.4	92	18	360		26.39			M	SP		30.11
01	2237	11	OVC004	8.00		16	-8.9	15	-9.2	14	-10.0	92	18	010		26.39			M	SP		30.10
01	2251	11	OVC005	7.00		16	-9.0	15	-9.5	12	-11.0	84	17	020		26.37			M	SP		30.08
01	2253	11	OVC005	7.00		16	-8.9	15	-9.3	13	-10.6	88	16	020		26.38			30.12	AA		30.09
01	2324	11	OVC006	9.00		15	-9.4	14	-9.7	13	-10.6	92	15	020		26.37			M	SP		30.08
01	2353	11	BKN008 OVC015	10.00		15	-9.4	14	-10.0	11	-11.7	84	14	010		26.40			30.14	AA		30.12

Dynamically generated Thu May 01 10:27:08 EDT 2014 via *http://cdo.ncdc.noaa.gov/qclcd/OCLCD*

Table A.2 Storm 2-3, Hourly Remarks, 1 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
01	0053	AO2 SLP092 T00671033
01	0153	AO2 SLP096 T00611028
01	0253	AO2 SLP100 T00501017 51013
01	0353	AO2 SLP100 T00391006
01	0453	AO2 SLP104 T00171011
01	0553	AO2 SLP113 T00001011 10072 20000 53003 (XX)
01	0600	AO2 T00001011 (XX)EQDD10+000000ADE726
01	0609	AO2 SFC VIS 2 1/2 T00001006 (XX)
01	0638	AO2 T00000000 (XX)
01	0653	AO2 TWR VIS 1/4 SLP121 T00000000 (XX)
01	0753	AO2 SLP130 T00000000 (XX)
01	0853	AO2 SLP138 T00170017 53013 (XX)
01	0925	AO2 SFC VIS 1/4 T00280022 (XX)
01	0953	AO2 SFC VIS 1 SLP131 T00330028 (XX)
01	1005	AO2 SFC VIS 2 VIS 1 3/4V2 1/2 T00330028 (XX)
01	1015	AO2 SFC VIS 3 T00330028 (XX)
01	1018	AO2 SFC VIS 3 T00390028 (XX)
01	1034	AO2 CIG 003V006 T00500028 (XX)
01	1041	AO2 T00560033 (XX)EQDD10+000000ADE726
01	1053	AO2 SLP125 T00830028 (XX)
01	1153	AO2 SLP116 T01280022 10128 20000 57013 (XX)
01	1253	AO2 SLP111 T01440017 (XX)
01	1353	AO2 SLP089 T01500022 (XX)
01	1453	AO2 SLP086 T01500028 57026
01	1553	AO2 SLP091 T01280028 (XX)
01	1653	AO2 SLP113 T00940022 (XX)
01	1753	AO2 SLP134 T00331033 10161 20033 53022 (XX)EQDD10+000000ADE726
01	1843	AO2 PK WND 02027/0041 UPB30 PRESRR P0000 T10221044
01	1850	AO2 PK WND 02029/0049 SFC VIS 6 UPB30E44 CIG 003V010 P0000
01	1851	AO2 PK WND 02029/0049 SFC VIS 5 UPB30E44 CIG 006V010 PRESRR SLP180 P0000 T10331050
01	1856	AO2 PK WND 02029/0054 SFC VIS 4 T10331050
01	1909	AO2 PK WND 02029/0054 SFC VIS 3 T10441050
01	1936	AO2 PK WND 02029/0054 SFC VIS 1 3/4 I1000 T10501061
01	1951	AO2 PK WND 02029/0054 I1000 FIBI (XX)
01	1953	AO2 PK WND 02029/0054 SFC VIS 3 SLP192 I1000 T10561067
01	2000	AO2 SFC VIS 1 3/4 T10561067
01	2010	AO2 SFC VIS 1 I1000 T10611067
01	2034	AO2 I1001 T10671072
01	2053	AO2 SFC VIS 1 1/2 SLP205 60000 I1002 I3002 T10671078 51051
01	2106	AO2 SFC VIS 1 1/4 T10721083
01	2129	AO2 I1000 T10721083
01	2151	AO2 SFC VIS 2 1/2 I1001
01	2153	AO2 SFC VIS 3 SLP203 I1001 T10781089
01	2224	AO2 CIG 002V006 PRESRR T10831094

Table A.2 Storm 2-3, Hourly Remarks, 1 MAR 2014, National Climatic Data Center, continued

01	2237	AO2 CIG 002V007 T10891100
01	2251	AO2 FIBI (XX)
01	2253	AO2 SLP200 T10891106
01	2324	AO2 T10941106
01	2353	AO2 CIG 007V012 SLP205 60000 I6003 T10941117 10033 21094 401611094 53011

Dynamically generated Thu May 01 10:27:45 EDT 2014 via http://cdo.ncdc.noaa.gov/qclcd/QCLCD

Table A.3 Storm 2-3, Hourly Precipitation, 1 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
01													01							T						01

Table A.4 Storm 2-3, Hourly Observations, 2 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
02	0021	11	OVC010	10.00		15	-9.4	14	-10.0	11	-11.7	84	16	010		26.40			M	SP		30.12
02	0044	11	SCT010 BKN016 BKN120	9.00		15	-9.4	14	-10.2	10	-12.2	80	16	010	22	26.39			M	SP		30.11
02	0051	11	FEW011 SCT016 BKN120	10.00		16	-9.0	14	-9.8	10	-12.0	77	15	020		26.39			M	SP		30.11
02	0053	11	SCT016 BKN120	10.00		15	-9.4	14	-10.2	10	-12.2	80	13	010		26.40			30.13	AA		30.12
02	0104	11	FEW011 BKN016	10.00		15	-9.4	14	-10.2	10	-12.2	80	14	020		26.39			M	SP		30.11
02	0113	11	FEW011 SCT016 BKN120	10.00		15	-9.4	14	-10.2	10	-12.2	80	16	020		26.38			M	SP		30.09
02	0153	11	SCT055 BKN070 OVC090	9.00	UP	15	-9.4	14	-10.2	10	-12.2	80	24	360	29	26.38			30.11	AA	T	30.09
02	0203	11	SCT009 BKN045 OVC070	8.00	UP	14	-10.0	13	-10.6	10	-12.2	84	25	360		26.39			M	SP		30.10
02	0212	11	BKN009 OVC048	8.00		15	-9.4	14	-10.2	10	-12.2	80	25	350	31	26.38			M	SP		30.09
02	0250	11	OVC010	6.00	-SN BR	12	-11.0	11	-11.5	9	-13.0	88	20	350		26.40			M	SP		30.12
02	0253	11	OVC010	5.00	-SN BR	13	-10.6	12	-11.1	9	-12.8	84	21	350		26.40			30.13	AA	T	30.12
02	0317	11	OVC010	2.50	-SN	13	-10.6	12	-11.2	8	-13.3	80	20	350		26.39			M	SP		30.11
02	0326	11	OVC010	5.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	22	360	28	26.40			M	SP		30.12
02	0345	11	OVC008	5.00	-SN	12	-11.1	11	-11.8	7	-13.9	80	22	360		26.39			M	SP		30.10
02	0353	11	BKN008 OVC011	4.00	-SN	12	-11.1	11	-11.8	7	-13.9	80	17	360		26.40			30.15	AA	T	30.12
02	0451	11	OVC010	6.00	-SN	10	-12.0	9	-12.8	5	-15.0	80	15	030	24	26.40			M	SP		30.12
02	0453	11	OVC010	6.00	-SN	10	-12.2	9	-12.8	5	-15.0	80	17	030	24	26.40			30.16	AA	T	30.12
02	0520	11	BKN008 OVC012	7.00	-SN	9	-12.8	8	-13.4	4	-15.6	80	20	030		26.40			M	SP		30.12
02	0553	11	OVC013	8.00		9	-12.8	8	-13.5	3	-16.1	76	14	360	23	26.43			30.23	AA	T	30.15
02	0603	11	OVC015	10.00		9	-12.8	8	-13.5	3	-16.1	76	18	020		26.44			M	SP		30.16
02	0653	11	BKN017 OVC110	10.00		9	-12.8	8	-13.5	3	-16.1	76	18	360	25	26.44			30.26	AA		30.16
02	0720	11	FEW009 BKN100 OVC110	10.00		8	-13.3	7	-13.9	3	-16.1	80	16	020		26.43			M	SP		30.15
02	0751	11	BKN011	8.00		9	-13.0	8	-13.5	3	-16.0	76	16	020		26.41			M	SP		30.13
02	0753	11	BKN011	7.00		8	-13.3	7	-13.9	3	-16.1	80	18	010		26.41			30.25	AA		30.13
02	0851	11	FEW008 BKN015 OVC085	10.00		9	-13.0	7	-13.7	1	-17.0	70	17	350		26.48			M	SP		30.21
02	0853	11	BKN015 BKN085	10.00		9	-12.8	7	-13.6	2	-16.7	73	18	350		26.48			30.33	AA		30.21
02	0918	11	OVC015	3.00	BLSN	8	-13.3	7	-14.0	2	-16.7	76	16	360		26.49			M	SP		30.22
02	0924	11	OVC015	1.75	-SN	8	-13.3	7	-14.0	2	-16.7	76	15	340		26.50			M	SP		30.23
02	0929	11	BKN011 OVC016	1.00	-SN	8	-13.3	7	-14.0	2	-16.7	76	15	350		26.50			M	SP		30.23
02	0935	11	BKN009 OVC016	0.75	-SN	8	-13.3	7	-13.9	3	-16.1	80	16	360		26.49			M	SP		30.22
02	0951	11	VV010	0.75	-SN	9	-13.0	8	-13.5	3	-16.0	76	17	010		26.47			M	SP		30.20
02	0953	11	VV010	0.75	-SN BR	8	-13.3	7	-13.8	4	-15.6	84	16	010		26.47			30.34	AA	0.04	30.20
02	1029	11	BKN008 OVC015	0.75	-SN	10	-12.2	9	-13.0	4	-15.6	76	16	010		26.47			M	SP		30.20
02	1036	11	SCT008 OVC015	0.75	HZ	10	-12.2	9	-13.0	4	-15.6	76	15	020		26.46			M	SP		30.18
02	1053	11	FEW008 OVC017	2.00	HZ	10	-12.2	8	-13.1	3	-16.1	73	17	010		26.46			30.32	AA	0.01	30.18
02	1136	11	BKN016 OVC060	3.00	UP	10	-12.2	9	-13.0	4	-15.6	76	18	010		26.46			M	SP		30.19
02	1153	11	OVC016	2.50	-SN	10	-12.2	8	-13.1	3	-16.1	73	21	010		26.46			30.32	AA	T	30.18
02	1223	11	OVC016	1.50	-SN	9	-12.8	8	-13.5	3	-16.1	76	21	010		26.44			M	SP		30.16
02	1227	11	OVC015	0.75	-SN	9	-12.8	8	-13.5	3	-16.1	76	16	350		26.48			M	SP		30.21
02	1248	11	BKN012 OVC017	1.00	-SN	9	-13.0	8	-13.5	3	-16.0	76	13	360		26.48			M	SP		30.21

Table A.4 Storm 2-3, Hourly Observations, 2 MAR 2014, National Climatic Data Center, continued

02	1251	11	BKN012 OVC017	0.75	-SN	9	-13.0	8	-13.5	3	-16.0	76	17	360		26.47			M	SP		30.20
02	1253	11	BKN012 OVC019	1.00	-SN	8	-13.3	7	-13.9	3	-16.1	80	18	360		26.46			30.33	AA	0.02	30.19
02	1304	11	SCT010 OVC019	1.00	HZ	9	-12.8	8	-13.4	4	-15.6	80	17	360		26.45			M	SP		30.17
02	1309	11	BKN010 OVC019	0.75	-SN	9	-12.8	8	-13.4	4	-15.6	80	17	360		26.46			M	SP		30.19
02	1314	11	SCT010 OVC019	1.00	-SN	9	-12.8	8	-13.4	4	-15.6	80	20	360		26.46			M	SP		30.18
02	1335	11	FEW009 OVC021	1.00	HZ	9	-12.8	8	-13.5	3	-16.1	76	20	350	26	26.46			M	SP		30.18
02	1349	11	FEW011 OVC021	5.00	HZ	9	-13.0	8	-13.5	3	-16.0	76	21	360	29	26.45			M	SP		30.17
02	1350	11	FEW013 OVC021	5.00	HZ	9	-12.8	8	-13.5	3	-16.1	76	20	360	29	26.45			30.31	AA	T	30.17
02	1453	11	FEW014 OVC021	4.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	23	360		26.46			30.33	AA	T	30.18
02	1553	11	OVC019	7.00		9	-12.8	7	-13.6	2	-16.7	73	17	350		26.46			30.34	AA		30.19
02	1653	11	OVC019	6.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	18	350		26.49			30.37	AA		30.22
02	1753	11	OVC018	7.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	17	360		26.49			30.38	AA		30.22
02	1841	11	OVC019	2.50	HZ	7	-13.9	6	-14.6	1	-17.2	76	16	360		26.50			M	SP		30.23
02	1853	11	OVC021	2.50	HZ	7	-13.9	6	-14.6	1	-17.2	76	15	010		26.50			30.40	AA	T	30.23
02	1900	11	OVC021	10.00	HZ	7	-13.9	6	-14.4	2	-16.7	80	16	360		26.51			M	SP		30.24
02	1925	11	FEW009 OVC026	6.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	15	360		26.52			M	SP		30.25
02	1953	11	OVC028	10.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	14	350		26.54			30.43	AA		30.27
02	2025	11	OVC030	10.00	HZ	8	-13.3	7	-14.0	2	-16.7	76	15	360		26.55			M	SP		30.28
02	2051	11	BKN029 OVC034	10.00	HZ	9	-13.0	8	-13.5	3	-16.0	76	16	350		26.55			M	SP		30.28
02	2053	11	BKN029 OVC034	10.00	HZ	8	-13.3	7	-13.9	3	-16.1	80	20	350		26.55			30.44	AA		30.28
02	2111	11	OVC030	10.00		8	-13.3	7	-14.0	2	-16.7	76	14	350		26.57			M	SP		30.30
02	2127	11	SCT007 OVC030	8.00		7	-13.9	6	-14.4	2	-16.7	80	14	360		26.57			M	SP		30.30
02	2136	11	BKN007 OVC030	9.00		7	-13.9	6	-14.4	2	-16.7	80	14	350		26.57			M	SP		30.31
02	2153	11	SCT007	10.00		6	-14.4	5	-14.9	2	-16.7	83	14	350		26.57			30.48	AA		30.31
02	2253	11	CLR	10.00		6	-14.4	5	-15.0	1	-17.2	80	10	350		26.58			30.49	AA		30.32
02	2353	11	CLR	10.00		5	-15.0	4	-15.4	1	-17.2	83	10	360		26.57			30.48	AA		30.31

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Table A.5 Storm 2-3, Hourly Remarks, 2 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
02	0021	AO2 T10941117
02	0044	AO2 T10941122
02	0051	AO2 FIBI
02	0053	AO2 SLP203 T10941122
02	0104	AO2 T10941122
02	0113	AO2 PRESFR T10941122
02	0153	AO2 UPB49 SLP195 P0000 T10941122
02	0203	AO2 PK WND 35026/0800 P0000 T11001122
02	0212	AO2 PK WND 36027/0809 UPE05 P0000 T10941122
02	0250	AO2 PK WND 36028/0830 UPE05SNB17 P0000
02	0253	AO2 PK WND 36028/0830 UPE05SNB17 SLP204 P0000 60000 T11061128 53000
02	0317	AO2 CIG 006V013 P0000 T11061133
02	0326	AO2 P0000 T11111133
02	0345	AO2 P0000 T11111139
02	0353	AO2 SLP209 P0000 T11111139
02	0451	AO2 PRESRR P0000 FIBI
02	0453	AO2 SLP213 P0000 T11221150
02	0520	AO2 P0000 T11281156
02	0553	AO2 SNE23 PRESRR SLP236 P0000 60000 T11281161 11094 21128 53010 (XX)
02	0603	AO2 T11281161 (XX)
02	0653	AO2 SLP247 T11281161 (XX)
02	0720	AO2 T11331161 (XX)
02	0751	AO2 FIBI (XX)
02	0753	AO2 SLP244 T11331161 (XX)
02	0851	AO2 FIBI (XX)
02	0853	AO2 SLP272 T11281167 53016 (XX)
02	0918	AO2 UPB05E13 P0001 T11331167 (XX)
02	0924	AO2 UPB05E13SNB19 P0001 T11331167 (XX)
02	0929	AO2 UPB05E13SNB19 P0002 T11331167 (XX)
02	0935	AO2 UPB05E13SNB19 P0002 T11331161 (XX)
02	0951	AO2 UPB05E13SNB19 P0004 FIBI (XX)
02	0953	AO2 UPB05E13SNB19 SLP273 P0004 T11331156 (XX)
02	1029	AO2 SFC VIS 1 1/4 P0001 T11221156 (XX)
02	1036	AO2 SFC VIS 4 SNE34 P0001 T11221156 (XX)
02	1053	AO2 SFC VIS 6 SNE34B39E48 SLP266 P0001 T11221161 (XX)
02	1136	AO2 SFC VIS 3 UPB20 P0000 T11221156 (XX)
02	1153	AO2 TWR VIS 3 VIS 1 1/2V4 UPB20E43SNB43 SLP266 P0000 60005 T11221161 11117 21133 55008 (XX)
02	1223	AO2 TWR VIS 2 UPB05E13SNE05B13 P0001 T11281161 (XX)
02	1227	AO2 SFC VIS 1 1/2 UPB05E13SNE05B13 PRESRR P0001 T11281161 (XX)
02	1248	AO2 UPB05E13SNE05B13 P0001 (XX)
02	1251	AO2 TWR VIS 1 UPB05E13SNE05B13 P0001 FIBI (XX)
02	1253	AO2 UPB05E13SNE05B13 SLP270 P0002 T11331161 (XX)
02	1304	AO2 SFC VIS 1 1/4 SNE03 P0000 T11281156 (XX)
02	1309	AO2 TWR VIS 1 SNE03B06 P0000 T11281156 (XX)

Table A.5 Storm 2-3, Hourly Remarks, 2 MAR 2014, National Climatic Data Center, continued

02	1314	AO2 SNE03B06 P0000 T11281156 (XX)
02	1335	AO2 SFC VIS 3 SNE03B06E32 P0000 T11281161 (XX)
02	1349	AO2 SNE03B06E32 P0000 (XX)
02	1350	AO2 SNE03B06E32 SLP265 P0000 T11281161 (XX)
02	1453	AO2 SNB16E26 SLP270 P0000 60002 T11331167 55001 (XX)
02	1553	AO2 SLP274 T11281167 (XX)
02	1653	AO2 SLP286 T11331167 (XX)
02	1753	AO2 SLP287 60002 T11331167 11122 21139 51012 (XX)
02	1841	AO2 SFC VIS 6 SNB17E35 P0000 T11391172
02	1853	AO2 SFC VIS 6 SNB17E35 SLP294 P0000 T11391172
02	1900	AO2 T11391167
02	1925	AO2 T11331167
02	1953	AO2 SLP305 T11331167
02	2025	AO2 T11331167
02	2051	AO2 FIBI (XX)
02	2053	AO2 SLP308 60000 T11331161 52019
02	2111	AO2 T11331167
02	2127	AO2 T11391167
02	2136	AO2 T11391167
02	2153	AO2 SLP321 T11441167EQDD10+000000ADE726
02	2253	AO2 SLP324 T11441172
02	2353	AO2 SLP321 60000 T11501172 11133 21150 410941150 50010

Dynamically generated Thu May 01 10:30:09 EDT 2014 via http://cdo.ncdc.noaa.gov/qclcd/OCLCD

Table A.6 Storm 2-3, Hourly Precipitation, 2 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
02		T	T	T	T	T				0.04	0.01	T	02	0.02	T	T				T						02

Table A.7 Storm 2-3, Hourly Observations, 3 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
03	0053	11	CLR	10.00		4	-15.6	3	-15.8	1	-17.2	87	11	010		26.57			30.47	AA		30.30
03	0153	11	CLR	10.00		5	-15.0	4	-15.4	1	-17.2	83	6	340		26.57			30.47	AA		30.30
03	0253	11	CLR	10.00		5	-15.0	4	-15.4	1	-17.2	83	9	350		26.57			30.47	AA		30.30
03	0351	11	BKN008	6.00	BR	5	-15.0	4	-15.4	1	-17.0	83	8	310		26.57			M	SP		30.30
03	0353	11	BKN008	5.00	BR	5	-15.0	4	-15.4	1	-17.2	83	7	320		26.56			30.46	AA		30.29
03	0439	11	SCT006	10.00		4	-15.6	3	-15.8	1	-17.2	87	6	340		26.56			M	SP		30.29
03	0453	11	CLR	10.00		4	-15.6	3	-16.0	-0	-17.8	83	7	350		26.56			30.47	AA		30.29
03	0527	11	SCT007	8.00		4	-15.6	3	-15.8	1	-17.2	87	7	280		26.57			M	SP		30.30
03	0535	11	BKN007	9.00		4	-15.6	3	-15.8	1	-17.2	87	7	290		26.57			M	SP		30.30
03	0549	11	SCT007	10.00		3	-16.0	3	-16.3	1	-17.0	91	7	310		26.57			M	SP		30.30
03	0553	11	SCT007	10.00		4	-15.6	3	-15.8	1	-17.2	87	6	320		26.57			30.47	AA		30.30
03	0653	11	FEW004	10.00		4	-15.6	3	-16.0	-0	-17.8	83	5	290		26.57			30.47	AA		30.30
03	0753	11	CLR	10.00		7	-13.9	6	-14.4	2	-16.7	80	3	330		26.55			30.45	AA		30.28
03	0853	11	CLR	10.00		13	-10.6	11	-11.4	7	-13.9	77	8	250		26.60			30.49	AA		30.34
03	0953	11	CLR	10.00		17	-8.3	14	-9.8	7	-13.9	65	7	240		26.57			30.45	AA		30.31
03	1053	11	CLR	10.00		24	-4.4	20	-6.6	11	-11.7	58	6	150		26.53			30.39	AA		30.26
03	1153	11	CLR	10.00		28	-2.2	24	-4.6	15	-9.4	58	6	180		26.51			30.35	AA		30.24
03	1253	11	CLR	10.00		35	1.7	30	-1.2	21	-6.1	57	5	VR		26.47			30.30	AA		30.20
03	1353	11	CLR	10.00		39	3.9	32	0.2	22	-5.6	51	14	190		26.46			30.27	AA		30.18
03	1453	11	CLR	10.00		42	5.6	34	1.3	23	-5.0	47	16	180	24	26.44			30.24	AA		30.16
03	1553	11	CLR	10.00		42	5.6	35	1.5	24	-4.4	49	14	210	22	26.42			30.21	AA		30.14
03	1653	11	CLR	10.00		44	6.7	37	2.6	27	-2.8	51	11	180		26.39			30.18	AA		30.11
03	1753	11	CLR	10.00		42	5.6	36	2.2	28	-2.2	58	15	170		26.39			30.18	AA		30.11
03	1853	11	CLR	10.00		39	3.9	34	0.9	26	-3.3	60	17	170		26.39			30.18	AA		30.10
03	1953	11	CLR	10.00		33	0.6	27	-2.5	17	-8.3	52	17	160		26.39			30.19	AA		30.10
03	2053	11	CLR	10.00		31	-0.6	26	-3.2	17	-8.3	56	14	150		26.39			30.18	AA		30.10
03	2153	11	CLR	10.00		29	-1.7	25	-3.9	17	-8.3	61	15	170		26.39			30.18	AA		30.10
03	2253	11	CLR	10.00		29	-1.7	25	-3.7	18	-7.8	63	14	180		26.38			30.14	AA		30.09
03	2353	11	CLR	10.00		29	-1.7	26	-3.4	20	-6.7	69	15	200		26.36			30.11	AA		30.07

Dynamically generated Thu May 01 10:31:12 EDT 2014 via http://cdo.ncdc.noaa.gov/qclcd/QCLCD

Table A.8 Storm 2-3, Hourly Remarks, 3 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
03	0053	AO2 SLP319 T11561172
03	0153	AO2 SLP318 T11501172
03	0253	AO2 SLP319 T11501172 55004
03	0351	AO2 CIG 005V010
03	0353	AO2 CIG 005V010 SLP316 T11501172
03	0439	AO2 T11561172EQDD10+000000ADE726
03	0453	AO2 SLP317 T11561178
03	0527	AO2 T11561172EQDD10+000000ADE726
03	0535	AO2 T11561172
03	0549	AO2EQDD10+000000ADE726
03	0553	AO2 SLP319 70007 T11561172 11150 21161 53001 (XX)EQDD10+000000ADE726
03	0653	AO2 SLP319 T11561178 (XX)EQDD10+000000ADE726
03	0753	AO2 SLP311 T11391167 (XX)
03	0853	AO2 SLP324 T11061139 53013 (XX)
03	0953	AO2 SLP311 T10831139 (XX)
03	1053	AO2 SLP290 T10441117 (XX)
03	1153	AO2 SLP277 T10221094 11022 21156 56031 (XX)
03	1253	AO2 SLP260 T00171061 (XX)
03	1353	AO2 SLP249 T00391056 FIBI (XX)
03	1453	AO2 SLP240 T00561050 56023 (XX)
03	1553	AO2 SLP231 T00561044 (XX)
03	1653	AO2 SLP221 T00671028 (XX)
03	1753	AO2 SLP221 T00561022 10067 21022 56017 (XX)
03	1853	AO2 SLP221 T00391033
03	1953	AO2 SLP225 T00061083
03	2053	AO2 SLP219 T10061083 58003
03	2153	AO2 SLP220 T10171083
03	2253	AO2 SLP208 T10171078
03	2353	AO2 SLP198 T10171067 10056 21022 400671161 58008

Dynamically generated Thu May 01 10:31:48 EDT 2014 via http://cdo.ncdc.noaa.gov/qclcd/QCLCD

Table A.9 Storm 2-3, Hourly Precipitation, 3 MAR 2014, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(03/2014)

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
03													03													03

Table A.10 Storm 2-3, Hourly Observations, MAR 1-3 2014, WTAMU SchoolNET

"DATE"	"TIME" ... HH:MM	AMB TEMP (deg F)	REL HUM (%)	DEW POINT (deg F)	HEAT INDEX (deg F)	BAR PRES in Hg	PRES TREND	RAIN FALL (IN)	RF RATE IN/HR	-- -- --	WIND SPEED (MPH)	WIND DIR	PEAK WIND (MPH)	PEAK DIR	AVG WIND (MPH)	AVG DIR	WIND CHILL (deg F)	INSIDE TEMP (deg F)	INSIDE HUMIDITY (%)
"03/01/2014"	"00:00"	52.1	32.0	22.9	52.1	30.04	0.06	0.00	0.00	--	0.0	12	0.0	12	0.5	12	52.1	70.1	43.0
"03/01/2014"	"01:00"	48.3	36.0	22.3	48.3	30.06	0.07	0.00	0.00	--	0.0	12	0.0	12	1.1	12	48.3	69.9	42.0
"03/01/2014"	"02:00"	47.4	37.0	22.2	47.4	30.08	0.08	0.00	0.00	--	0.0	12	0.0	12	0.0	12	47.4	69.9	42.0
"03/01/2014"	"03:00"	43.6	43.0	22.4	43.6	30.08	0.08	0.00	0.00	--	0.0	9	0.0	9	0.7	9	43.6	69.9	43.0
"03/01/2014"	"04:00"	42.5	48.0	24.1	42.5	30.08	0.07	0.00	0.00	--	0.0	9	0.0	9	0.0	9	42.5	70.1	42.0
"03/01/2014"	"05:00"	38.3	56.0	24.0	38.3	30.09	0.06	0.00	0.00	--	0.0	9	1.0	9	0.0	11	38.3	70.2	43.0
"03/01/2014"	"06:00"	37.5	68.0	28.0	37.5	30.12	0.06	0.00	0.00	--	0.0	3	0.0	3	0.0	3	37.5	70.1	43.0
"03/01/2014"	"07:00"	35.3	76.0	28.5	35.3	30.11	0.06	0.00	0.00	--	0.0	2	0.0	2	0.0	2	35.3	69.9	43.0
"03/01/2014"	"08:00"	35.5	82.0	30.5	35.5	30.15	0.06	0.00	0.00	--	0.0	3	0.0	3	0.0	3	35.5	69.9	44.0
"03/01/2014"	"09:00"	42.8	77.0	36.1	42.8	30.15	0.04	0.00	0.00	--	2.0	7	2.0	7	3.9	6	42.8	69.7	43.0
"03/01/2014"	"10:00"	47.5	67.0	37.2	47.5	30.15	0.04	0.00	0.00	--	2.0	6	7.0	6	3.6	6	47.5	69.9	43.0
"03/01/2014"	"11:00"	51.6	59.0	37.8	51.6	30.14	0.03	0.00	0.00	--	8.0	8	10.0	7	5.3	7	45.3	69.4	42.0
"03/01/2014"	"12:00"	59.5	44.0	37.5	59.5	30.12	0.05	0.00	0.00	--	5.0	8	9.0	7	6.3	8	58.4	69.7	42.0
"03/01/2014"	"13:00"	67.2	32.0	36.1	67.2	30.07	0.04	0.00	0.00	--	9.0	7	10.0	8	7.5	7	62.8	70.1	42.0
"03/01/2014"	"14:00"	63.9	39.0	38.3	63.9	30.02	0.01	0.00	0.00	--	16.0	5	16.0	5	5.4	5	54.4	69.9	43.0
"03/01/2014"	"15:00"	62.4	42.0	38.9	62.4	30.02	-0.01	0.00	0.00	--	11.0	6	9.0	7	5.3	6	55.4	69.0	44.0
"03/01/2014"	"16:00"	57.7	48.0	38.1	57.7	30.02	-0.02	0.00	0.00	--	5.0	7	15.0	5	8.5	6	56.5	69.7	43.0
"03/01/2014"	"17:00"	53.6	56.0	38.3	53.6	30.07	-0.07	0.00	0.00	--	4.0	6	11.0	4	7.2	5	53.6	69.9	44.0
"03/01/2014"	"18:00"	45.9	71.0	37.1	45.9	30.11	-0.08	0.00	0.00	--	13.0	4	21.0	4	9.8	5	32.6	70.2	43.0
"03/01/2014"	"19:00"	32.4	73.0	24.8	32.4	30.21	-0.06	0.00	0.00	--	21.0	1	23.0	2	17.7	2	7.0	70.1	43.0
"03/01/2014"	"20:00"	25.4	87.0	22.0	25.4	30.28	-0.04	0.00	0.00	--	12.0	1	19.0	16	14.5	2	7.3	69.7	42.0
"03/01/2014"	"21:00"	22.9	90.0	20.4	22.9	30.32	0.02	0.00	0.00	--	12.0	1	13.0	2	11.4	2	4.1	69.7	42.0
"03/01/2014"	"22:00"	21.1	91.0	18.8	21.1	30.36	0.09	0.00	0.00	--	11.0	2	14.0	1	12.6	1	3.5	69.7	42.0
"03/01/2014"	"23:00"	18.8	90.0	16.3	18.8	30.37	0.16	0.00	0.00	--	10.0	3	10.0	2	10.4	3	2.5	69.9	43.0
"03/02/2014"	"00:00"	18.7	89.0	16.0	18.7	30.40	0.21	0.00	0.00	--	12.0	2	14.0	1	9.1	2	-1.3	69.7	44.0
"03/02/2014"	"01:00"	17.0	84.0	13.0	17.0	30.41	0.22	0.00	0.00	--	10.0	2	20.0	3	10.6	2	0.3	70.1	42.0
"03/02/2014"	"02:00"	16.8	83.0	12.5	16.8	30.40	0.21	0.00	0.00	--	13.0	16	20.0	1	13.2	1	-5.4	69.6	43.0
"03/02/2014"	"03:00"	15.9	82.0	11.4	15.9	30.45	0.17	0.00	0.00	--	9.0	16	14.0	16	11.2	16	1.1	69.9	44.0
"03/02/2014"	"04:00"	14.4	82.0	9.9	14.4	30.44	0.10	0.00	0.00	--	13.0	2	13.0	2	12.1	2	-8.5	69.7	44.0
"03/02/2014"	"05:00"	12.2	80.0	7.2	12.2	30.46	0.09	0.00	0.00	--	12.0	3	14.0	2	13.0	3	-9.6	69.6	44.0
"03/02/2014"	"06:00"	11.6	82.0	7.2	11.6	30.49	0.09	0.00	0.00	--	12.0	2	17.0	2	12.1	2	-10.4	69.2	44.0
"03/02/2014"	"07:00"	10.6	78.0	5.1	10.6	30.53	0.06	0.00	0.00	--	12.0	2	14.0	3	11.2	2	-11.7	69.2	42.0
"03/02/2014"	"08:00"	10.5	80.0	5.5	10.5	30.52	0.06	0.00	0.00	--	8.0	2	13.0	1	10.0	2	-2.8	69.0	42.0
"03/02/2014"	"09:00"	11.4	80.0	6.4	11.4	30.61	0.06	0.00	0.00	--	9.0	16	10.0	1	7.2	1	-4.3	69.2	42.0
"03/02/2014"	"10:00"	10.5	85.0	6.9	10.5	30.61	0.12	0.00	0.00	--	12.0	16	13.0	2	8.0	1	-11.8	69.2	44.0
"03/02/2014"	"11:00"	12.1	84.0	8.2	12.1	30.60	0.07	0.00	0.00	--	10.0	3	13.0	2	9.4	2	-5.7	69.2	44.0
"03/02/2014"	"12:00"	10.8	81.0	6.1	10.8	30.55	0.10	0.00	0.00	--	17.0	3	21.0	3	13.4	3	-19.4	69.4	42.0
"03/02/2014"	"13:00"	11.0	82.0	6.6	11.0	30.61	0.09	0.00	0.00	--	9.0	1	10.0	16	10.5	1	-4.8	69.0	42.0
"03/02/2014"	"14:00"	10.4	78.0	4.9	10.4	30.63	0.06	0.00	0.00	--	11.0	16	18.0	16	10.8	16	-10.0	68.9	42.0
"03/02/2014"	"15:00"	9.9	78.0	4.4	9.9	30.65	0.07	0.00	0.00	--	12.0	1	15.0	1	11.2	1	-12.6	69.2	42.0
"03/02/2014"	"16:00"	9.8	81.0	5.1	9.8	30.69	0.09	0.00	0.00	--	12.0	15	13.0	1	10.5	1	-12.7	69.0	42.0
"03/02/2014"	"17:00"	9.4	82.0	5.0	9.4	30.72	0.04	0.00	0.00	--	11.0	16	16.0	16	11.2	1	-11.2	69.2	43.0
"03/02/2014"	"18:00"	9.2	81.0	4.5	9.2	30.75	0.06	0.00	0.00	--	13.0	1	15.0	1	11.3	1	-15.3	69.2	42.0
"03/02/2014"	"19:00"	9.5	82.0	5.1	9.5	30.78	0.11	0.00	0.00	--	5.0	2	9.0	1	9.9	1	5.9	69.0	43.0
"03/02/2014"	"20:00"	10.0	80.0	5.1	10.0	30.81	0.08	0.00	0.00	--	9.0	1	5.0	1	8.9	16	-6.0	69.0	41.0
"03/02/2014"	"21:00"	9.3	80.0	4.4	9.3	30.86	0.10	0.00	0.00	--	9.0	16	12.0	16	8.0	1	-6.8	69.2	42.0
"03/02/2014"	"22:00"	9.4	83.0	5.3	9.4	30.89	0.12	0.00	0.00	--	7.0	1	8.0	1	6.2	1	-1.2	69.4	41.0

Table A.10 Storm 2-3, Hourly Observations, MAR 1-3 2014, WTAMU SchoolNET, continued

"03/02/2014"	"23:00"	8.6	84.0	4.7	8.6	30.90	0.12	0.00	0.00	- -	5.0	1	8.0	1	5.3	1	5.0	68.9	44.0
"03/03/2014"	"00:00"	8.0	85.0	4.4	8.0	30.91	0.13	0.00	0.00	- -	3.0	1	3.0	1	5.1	1	8.0	68.7	42.0
"03/03/2014"	"01:00"	7.9	86.0	4.5	7.9	30.89	0.12	0.00	0.00	- -	2.0	1	5.0	1	4.2	1	7.9	69.2	41.0
"03/03/2014"	"02:00"	7.4	86.0	4.1	7.4	30.88	0.11	0.00	0.00	- -	3.0	1	6.0	1	4.0	1	7.4	69.2	42.0
"03/03/2014"	"03:00"	6.3	85.0	2.7	6.3	30.88	0.09	0.00	0.00	- -	1.0	15	5.0	15	2.6	15	6.3	69.0	42.0
"03/03/2014"	"04:00"	6.4	85.0	2.8	6.4	30.88	0.08	0.00	0.00	- -	3.0	14	4.0	14	3.6	14	6.4	69.2	41.0
"03/03/2014"	"05:00"	5.9	84.0	2.1	5.9	30.90	0.04	0.00	0.00	- -	1.0	14	2.0	14	2.0	14	5.9	69.2	42.0
"03/03/2014"	"06:00"	6.3	86.0	3.0	6.3	30.89	0.02	0.00	0.00	- -	3.0	16	2.0	16	4.8	16	6.3	68.9	42.0
"03/03/2014"	"07:00"	5.7	85.0	2.1	5.7	30.90	0.00	0.00	0.00	- -	1.0	15	3.0	15	1.8	15	5.7	68.7	43.0
"03/03/2014"	"08:00"	7.4	84.0	3.6	7.4	30.94	0.00	0.00	0.00	- -	6.0	12	8.0	12	5.8	12	-0.2	68.9	42.0
"03/03/2014"	"09:00"	14.0	80.0	9.0	14.0	30.92	0.01	0.00	0.00	- -	0.0	12	0.0	12	0.3	12	14.0	69.4	43.0
"03/03/2014"	"10:00"	19.9	69.0	11.4	19.9	30.89	0.01	0.00	0.00	- -	0.0	12	0.0	12	0.0	12	19.9	69.2	42.0
"03/03/2014"	"11:00"	27.2	61.0	15.6	27.2	30.85	0.00	0.00	0.00	- -	0.0	12	0.0	12	0.0	12	27.2	68.5	42.0
"03/03/2014"	"12:00"	32.5	55.0	18.1	32.5	30.81	-0.01	0.02	0.00	- -	0.0	10	0.0	12	0.0	10	32.5	68.9	43.0
"03/03/2014"	"13:00"	36.4	55.0	21.8	36.4	30.78	0.01	0.04	0.00	- -	2.0	8	6.0	8	2.9	9	36.4	69.0	43.0
"03/03/2014"	"14:00"	38.9	53.0	23.2	38.9	30.74	-0.03	0.04	0.00	- -	10.0	10	10.0	10	6.3	9	27.3	69.4	43.0
"03/03/2014"	"15:00"	40.1	59.0	27.0	40.1	30.70	-0.05	0.04	0.00	- -	8.0	8	13.0	10	6.2	9	31.8	69.0	44.0
"03/03/2014"	"16:00"	41.6	58.0	28.0	41.6	30.67	-0.07	0.04	0.00	- -	1.0	7	1.0	7	3.9	9	41.6	69.4	43.0
"03/03/2014"	"17:00"	43.7	56.0	29.1	43.7	30.63	-0.15	0.04	0.00	- -	2.0	8	8.0	8	2.8	9	43.7	69.7	43.0
"03/03/2014"	"18:00"	42.6	59.0	29.3	42.6	30.61	-0.15	0.04	0.00	- -	6.0	8	8.0	9	3.5	8	38.4	69.6	43.0
"03/03/2014"	"19:00"	39.0	63.0	27.5	39.0	30.61	-0.15	0.04	0.00	- -	3.0	8	4.0	8	3.6	8	39.0	69.4	43.0
"03/03/2014"	"20:00"	35.3	70.0	26.6	35.3	30.60	-0.13	0.04	0.00	- -	3.0	8	6.0	7	5.2	8	35.3	69.2	44.0
"03/03/2014"	"21:00"	34.7	67.0	24.9	34.7	30.59	-0.11	0.04	0.00	- -	4.0	8	5.0	8	4.1	8	34.7	69.2	44.0
"03/03/2014"	"22:00"	32.7	70.0	24.1	32.7	30.59	-0.11	0.04	0.00	- -	3.0	9	5.0	9	5.5	9	32.7	69.2	43.0
"03/03/2014"	"23:00"	31.3	70.0	22.7	31.3	30.57	-0.09	0.04	0.00	- -	6.0	8	5.0	8	3.4	7	26.0	68.7	43.0

APPENDIX A

Storm 2-3

VIDEO DATA

Table A.11. Statistical Comparison of De-icing Videos for Storm 2-3

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	100.0	0.0	3/1, Baseline Dry Pavement
	2	C	0.0	0.0	3/2, After 1st Snow
	3	C	0.0	0.0	3/2, After More Snow
	4	C	14.3	8.1	3/2, After 1st Plow, 1st De-icing
	5	C	16.7	8.6	3/2, After 2nd Plow
	6	C	29.0	7.7	3/3, After 2nd De-icing, During Slushing
	7	C	27.1	6.4	3/3, After 2nd De-icing, During Slushing
	8	C	60.5	11.6	3/3 After 2nd De-icing, Slushing
	9	C	90.0	8.9	3/3, After 3rd Plow
	1	MD20	100.0	0.0	3/1, Baseline Dry Pavement
	2	MD20	0.0	0.0	3/2, After 1st Snow
	3	MD20	0.0	0.0	3/2, After More Snow
	4	MD20	12.2	8.3	3/2, After 1st Plow, 1st De-icing
	5	MD20	16.7	8.7	3/2, After 2nd Plow
	6	MD20	32.2	8.3	3/3, After 2nd De-icing, During Slushing
	7	MD20	27.8	9.7	3/3, After 2nd De-icing, During Slushing
	8	MD20	68.9	16.2	3/3 After 2nd De-icing, Slushing
	9	MD20	87.8	10.9	3/3, After 3rd Plow
	1	RS	100.0	0.0	3/1, Baseline Dry Pavement
	2	RS	0.0	0.0	3/2, After 1st Snow
	3	RS	0.0	0.0	3/2, After More Snow
	4	RS	15.8	10.0	3/2, After 1st Plow, 1st De-icing
	5	RS	19.2	10.0	3/2, After 2nd Plow
	6	RS	29.2	7.9	3/3, After 2nd De-icing, During Slushing
	7	RS	32.5	9.7	3/3, After 2nd De-icing, During Slushing
	8	RS	89.2	5.1	3/3 After 2nd De-icing, Slushing
	9	RS	94.2	6.7	3/3, After 3rd Plow

Table A.12. Raw Data from De-icing Videos for Storm 2-3

De-Icing Video			LANE	STATION	TREATMENT	WDL			EOT			TAW		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
1	3/1/2014	15:25	NB	0-10	Control	100	1	1	100	1	1	100	1	1
				10-20	Meltdown-20	100	1	1	100	1	1	100	1	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt	100	1	1	100	1	1	100	1	1
				40-50	Control	100	1	1	100	1	1	100	1	1
				50-60	Road Salt	100	1	1	100	1	1	100	1	1
				60-70	Control	100	1	1	100	1	1	100	1	1
			SB	60-70	Road Salt	100	1	1	100	1	1	100	1	1
				50-60	Control	100	1	1	100	1	1	100	1	1
				40-50	Road Salt	100	1	1	100	1	1	100	1	1
				30-40	Control	100	1	1	100	1	1	100	1	1
				20-30	Meltdown-20	100	1	1	100	1	1	100	1	1
				10-20	Control	100	1	1	100	1	1	100	1	1
				0-10	Meltdown-20	100	1	1	100	1	1	100	1	1
2	3/2/2014	10:32	NB	0-10	Control	0	8	3	0	8	3	0	8	3
				10-20	Meltdown-20	0	8	3	0	8	3	0	8	3
				20-30	Control	0	8	3	0	8	3	0	8	3
				30-40	Road Salt	0	8	3	0	8	3	0	8	3
				40-50	Control	0	8	3	0	8	3	0	8	3
				50-60	Road Salt	0	8	3	0	8	3	0	8	3
				60-70	Control	0	8	3	0	8	3	0	8	3
			SB	60-70	Road Salt	0	8	3	0	8	3	0	8	3
				50-60	Control	0	8	3	0	8	3	0	8	3
				40-50	Road Salt	0	8	3	0	8	3	0	8	3
				30-40	Control	0	8	3	0	8	3	0	8	3
				20-30	Meltdown-20	0	8	3	0	8	3	0	8	3
				10-20	Control	0	8	3	0	8	3	0	8	3
				0-10	Meltdown-20	0	8	3	0	8	3	0	8	3
3	3/2/2014	11:09	NB	0-10	Control	0	8	3	0	8	3	0	8	3
				10-20	Meltdown-20	0	8	3	0	8	3	0	8	3
				20-30	Control	0	8	3	0	8	3	0	8	3
				30-40	Road Salt	0	8	3	0	8	3	0	8	3
				40-50	Control	0	8	3	0	8	3	0	8	3
				50-60	Road Salt	0	8	3	0	8	3	0	8	3
				60-70	Control	0	8	3	0	8	3	0	8	3
			SB	60-70	Road Salt	0	8	3	0	8	3	0	8	3
				50-60	Control	0	8	3	0	8	3	0	8	3
				40-50	Road Salt	0	8	3	0	8	3	0	8	3
				30-40	Control	0	8	3	0	8	3	0	8	3
				20-30	Meltdown-20	0	8	3	0	8	3	0	8	3
				10-20	Control	0	8	3	0	8	3	0	8	3
				0-10	Meltdown-20	0	8	3	0	8	3	0	8	3

Table A.12. Raw Data from De-icing Videos for Storm 2-3 Continued

De-Icing Video			LANE	STATION	TREATMENT	WDL			EOT			TAW		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
4	3/2/2014	14:20	NB	0-10	Control	10	6	4	10	9	5	10	9	4
				10-20	Meltdown-20	10	6	4	10	9	4	10	9	4
				20-30	Control	10	6	4	20	9	4	20	9	4
				30-40	Road Salt	10	6	4	10	9	4	30	7	4
				40-50	Control	10	6	4	10	9	5	10	9	4
				50-60	Road Salt	20	6	4	20	9	4	20	7	3
				60-70	Control	0	9	5	0	9	5	10	9	4
			SB	60-70	Road Salt	0	9	5	0	9	4	10	7	3
				50-60	Control	20	6	4	30	6	4	10	9	4
				40-50	Road Salt	20	6	4	30	6	4	20	9	3
				30-40	Control	20	6	4	20	9	4	20	6	4
				20-30	Meltdown-20	20	6	4	30	9	4	10	9	4
				10-20	Control	10	6	4	20	9	4	30	6	4
				0-10	Meltdown-20	0	9	5	10	9	4	10	7	3
5	3/2/2014	15:17	NB	0-10	Control	10	6	4	10	9	5	10	6	4
				10-20	Meltdown-20	10	6	4	10	9	4	20	7	4
				20-30	Control	20	6	4	10	9	4	20	6	4
				30-40	Road Salt	30	6	4	20	7	4	30	7	4
				40-50	Control	20	6	4	10	9	4	20	6	4
				50-60	Road Salt	10	6	4	10	9	4	30	7	4
				60-70	Control	0	9	5	0	9	5	10	9	5
			SB	60-70	Road Salt	20	6	4	0	7	5	10	7	4
				50-60	Control	30	6	4	20	9	4	20	6	4
				40-50	Road Salt	20	6	4	20	7	4	30	7	4
				30-40	Control	20	6	4	20	9	4	20	6	4
				20-30	Meltdown-20	10	6	4	20	9	4	30	7	4
				10-20	Control	30	6	4	20	9	4	30	6	4
				0-10	Meltdown-20	10	6	4	10	9	4	30	7	4
6	3/3/2014	9:33	NB	0-10	Control	20	5	4	30	6	4	40	5	4
				10-20	Meltdown-20	30	6	4	30	6	4	40	6	4
				20-30	Control	20	6	4	30	9	4	40	6	4
				30-40	Road Salt	30	6	4	40	6	4	40	7	3
				40-50	Control	20	6	4	30	9	4	30	6	4
				50-60	Road Salt	20	6	4	40	9	4	30	5	3
				60-70	Control	20	6	4	30	5	4	30	5	4
			SB	60-70	Road Salt	20	6	4	20	9	4	20	7	4
				50-60	Control	30	6	4	30	6	4	20	6	4
				40-50	Road Salt	30	6	4	30	6	4	30	7	4
				30-40	Control	20	6	4	30	9	4	20	6	4
				20-30	Meltdown-20	40	5	4	40	6	4	40	5	4
				10-20	Control	40	6	4	40	6	4	40	7	3
				0-10	Meltdown-20	20	6	4	30	9	4	20	7	4

Table A.12. Raw Data from De-icing Videos for Storm 2-3 Continued

De-Icing Video			LANE	STATION	TREATMENT	WDL			EOT			TAW		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
7	3/3/2014	9:45	NB	0-10	Control	20	6	4	30	5	4	30	5	4
				10-20	Meltdown-20	20	6	4	30	6	4	30	7	4
				20-30	Control	20	6	4	30	6	4	30	6	4
				30-40	Road Salt	40	6	4	40	6	3	40	7	3
				40-50	Control	20	6	4	30	6	4	20	6	4
				50-60	Road Salt	40	5	4	40	6	3	20	7	3
				60-70	Control	40	5	4	40	6	4	30	5	4
			SB	60-70	Road Salt	20	6	4	20	9	4	20	7	4
				50-60	Control	30	6	4	30	6	4	20	7	3
				40-50	Road Salt	40	6	4	40	6	3	30	7	3
				30-40	Control	20	6	4	30	6	4	20	6	4
				20-30	Meltdown-20	40	5	4	40	6	3	30	7	3
				10-20	Control	30	6	4	30	6	4	20	7	4
				0-10	Meltdown-20	20	6	4	30	6	4	10	7	3
8	3/3/2014	10:28	NB	0-10	Control	60	4	2	60	5	3	60	5	4
				10-20	Meltdown-20	90	3	2	90	4	2	80	4	2
				20-30	Control	80	5	2	70	5	3	70	7	3
				30-40	Road Salt	90	3	2	100	3	2	90	4	2
				40-50	Control	70	4	2	80	4	2	70	7	3
				50-60	Road Salt	90	3	2	90	3	2	90	3	2
				60-70	Control	60	5	2	70	5	3	50	5	4
			SB	60-70	Road Salt	80	3	2	90	4	2	80	4	2
				50-60	Control	50	5	2	40	6	3	40	7	3
				40-50	Road Salt	90	3	2	90	4	2	90	3	2
				30-40	Control	60	5	4	50	5	3	50	5	3
				20-30	Meltdown-20	70	5	2	70	5	3	50	5	3
				10-20	Control	60	4	2	50	6	2	70	4	3
				0-10	Meltdown-20	50	5	4	70	5	2	50	5	3
9	3/3/2014	10:53	NB	0-10	Control	90	3	1	90	3	2	90	3	2
				10-20	Meltdown-20	100	3	1	100	3	2	100	3	1
				20-30	Control	100	3	1	90	3	2	100	3	1
				30-40	Road Salt	100	3	1	100	3	1	100	3	1
				40-50	Control	100	3	1	90	3	2	100	3	1
				50-60	Road Salt	100	3	1	100	3	2	100	3	1
				60-70	Control	100	3	1	100	3	2	100	3	2
			SB	60-70	Road Salt	90	3	2	80	4	2	90	3	2
				50-60	Control	90	3	2	90	4	2	90	4	2
				40-50	Road Salt	90	3	2	90	3	2	90	3	2
				30-40	Control	80	3	2	80	4	3	70	7	3
				20-30	Meltdown-20	80	3	2	90	3	2	80	3	2
				10-20	Control	80	3	2	80	3	2	80	7	3
				0-10	Meltdown-20	70	3	2	90	3	2	80	4	3

APPENDIX A

Storm 2-3

IMAGE DATA

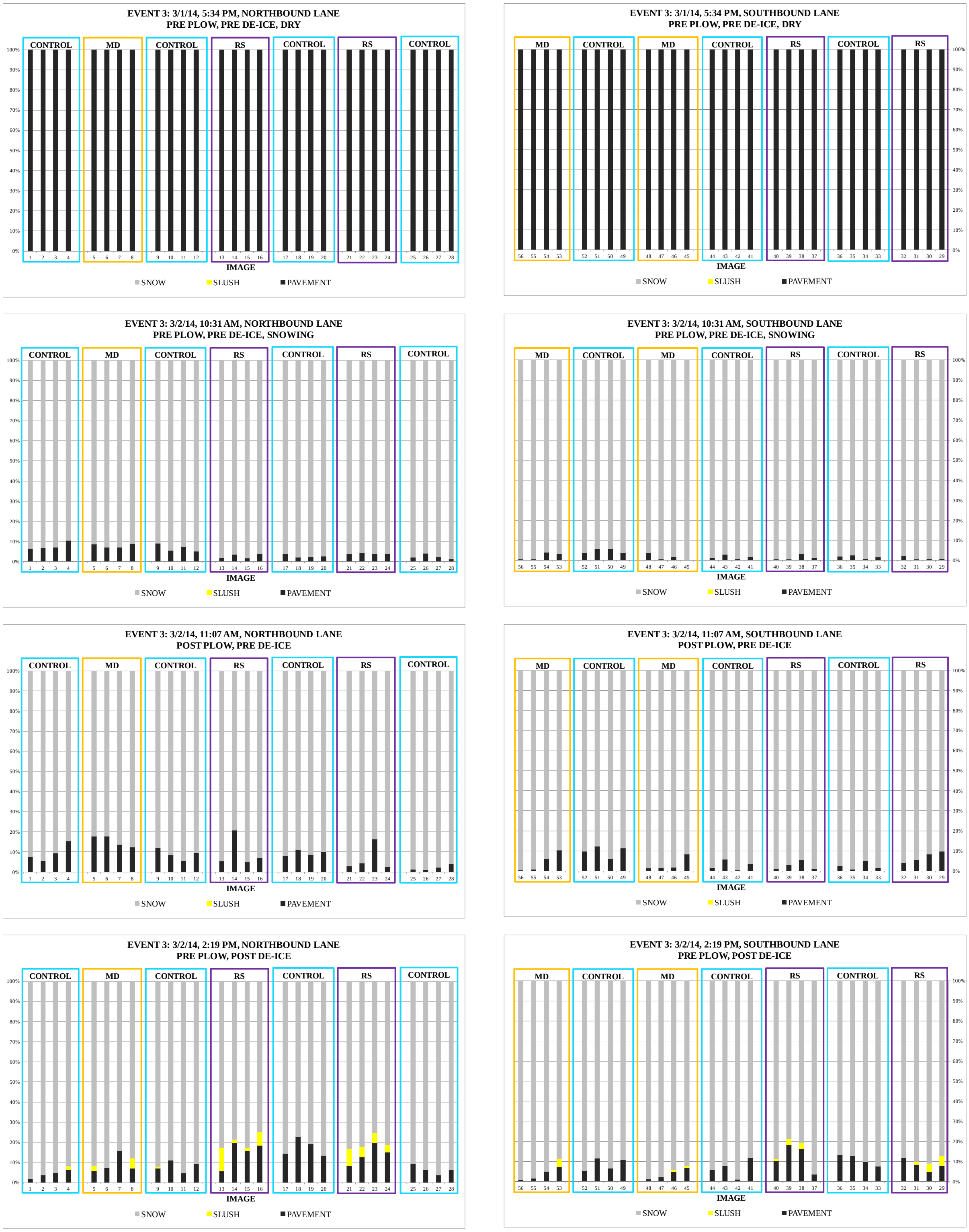

Figure A.2. Deicing Image Data Summary, Storm Event 2-3, March 1-3, 2014

Figure A.2. Deicing Image Data Summary, Storm Event 2-3, March 1-3, 2014, continued

Table A.13. Raw Data from De-icing Photos for Storm 2-3

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
1	3/1/2014	17:34	NB	2	Control	0	0	100	0	0	100	0	0	100
				4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				16	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				22	Control	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	Road Salt	0	0	100	0	0	100	0	0	100
				34	Road Salt	0	0	100	0	0	100	0	0	100
				36	Road Salt	0	0	100	0	0	100	0	0	100
				38	Road Salt	0	0	100	0	0	100	0	0	100
				42	Control	0	0	100	0	0	100	0	0	100
				44	Control	0	0	100	0	0	100	0	0	100
				46	Control	0	0	100	0	0	100	0	0	100
				48	Control	0	0	100	0	0	100	0	0	100
				52	Road Salt	0	0	100	0	0	100	0	0	100
				54	Road Salt	0	0	100	0	0	100	0	0	100
				56	Road Salt	0	0	100	0	0	100	0	0	100
				58	Road Salt	0	0	100	0	0	100	0	0	100
				62	Control	0	0	100	0	0	100	0	0	100
				64	Control	0	0	100	0	0	100	0	0	100
				66	Control	0	0	100	0	0	100	0	0	100
				68	Control	0	0	100	0	0	100	0	0	100
			SB	68	Road Salt	0	0	100	0	0	100	0	0	100
				66	Road Salt	0	0	100	0	0	100	0	0	100
				64	Road Salt	0	0	100	0	0	100	0	0	100
				62	Road Salt	0	0	100	0	0	100	0	0	100
				58	Control	0	0	100	0	0	100	0	0	100
				56	Control	0	0	100	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	0	0	100	0	0	100	0	0	100
				48	Road Salt	0	0	100	0	0	100	0	0	100
				46	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				38	Control	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				26	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	MD 20	0	0	100	0	0	100	0	0	100
				6	MD 20	0	0	100	0	0	100	0	0	100
				4	MD 20	0	0	100	0	0	100	0	0	100
				2	MD 20	0	0	100	0	0	100	0	0	100

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
2	3/2/2014	10:31	NB	2	Control	100	0	0	100	0	0	100	0	0
				4	Control	100	0	0	100	0	0	100	0	0
				6	Control	100	0	0	100	0	0	100	0	0
				8	Control	100	0	0	100	0	0	100	0	0
				12	MD 20	100	0	0	100	0	0	100	0	0
				14	MD 20	100	0	0	100	0	0	100	0	0
				16	MD 20	100	0	0	100	0	0	100	0	0
				18	MD 20	100	0	0	100	0	0	100	0	0
				22	Control	100	0	0	100	0	0	100	0	0
				24	Control	100	0	0	100	0	0	100	0	0
				26	Control	100	0	0	100	0	0	100	0	0
				28	Control	100	0	0	100	0	0	100	0	0
				32	Road Salt	100	0	0	100	0	0	100	0	0
				34	Road Salt	100	0	0	100	0	0	100	0	0
				36	Road Salt	100	0	0	100	0	0	100	0	0
				38	Road Salt	100	0	0	100	0	0	100	0	0
				42	Control	100	0	0	100	0	0	100	0	0
				44	Control	100	0	0	100	0	0	100	0	0
				46	Control	100	0	0	100	0	0	100	0	0
				48	Control	100	0	0	100	0	0	100	0	0
				52	Road Salt	100	0	0	100	0	0	100	0	0
				54	Road Salt	100	0	0	100	0	0	100	0	0
				56	Road Salt	100	0	0	100	0	0	100	0	0
				58	Road Salt	100	0	0	100	0	0	100	0	0
				62	Control	100	0	0	100	0	0	100	0	0
				64	Control	100	0	0	100	0	0	100	0	0
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	100	0	0	100	0	0	100	0	0
			SB	68	Road Salt	100	0	0	100	0	0	100	0	0
				66	Road Salt	100	0	0	100	0	0	100	0	0
				64	Road Salt	100	0	0	100	0	0	100	0	0
				62	Road Salt	100	0	0	100	0	0	100	0	0
				58	Control	100	0	0	100	0	0	100	0	0
				56	Control	100	0	0	100	0	0	100	0	0
				54	Control	100	0	0	100	0	0	100	0	0
				52	Control	100	0	0	100	0	0	100	0	0
				48	Road Salt	100	0	0	100	0	0	100	0	0
				46	Road Salt	100	0	0	100	0	0	100	0	0
				44	Road Salt	100	0	0	100	0	0	100	0	0
				42	Road Salt	100	0	0	100	0	0	100	0	0
				38	Control	100	0	0	100	0	0	100	0	0
				36	Control	100	0	0	100	0	0	100	0	0
				34	Control	100	0	0	100	0	0	100	0	0
				32	Control	100	0	0	100	0	0	100	0	0
				28	MD 20	100	0	0	100	0	0	100	0	0
				26	MD 20	100	0	0	100	0	0	100	0	0
				24	MD 20	100	0	0	100	0	0	100	0	0
				22	MD 20	100	0	0	100	0	0	100	0	0
				18	MD 20	100	0	0	100	0	0	100	0	0
				16	Control	100	0	0	100	0	0	100	0	0
				14	Control	100	0	0	100	0	0	100	0	0
				12	Control	100	0	0	100	0	0	100	0	0
				8	MD 20	100	0	0	100	0	0	100	0	0
				6	MD 20	100	0	0	100	0	0	100	0	0
				4	MD 20	100	0	0	100	0	0	100	0	0
				2	MD 20	100	0	0	100	0	0	100	0	0

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
3	3/2/2014	11:07	NB	2	Control	100	0	0	100	0	0	100	0	0
				4	Control	100	0	0	100	0	0	100	0	0
				6	Control	100	0	0	100	0	0	100	0	0
				8	Control	100	0	0	100	0	0	100	0	0
				12	MD 20	100	0	0	100	0	0	100	0	0
				14	MD 20	100	0	0	100	0	0	100	0	0
				16	MD 20	100	0	0	100	0	0	100	0	0
				18	MD 20	100	0	0	100	0	0	100	0	0
				22	Control	100	0	0	100	0	0	100	0	0
				24	Control	100	0	0	100	0	0	100	0	0
				26	Control	100	0	0	100	0	0	100	0	0
				28	Control	100	0	0	100	0	0	100	0	0
				32	Road Salt	100	0	0	100	0	0	100	0	0
				34	Road Salt	100	0	0	60	0	40	100	0	0
				36	Road Salt	100	0	0	100	0	0	100	0	0
				38	Road Salt	100	0	0	100	0	0	100	0	0
				42	Control	100	0	0	100	0	0	100	0	0
				44	Control	100	0	0	100	0	0	100	0	0
				46	Control	100	0	0	100	0	0	100	0	0
				48	Control	100	0	0	100	0	0	100	0	0
				52	Road Salt	100	0	0	100	0	0	100	0	0
				54	Road Salt	100	0	0	100	0	0	100	0	0
				56	Road Salt	100	0	0	100	0	0	100	0	0
				58	Road Salt	100	0	0	100	0	0	100	0	0
				62	Control	100	0	0	100	0	0	100	0	0
				64	Control	100	0	0	100	0	0	100	0	0
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	100	0	0	100	0	0	100	0	0
			SB	68	Road Salt	100	0	0	100	0	0	100	0	0
				66	Road Salt	100	0	0	100	0	0	100	0	0
				64	Road Salt	100	0	0	100	0	0	100	0	0
				62	Road Salt	100	0	0	100	0	0	100	0	0
				58	Control	100	0	0	100	0	0	100	0	0
				56	Control	100	0	0	100	0	0	100	0	0
				54	Control	100	0	0	100	0	0	100	0	0
				52	Control	100	0	0	100	0	0	100	0	0
				48	Road Salt	100	0	0	100	0	0	100	0	0
				46	Road Salt	100	0	0	100	0	0	100	0	0
				44	Road Salt	100	0	0	100	0	0	100	0	0
				42	Road Salt	100	0	0	100	0	0	100	0	0
				38	Control	100	0	0	100	0	0	100	0	0
				36	Control	100	0	0	100	0	0	100	0	0
				34	Control	100	0	0	100	0	0	100	0	0
				32	Control	100	0	0	100	0	0	100	0	0
				28	MD 20	100	0	0	100	0	0	100	0	0
				26	MD 20	100	0	0	100	0	0	100	0	0
				24	MD 20	100	0	0	100	0	0	100	0	0
				22	MD 20	100	0	0	100	0	0	100	0	0
				18	MD 20	100	0	0	100	0	0	100	0	0
				16	Control	100	0	0	100	0	0	100	0	0
				14	Control	100	0	0	100	0	0	100	0	0
				12	Control	100	0	0	100	0	0	100	0	0
				8	MD 20	100	0	0	100	0	0	100	0	0
				6	MD 20	100	0	0	100	0	0	100	0	0
				4	MD 20	100	0	0	100	0	0	100	0	0
				2	MD 20	100	0	0	100	0	0	100	0	0

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
4	3/2/2014	14:19	NB	2	Control	100	0	0	100	0	0	100	0	0
				4	Control	100	0	0	100	0	0	100	0	0
				6	Control	100	0	0	100	0	0	100	0	0
				8	Control	100	0	0	90	10	0	100	0	0
				12	MD 20	95	5	0	90	10	0	100	0	0
				14	MD 20	100	0	0	100	0	0	100	0	0
				16	MD 20	80	10	10	100	0	0	100	0	0
				18	MD 20	90	10	0	90	10	0	90	10	0
				22	Control	95	5	0	100	0	0	100	0	0
				24	Control	100	0	0	100	0	0	100	0	0
				26	Control	90	0	10	100	0	0	100	0	0
				28	Control	90	0	10	90	0	10	100	0	0
				32	Road Salt	70	30	0	80	20	0	80	20	0
				34	Road Salt	100	0	0	50	10	40	100	0	0
				36	Road Salt	90	10	0	70	0	30	100	0	0
				38	Road Salt	70	30	0	40	10	50	100	0	0
				42	Control	100	0	0	70	0	30	100	0	0
				44	Control	80	0	20	70	0	30	100	0	0
				46	Control	90	0	10	70	0	30	100	0	0
				48	Control	80	20	0	100	0	0	100	0	0
				52	Road Salt	80	20	0	80	20	0	90	10	0
				54	Road Salt	80	20	0	60	10	30	100	0	0
				56	Road Salt	80	20	0	90	10	0	100	0	0
				58	Road Salt	80	10	10	66	12	22	100	0	0
				62	Control	100	0	0	100	0	0	100	0	0
				64	Control	100	0	0	100	0	0	100	0	0
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	95	0	5	100	0	0	100	0	0
			SB	68	Road Salt	95	5	0	80	20	0	96	4	0
				66	Road Salt	95	5	0	80	20	0	100	0	0
				64	Road Salt	100	0	0	90	10	0	100	0	0
				62	Road Salt	100	0	0	90	0	10	100	0	0
				58	Control	100	0	0	100	0	0	100	0	0
				56	Control	100	0	0	100	0	0	100	0	0
				54	Control	100	0	0	100	0	0	100	0	0
				52	Control	100	0	0	100	0	0	100	0	0
				48	Road Salt	100	0	0	100	0	0	100	0	0
				46	Road Salt	90	10	0	80	0	20	90	10	0
				44	Road Salt	80	20	0	80	0	20	100	0	0
				42	Road Salt	95	5	0	80	0	20	100	0	0
				38	Control	100	0	0	80	0	20	100	0	0
				36	Control	100	0	0	100	0	0	100	0	0
				34	Control	90	0	10	100	0	0	100	0	0
				32	Control	100	0	0	90	0	10	100	0	0
				28	MD 20	95	5	0	100	0	0	100	0	0
				26	MD 20	95	5	0	100	0	0	100	0	0
				24	MD 20	100	0	0	100	0	0	100	0	0
				22	MD 20	100	0	0	100	0	0	100	0	0
				18	MD 20	100	0	0	100	0	0	100	0	0
				16	Control	100	0	0	100	0	0	100	0	0
				14	Control	100	0	0	100	0	0	100	0	0
				12	Control	100	0	0	100	0	0	100	0	0
				8	MD 20	95	5	0	80	20	0	100	0	0
				6	MD 20	100	0	0	100	0	0	100	0	0
				4	MD 20	100	0	0	100	0	0	100	0	0
				2	MD 20	100	0	0	100	0	0	100	0	0

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
5	3/2/2014	14:51	NB	2	Control	100	0	0	100	0	0	100	0	0
				4	Control	100	0	0	100	0	0	100	0	0
				6	Control	95	5	0	100	0	0	90	10	0
				8	Control	85	0	15	100	0	0	100	0	0
				12	MD 20	80	10	10	80	20	0	80	20	0
				14	MD 20	90	10	0	80	20	0	80	20	0
				16	MD 20	70	30	0	70	0	30	90	10	0
				18	MD 20	95	5	0	90	10	0	80	20	0
				22	Control	95	5	0	90	10	0	90	10	0
				24	Control	100	0	0	100	0	0	100	0	0
				26	Control	80	20	0	70	10	20	80	20	0
				28	Control	90	10	0	100	0	0	100	0	0
				32	Road Salt	75	25	0	60	40	0	60	40	0
				34	Road Salt	30	30	40	50	40	10	50	40	10
				36	Road Salt	70	30	0	60	40	0	60	40	0
				38	Road Salt	55	45	0	50	50	0	50	50	0
				42	Control	70	10	20	80	20	0	90	10	0
				44	Control	80	0	20	50	30	20	100	0	0
				46	Control	80	0	20	72	10	18	100	0	0
				48	Control	90	10	0	100	0	0	100	0	0
				52	Road Salt	90	10	0	50	50	0	90	10	0
				54	Road Salt	80	20	0	50	40	10	70	30	0
				56	Road Salt	70	30	0	30	50	20	77	23	0
				58	Road Salt	90	10	0	70	30	0	60	40	0
				62	Control	90	10	0	100	0	0	100	0	0
				64	Control	100	0	0	100	0	0	100	0	0
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	100	0	0	100	0	0	100	0	0
			SB	68	Road Salt	70	30	0	40	60	0	70	30	0
				66	Road Salt	70	30	0	60	40	0	70	30	0
				64	Road Salt	70	30	0	34	66	0	80	20	0
				62	Road Salt	80	20	0	60	40	0	70	30	0
				58	Control	70	30	0	70	30	0	100	0	0
				56	Control	80	0	20	70	30	0	90	10	0
				54	Control	90	0	10	60	40	0	100	0	0
				52	Control	100	0	0	60	40	0	100	0	0
				48	Road Salt	70	30	0	70	30	0	80	20	0
				46	Road Salt	60	40	0	30	60	10	70	30	0
				44	Road Salt	45	55	0	40	50	10	50	50	0
				42	Road Salt	50	20	30	50	30	20	70	30	0
				38	Control	70	0	30	70	0	30	100	0	0
				36	Control	100	0	0	100	0	0	90	10	0
				34	Control	80	0	20	90	0	10	90	0	10
				32	Control	80	0	20	100	0	0	100	0	0
				28	MD 20	70	30	0	50	30	20	100	0	0
				26	MD 20	90	0	10	90	10	0	90	10	0
				24	MD 20	80	20	0	70	30	0	80	20	0
				22	MD 20	95	5	0	100	0	0	90	10	0
				18	MD 20	76	2	22	50	30	20	100	0	0
				16	Control	100	0	0	90	0	10	100	0	0
				14	Control	80	20	0	80	0	20	100	0	0
				12	Control	100	0	0	100	0	0	100	0	0
				8	MD 20	80	20	0	60	40	0	80	20	0
				6	MD 20	90	10	0	70	30	0	90	10	0
				4	MD 20	100	0	0	80	0	20	100	0	0
				2	MD 20	100	0	0	90	10	0	100	0	0

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
6	3/3/2014	9:56	NB	2	Control	60	10	30	70	0	30	70	10	20
				4	Control	70	10	20	70	20	10	80	0	20
				6	Control	70	0	30	60	20	20	70	10	20
				8	Control	100	0	0	90	10	0	100	0	0
				12	MD 20	40	30	30	50	30	20	60	10	30
				14	MD 20	50	20	30	30	30	40	60	10	30
				16	MD 20	40	20	40	40	20	40	50	20	30
				18	MD 20	50	30	20	50	30	20	60	20	20
				22	Control	50	30	20	40	50	10	70	30	0
				24	Control	50	10	40	10	30	60	70	20	10
				26	Control	60	20	20	70	10	20	80	0	20
				28	Control	80	0	20	70	10	20	90	0	10
				32	Road Salt	20	30	50	20	30	50	40	10	50
				34	Road Salt	20	10	70	20	10	70	30	20	50
				36	Road Salt	20	20	60	20	20	60	20	20	60
				38	Road Salt	30	30	40	30	20	50	30	10	60
				42	Control	40	40	20	30	30	40	50	20	30
				44	Control	30	0	70	18	8	74	30	0	70
				46	Control	35	17	48	30	10	60	40	10	50
				48	Control	30	30	40	30	10	60	50	10	40
				52	Road Salt	45	27	28	20	10	70	30	30	40
				54	Road Salt	40	20	40	40	20	40	40	20	40
				56	Road Salt	0	20	80	10	0	90	10	0	90
				58	Road Salt	20	30	50	20	30	50	40	10	50
				62	Control	50	30	20	70	10	20	60	10	30
				64	Control	70	10	20	70	10	20	80	0	20
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	80	10	10	80	10	10	100	0	0
			SB	68	Road Salt	0	60	40	10	40	50	20	40	40
				66	Road Salt	30	30	40	30	40	30	40	20	40
				64	Road Salt	20	10	70	10	20	70	10	30	60
				62	Road Salt	30	20	50	30	20	50	30	20	50
				58	Control	40	40	20	40	10	50	60	10	30
				56	Control	50	20	30	50	20	30	50	20	30
				54	Control	50	20	30	40	20	40	50	10	40
				52	Control	40	20	40	40	10	50	40	20	40
				48	Road Salt	0	25	75	0	20	80	0	30	70
				46	Road Salt	0	30	70	0	30	70	0	30	70
				44	Road Salt	0	20	80	0	20	80	0	20	80
				42	Road Salt	10	40	50	10	40	50	20	20	60
				38	Control	40	10	50	50	20	30	40	20	40
				36	Control	50	20	30	60	20	20	60	20	20
				34	Control	60	20	20	40	30	30	60	30	10
				32	Control	70	10	20	70	10	20	70	10	20
				28	MD 20	20	10	70	30	0	70	10	20	70
				26	MD 20	40	20	40	30	30	40	20	40	40
				24	MD 20	30	30	40	30	30	40	30	30	40
				22	MD 20	60	20	20	80	10	10	70	10	20
				18	MD 20	10	20	70	10	20	70	10	20	70
				16	Control	60	15	25	50	20	30	70	10	20
				14	Control	10	20	70	10	20	70	10	20	70
				12	Control	30	10	60	24	12	64	30	10	60
				8	MD 20	20	20	60	20	20	60	20	20	60
				6	MD 20	20	40	40	40	30	30	40	20	40
				4	MD 20	50	30	20	70	10	20	70	10	20
				2	MD 20	90	5	5	90	10	0	80	10	10

Table A.13. Raw Data from De-icing Photos for Storm 2-3, continued

De-Icing Photos			LANE	STATION	TREATMENT	EOT			TAW			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
7	3/3/2014	10:28	NB	2	Control	20	30	50	20	40	40	20	30	50
				4	Control	40	30	30	40	30	30	50	20	30
				6	Control	30	30	40	20	40	40	30	30	40
				8	Control	30	30	40	30	30	40	40	20	40
				12	MD 20	10	30	60	10	30	60	0	30	70
				14	MD 20	0	20	80	0	30	70	0	20	80
				16	MD 20	0	20	80	10	30	60	0	20	80
				18	MD 20	10	30	60	30	20	50	20	20	60
				22	Control	0	10	90	10	10	80	0	10	90
				24	Control	10	30	60	10	30	60	10	30	60
				26	Control	20	30	50	20	30	50	20	20	60
				28	Control	10	40	50	10	50	40	10	40	50
				32	Road Salt	0	20	80	10	10	80	0	30	70
				34	Road Salt	0	0	100	0	0	100	0	10	90
				36	Road Salt	0	10	90	0	0	100	0	10	90
				38	Road Salt	0	10	90	0	10	90	0	20	80
				42	Control	0	5	95	0	0	100	0	10	90
				44	Control	0	20	80	0	0	100	0	10	90
				46	Control	0	5	95	0	0	100	0	10	90
				48	Control	0	15	85	0	20	80	0	20	80
				52	Road Salt	0	20	80	0	10	90	0	20	80
				54	Road Salt	0	30	70	0	30	70	0	30	70
				56	Road Salt	0	0	100	0	0	100	0	0	100
				58	Road Salt	0	0	100	0	0	100	0	10	90
				62	Control	0	30	70	0	50	50	0	50	50
				64	Control	30	40	30	40	30	30	20	40	40
				66	Control	30	40	30	40	30	30	20	40	40
				68	Control	30	50	20	30	50	20	30	40	30
			SB	68	Road Salt	0	0	100	0	0	100	0	10	90
				66	Road Salt	0	0	100	0	0	100	0	0	100
				64	Road Salt	0	0	100	0	0	100	0	0	100
				62	Road Salt	0	5	95	0	0	100	0	0	100
				58	Control	30	20	50	30	20	50	10	30	60
				56	Control	20	10	70	20	10	70	10	30	60
				54	Control	10	40	50	10	20	70	10	30	60
				52	Control	20	30	50	10	20	70	10	30	60
				48	Road Salt	0	20	80	0	0	100	0	20	80
				46	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	10	90
				38	Control	0	30	70	17	26	57	0	20	80
				36	Control	20	50	30	1	46	53	20	40	40
				34	Control	30	30	40	30	30	40	20	30	50
				32	Control	20	50	30	20	40	40	20	40	40
				28	MD 20	0	5	95	0	0	100	0	10	90
				26	MD 20	0	10	90	0	10	90	0	10	90
				24	MD 20	0	5	95	0	0	100	0	0	100
				22	MD 20	0	80	20	10	70	20	10	60	30
				18	MD 20	0	10	90	0	0	100	0	10	90
				16	Control	20	30	50	10	30	60	0	40	60
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	5	95	0	0	100	0	0	100
				8	MD 20	0	5	95	0	0	100	0	0	100
				6	MD 20	0	20	80	0	0	100	0	20	80
				4	MD 20	20	50	30	20	50	30	10	60	30
				2	MD 20	20	60	20	25	57	18	10	60	30

APPENDIX B

Winter 2014/15

Storm 3-4

02-20-2015

APPENDIX B

Storm 3-4

WEATHER DATA

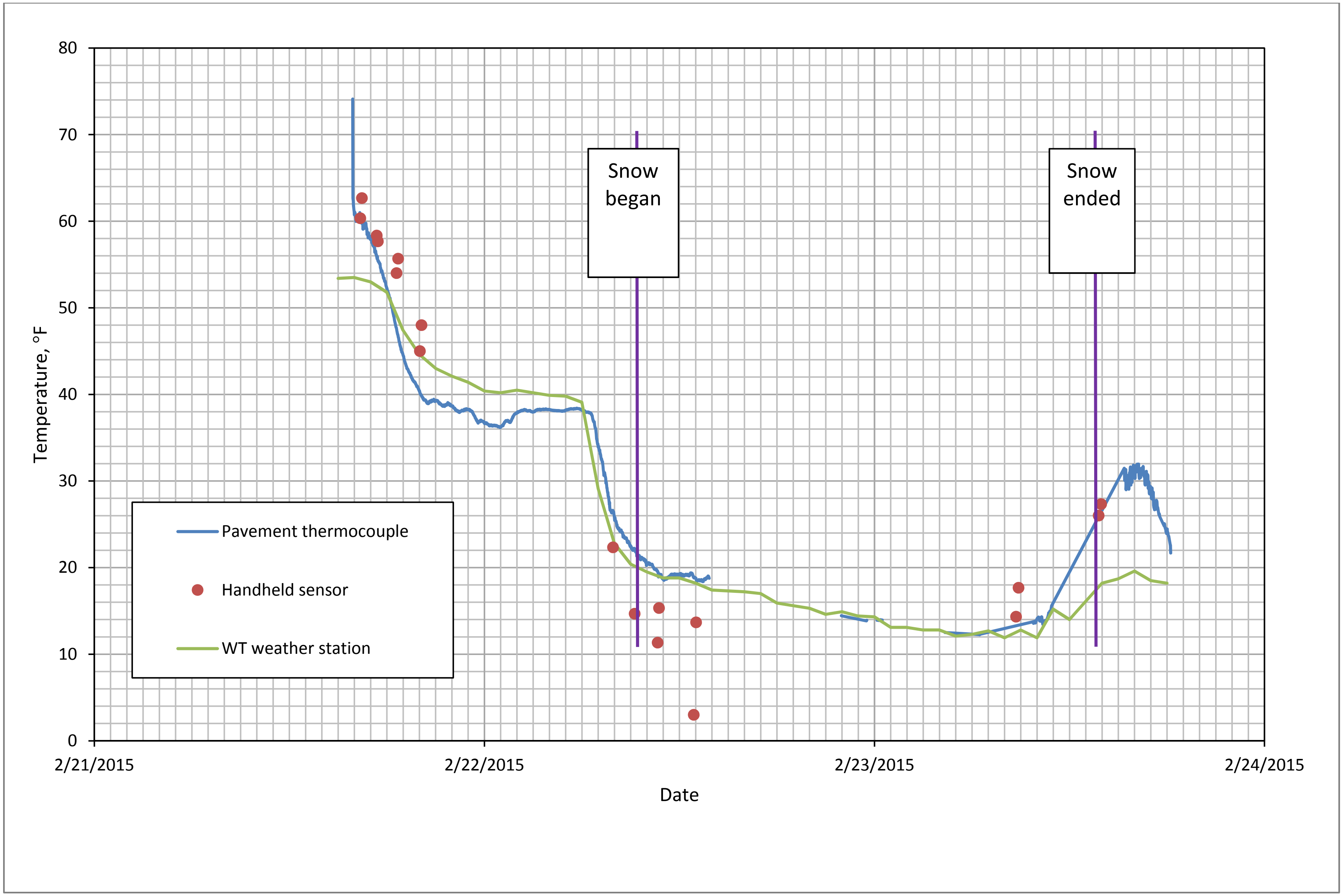

Figure B.1. Temperature Data at Field Test Site, Storm Event 3-4, FEB 21-23, 2015

Table B.1 On-Site Temperature Readings, Storm 3-4

Date	Time		Location (N/S)	Temperature				Snow Thickness	Comments	Initials
				R1	R2	R3	Average			
		2/21/2015 16:22	N	60	60	61	60.3			
		2/21/2015 16:28	S	63	62	63	62.7			
		2/21/2015 17:23	S	59	59	57	58.3			
		2/21/2015 17:27	N	58	58	57	57.7			
		2/21/2015 18:36	S	55	54	53	54.0			
		2/21/2015 18:42	N	56	56	55	55.7			
		2/21/2015 20:02	S	45	45	45	45.0			
		2/21/2015 20:08	N	49	48	47	48.0			
		2/22/2015 7:55	S	23	22	22	22.3			
		2/22/2015 9:15	S	17	14	13	14.7			
		2/22/2015 10:40	S	11	12	11	11.3			
		2/22/2015 10:45	N	16	15	15	15.3	blowing snow		
		2/22/2015 12:53	S	4	3	2	3.0	blowing snow		
		2/22/2015 13:02	N	16	15	10	13.7	1		
		2/23/2015 8:43	N	16	14	13	14.3	1		
		2/23/2015 8:52	S	18	18	17	17.7	1		
		2/23/2015 13:48	S	26	28	24	26.0	1		
		2/23/2015 13:57	N	28	26	28	27.3	1		

Table B.2 Storm 3-4, Hourly Observations, 21 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
21	0053	11	CLR	10.00		41	5.0	37	2.5	31	-0.6	68	17	010		26.18			29.79	AA		29.87
21	0153	11	CLR	10.00		39	3.9	35	1.7	30	-1.1	70	7	350		26.20			29.80	AA		29.89
21	0253	11	CLR	10.00		37	2.8	33	0.7	28	-2.2	70	16	340		26.22			29.84	AA		29.92
21	0341	11	BKN017	10.00		36	2.2	33	0.4	28	-2.2	73	13	350		26.21			M	SP		29.91
21	0351	11	FEW017	10.00		36	2.0	33	0.4	28	-2.0	73	13	350		26.21			M	SP		29.91
21	0353	11	FEW017	10.00		35	1.7	32	0.0	28	-2.2	76	13	350		26.21			29.84	AA		29.91
21	0453	11	CLR	10.00		34	1.1	31	-0.4	27	-2.8	76	11	350		26.23			29.86	AA		29.93
21	0553	11	CLR	10.00		32	0.0	30	-1.0	27	-2.8	82	9	360		26.24			29.89	AA		29.94
21	0623	11	BKN010	10.00		32	0.0	30	-1.0	27	-2.8	82	7	350		26.24			M	SP		29.94
21	0640	11	SCT010	10.00		31	-0.6	29	-1.4	27	-2.8	85	7	340		26.26			M	SP		29.96
21	0653	11	CLR	9.00		32	0.0	30	-0.8	28	-2.2	85	8	340		26.26			29.93	AA		29.96
21	0753	11	CLR	7.00		30	-1.1	29	-1.7	27	-2.8	89	5	310		26.28			29.97	AA		29.99
21	0853	11	CLR	10.00		36	2.2	34	0.8	30	-1.1	79	7	330		26.30			29.98	AA		30.01
21	0953	11	CLR	10.00		41	5.0	36	2.3	30	-1.1	65	6	060		26.34			30.02	AA		30.05
21	1053	11	CLR	10.00		44	6.7	38	3.2	30	-1.1	58	10	080		26.33			30.01	AA		30.04
21	1153	11	CLR	10.00		46	7.8	39	3.8	30	-1.1	54	10	120		26.32			30.00	AA		30.03
21	1253	11	FEW033	10.00		49	9.4	40	4.7	30	-1.1	48	13	080	17	26.30			29.98	AA		30.01
21	1353	11	CLR	10.00		51	10.6	41	5.0	29	-1.7	43	14	120	20	26.26			29.93	AA		29.96
21	1453	11	FEW045	10.00		52	11.1	42	5.3	29	-1.7	41	13	130		26.25			29.92	AA		29.95
21	1553	11	CLR	10.00		53	11.7	42	5.6	29	-1.7	40	11	120		26.23			29.90	AA		29.93
21	1653	11	CLR	10.00		53	11.7	42	5.4	28	-2.2	38	10	140		26.22			29.89	AA		29.92
21	1753	11	CLR	10.00		51	10.6	41	5.0	29	-1.7	43	13	130		26.22			29.90	AA		29.92
21	1853	11	CLR	10.00		45	7.2	38	3.3	29	-1.7	54	9	110		26.26			29.96	AA		29.96
21	1953	11	CLR	10.00		42	5.6	36	2.4	29	-1.7	60	13	120		26.27			29.98	AA		29.97
21	2053	11	FEW120	10.00		40	4.4	35	1.8	29	-1.7	65	11	120		26.29			30.00	AA		30.00
21	2153	11	CLR	10.00		40	4.4	36	2.0	30	-1.1	68	14	110		26.30			30.00	AA		30.01
21	2253	11	FEW110	10.00		40	4.4	36	2.2	31	-0.6	70	18	110		26.30			30.00	AA		30.01
21	2353	11	BKN120	10.00		40	4.4	36	2.2	31	-0.6	70	16	110		26.30			29.99	AA		30.01

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Table B.3 Storm 3-4, Hourly Remarks, 21 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
21	0053	AO2 PK WND 02028/0616 SLP089 T00501006
21	0153	AO2 SLP093 T00391011
21	0253	AO2 SLP105 T00281022 53017
21	0341	AO2 T00221022
21	0351	AO2
21	0353	AO2 SLP106 T00171022
21	0453	AO2 SLP113 T00111028
21	0553	AO2 SLP122 T00001028 10061 20000 53010 (XX)
21	0623	AO2 T00001028 (XX)
21	0640	AO2 T10061028 (XX)
21	0653	AO2 SLP135 T00001022 (XX)
21	0753	AO2 SLP150 T10111028 (XX)
21	0853	AO2 SLP154 T00221011 53021 (XX)
21	0953	AO2 SLP165 T00501011 (XX)
21	1053	AO2 SLP162 T00671011 (XX)
21	1153	AO2 SLP160 T00781011 10083 21011 50005 (XX)
21	1253	AO2 SLP153 T00941011 (XX)
21	1353	AO2 SLP137 T01061017 (XX)
21	1453	AO2 SLP131 T01111017 56025
21	1553	AO2 SLP125 T01171017 (XX)
21	1653	AO2 SLP121 T01171022 (XX)
21	1753	AO2 SLP126 T01061017 10122 20078 55009 (XX)
21	1853	AO2 SLP144 T00721017
21	1953	AO2 SLP152 T00561017
21	2053	AO2 SLP160 T00441017 51024
21	2153	AO2 SLP160 T00441011
21	2253	AO2 SLP159 T00441006
21	2353	AO2 SLP157 T00441006 10106 20039 401221011 51005

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Table B.4 Storm 3-4, Hourly Precipitation, 21 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
21													21													21

Table B.5 Storm 3.4, Hourly Observations, 22 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
22	0053	11	BKN065 BKN120	10.00		40	4.4	36	2.2	31	-0.6	70	16	110		26.33			30.01	AA		30.04
22	0143	11	BKN027 OVC060	10.00		40	4.4	36	2.2	31	-0.6	70	18	110		26.34			M	SP		30.05
22	0153	11	OVC027	10.00		40	4.4	36	2.2	31	-0.6	70	18	100	25	26.35			30.03	AA		30.06
22	0253	11	BKN029 OVC050	10.00		40	4.4	36	2.2	31	-0.6	70	15	100		26.37			30.05	AA		30.08
22	0307	11	SCT030 OVC050	10.00		40	4.4	36	2.2	31	-0.6	70	15	100		26.37			M	SP		30.08
22	0353	11	FEW032 OVC049	10.00		39	3.9	36	1.9	31	-0.6	73	13	090		26.39			30.08	AA		30.11
22	0453	11	OVC040	10.00		39	3.9	36	1.9	31	-0.6	73	11	060		26.42			30.11	AA		30.14
22	0536	11	SCT004 SCT008 OVC045	8.00		35	1.7	34	0.9	32	0.0	89	22	010	28	26.45			M	SP		30.17
22	0542	11	BKN003 OVC046	5.00	BR	34	1.1	33	0.6	32	0.0	92	17	020		26.46			M	SP		30.18
22	0553	11	BKN003 OVC046	3.00	-SN BR	33	0.6	33	0.3	32	0.0	96	23	020	31	26.46			30.17	AA	T	30.18
22	0614	11	BKN005 BKN011 OVC018	3.00	-SN BR	30	-1.1	30	-1.3	29	-1.7	96	29	020	38	26.48			M	SP		30.21
22	0627	11	SCT005 BKN010 OVC019	3.00	-SN BR	27	-2.8	27	-2.9	26	-3.3	96	26	020	34	26.48			M	SP		30.21
22	0634	11	BKN008 OVC019	3.00	-SN BR	26	-3.3	25	-3.7	24	-4.4	92	25	010	33	26.49			M	SP		30.22
22	0653	11	BKN008 OVC014	6.00	-SN BR	24	-4.4	23	-5.0	21	-6.1	88	25	020	38	26.52			30.27	AA	0.01	30.25
22	0753	11	OVC007	5.00	BR	20	-6.7	19	-7.0	18	-7.8	92	23	020	36	26.55			30.32	AA	T	30.28
22	0806	11	OVC007	1.75	-SN BR	21	-6.1	20	-6.6	18	-7.8	88	22	020	29	26.55			M	SP		30.28
22	0815	11	OVC007	1.00	-SN BR	20	-6.7	19	-7.0	18	-7.8	92	30	020	36	26.56			M	SP		30.29
22	0822	11	OVC007	1.50	-SN BR	20	-6.7	19	-7.1	17	-8.3	88	31	020	38	26.56			M	SP		30.29
22	0841	11	OVC007	2.00	BR	19	-7.2	18	-7.5	17	-8.3	92	28	030	38	26.57			M	SP		30.30
22	0853	11	OVC007	2.00	-SN BR	19	-7.2	18	-7.5	17	-8.3	92	25	030	45	26.57			30.36	AA	0.01	30.31
22	0907	11	OVC007	1.75	-SN BR	19	-7.2	18	-7.7	16	-8.9	88		M		26.57			M	SP		30.31
22	0915	11	OVC007	2.50	UP BR	19	-7.2	18	-7.7	16	-8.9	88		M		26.58			M	SP		30.32
22	0943	11	OVC007	3.00	BR	18	-7.8	17	-8.2	15	-9.4	88		M		26.60			M	SP		30.34
22	0951	11	OVC008	2.50	UP BR	18	-8.0	17	-8.1	16	-9.0	92	M	M		26.60			M	SP		30.34
22	0953	11	OVC008	2.50	UP BR	17	-8.3	16	-8.6	15	-9.4	92		M		26.60			30.39	AA	T	30.34
22	0956	11	OVC008	2.00	-SN BR	17	-8.3	16	-8.6	15	-9.4	92	23	030	34	26.60			M	SP		30.34
22	1010	11	OVC008	1.00	-SN BR	17	-8.3	16	-8.6	15	-9.4	92	23	030	34	26.61			M	SP		30.35
22	1018	11	BKN007 OVC011	0.75	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	23	030	34	26.61			M	SP		30.35
22	1022	11	BKN007 OVC011	1.25	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	23	030	34	26.62			M	SP		30.36
22	1040	11	SCT009 OVC014	0.75	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	23	020	30	26.60			M	SP		30.34
22	1051	11	BKN011 OVC018	1.25	-SN BR	18	-8.0	17	-8.4	14	-10.0	84	23	020	30	26.61			M	SP		30.35
22	1053	11	BKN011 OVC018	1.75	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	23	020	30	26.61			30.40	AA	T	30.35
22	1101	11	BKN011 OVC018	2.50	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	23	020	30	26.62			M	SP		30.36

Table B.5 Storm 3-4, Hourly Observations, 22 FEB 2015, National Climatic Data Center, continued

22	1118	11	SCT010 OVC016	1.75	-SN BR	18	-7.8	17	-8.4	14	-10.0	84	23	020	30	26.63			M	SP		30.37
22	1124	11	BKN010 OVC017	1.75	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	23	020	30	26.63			M	SP		30.37
22	1153	11	BKN013 OVC019	1.50	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	23	020	30	26.64			30.43	AA	T	30.38
22	1204	11	OVC015	1.00	-SN BR	18	-7.8	17	-8.2	15	-9.4	88	29	040	37	26.63			M	SP		30.37
22	1211	11	SCT011 OVC018	1.50	-SN BR	18	-7.8	17	-8.4	14	-10.0	84	25	040	37	26.63			M	SP		30.37
22	1246	11	BKN011 OVC018	1.25	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	28	020	36	26.63			M	SP		30.37
22	1253	11	FEW010 OVC014	1.50	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	29	010	41	26.64			30.44	AA	T	30.38
22	1315	11	FEW009 OVC016	1.75	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	24	010	32	26.64			M	SP		30.38
22	1329	11	OVC014	1.75	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	23	010	33	26.63			M	SP		30.37
22	1353	11	OVC014	1.25	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	26	020		26.63			30.43	AA	T	30.37
22	1413	11	BKN014 BKN019 OVC030	2.00	-SN BR	17	-8.3	16	-8.9	13	-10.6	84	22	020		26.63			M	SP		30.37
22	1421	11	SCT014 OVC027	3.00	-SN BR	17	-8.3	16	-8.9	13	-10.6	84	24	020		26.63			M	SP		30.37
22	1432	11	BKN014 OVC029	4.00	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	25	020	30	26.62			M	SP		30.36
22	1451	11	BKN014 OVC031	1.50	-SN BR	18	-8.0	17	-8.4	14	-10.0	84	22	030		26.62			M	SP		30.36
22	1453	11	BKN014 OVC031	1.50	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	20	020		26.62			30.42	AA	0.01	30.36
22	1504	11	SCT009 BKN015 OVC030	1.50	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	21	020	28	26.62			M	SP		30.36
22	1526	11	BKN012 OVC017	2.50	-SN BR	17	-8.3	16	-8.8	14	-10.0	88	23	020		26.62			M	SP		30.36
22	1531	11	FEW010 OVC015	3.00	-SN BR	17	-8.3	16	-8.9	13	-10.6	84	23	020		26.62			M	SP		30.36
22	1537	11	OVC013	2.50	-SN BR	17	-8.3	16	-8.9	13	-10.6	84	23	020		26.63			M	SP		30.37
22	1546	11	OVC013	1.75	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	22	020		26.63			M	SP		30.37
22	1551	11	BKN013 OVC018	2.00	-SN BR	16	-9.0	15	-9.5	12	-11.0	84	22	020		26.63			M	SP		30.37
22	1553	11	OVC013	2.00	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	22	020		26.63			30.43	AA	T	30.37
22	1619	11	OVC013	1.00	-SN BR	16	-8.9	15	-9.3	13	-10.6	88	21	020		26.64			M	SP		30.38
22	1653	11	OVC012	1.00	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	20	020	30	26.64			30.45	AA	T	30.38
22	1751	11	BKN012 BKN018 OVC023	4.00	-SN BR	16	-9.0	14	-9.8	10	-12.0	77	17	030		26.65			M	SP		30.40
22	1753	11	BKN012 OVC023	5.00	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	18	030		26.65			30.49	AA	T	30.40
22	1825	11	BKN013 OVC018	2.00	-SN BR	15	-9.4	14	-9.9	12	-11.1	88	15	030		26.66			M	SP		30.41
22	1835	11	BKN009 OVC015	2.00	-SN BR	15	-9.4	14	-9.9	12	-11.1	88	13	010		26.67			M	SP		30.42
22	1839	11	BKN009 OVC015	1.00	-SN BR	15	-9.4	14	-9.9	12	-11.1	88	14	020		26.67			M	SP		30.42
22	1853	11	OVC011	1.00	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	15	020		26.66			30.52	AA	0.01	30.41
22	1932	11	BKN010 OVC019	6.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	18	030		26.69			M	SP		30.44
22	1953	11	BKN011 OVC021	4.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	18	030		26.69			30.56	AA	T	30.44
22	2032	11	BKN011 OVC017	2.50	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	18	040		26.69			M	SP		30.44
22	2039	11	OVC011	4.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	17	030		26.70			M	SP		30.45
22	2049	11	BKN009 OVC015	2.50	-SN BR	14	-10.0	13	-10.6	10	-12.0	84	17	040		26.70			M	SP		30.45
22	2053	11	BKN009 OVC015	2.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	18	030		26.71			30.58	AA	T	30.46
22	2102	11	OVC012	1.75	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	16	020		26.72			M	SP		30.47
22	2109	11	BKN010 OVC014	2.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	15	020		26.72			M	SP		30.47
22	2153	11	OVC011	2.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	16	020		26.73			30.61	AA	T	30.49
22	2253	11	BKN012 OVC017	2.50	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	15	020		26.75			30.63	AA	T	30.50
22	2301	11	BKN012 OVC017	4.00	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	16	020		26.75			M	SP		30.50
22	2326	11	BKN012 OVC018	2.00	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	17	020		26.75			M	SP		30.50
22	2341	11	BKN010 OVC018	3.00	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	18	030		26.75			M	SP		30.51
22	2348	11	BKN010 OVC016	2.00	-SN BR	12	-11.0	11	-11.4	10	-12.0	92	15	040		26.75			M	SP		30.51
22	2353	11	BKN010 OVC018	2.50	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	15	040	23	26.76			30.64	AA	T	30.52

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Table B.6 Storm 3-4, Hourly Remarks, 22 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
22	0053	AO2 SLP162 T00441006
22	0143	AO2 T00441006
22	0153	AO2 SLP168 T00441006
22	0253	AO2 SLP175 T00441006 52020
22	0307	AO2 T00441006
22	0353	AO2 SLP186 T00391006
22	0453	AO2 SLP197 T00391006
22	0536	AO2 T00170000
22	0542	AO2 T00110000
22	0553	AO2 PK WND 02027/1153 SNB47 SLP218 P0000 60000 T00060000 10044 20006 53032
22	0614	AO2 PK WND 02033/1212 CIG 003V008 P0000 T10111017
22	0627	AO2 PK WND 02033/1216 P0000 T10281033 (XX)
22	0634	AO2 PK WND 02033/1216 P0000 T10331044 (XX)
22	0653	AO2 PK WND 03034/1240 CIG 005V011 PRESRR SLP251 P0000 T10441061 (XX)
22	0753	AO2 PK WND 02033/1343 SNE21 SLP268 P0000 I1001 T10671078 (XX)
22	0806	AO2 SNB05 P0000 I1000 T10611078 (XX)
22	0815	AO2 PK WND 02031/1415 SNB05 P0000 I1000 T10671078 (XX)
22	0822	AO2 PK WND 02033/1421 SNB05 P0000 I1000 T10671083 (XX)
22	0841	AO2 PK WND 03033/1440 SNB05E37 P0000 I1000 T10721083 (XX)
22	0853	AO2 PK WND 06039/1447 SNB05E37B42 CIG 006V010 SLP280 P0000 60000 I1000 I3001 T10721083 51038 (XX)
22	0907	AO2 PK WND 04033/1455 CIG 006V009 P0000 T10721089 (XX)
22	0915	AO2 PK WND 04033/1455 UPB15SNE15 CIG 006V009 P0000 T10721089 (XX)
22	0943	AO2 PK WND 04033/1455 UPB15E23SNE15B23E38 P0000 I1001 T10781094 (XX)
22	0951	AO2 PK WND 04033/1455 UPB15E23B48SNE15B23E38 P0000 I1001 FIBI (XX)
22	0953	AO2 PK WND 04033/1455 UPB15E23B48SNE15B23E38 SLP291 P0000 I1001 T10831094 (XX)
22	0956	AO2 UPE54SNB54 P0000 T10831094 (XX)
22	1010	AO2 UPE1554B01E03SNB1554E01B03 P0000 T10831094 (XX)
22	1018	AO2 UPE1554B01E03SNB1554E01B03 P0000 T10781094 (XX)
22	1022	AO2 UPE1554B01E03SNB1554E01B03 P0000 T10781094 (XX)
22	1040	AO2 UPE1554B01E03SNB1554E01B03 P0000 T10781094 (XX)
22	1051	AO2 UPE1554B01E03SNB1554E01B03 P0000 (XX)
22	1053	AO2 UPE1554B01E03SNB1554E01B03 SLP296 P0000 T10831100 (XX)
22	1101	AO2 P0000 T10831100 (XX)
22	1118	AO2 PK WND 030153/1710 P0000 T10781100 (XX)
22	1124	AO2 PK WND 030153/1710 P0000 T10781094 (XX)
22	1153	AO2 PK WND 030153/1710 SLP306 P0000 60000 I6002 T10781094 10006 21083 53021 (XX)
22	1204	AO2 PK WND 04032/1804 P0000 T10781094 (XX)

Table B.6 Storm 3-4, Hourly Remarks, 22 FEB 2015, National Climatic Data Center, continued

22	1211	AO2 PK WND 04032/1811 P0000 T10781100 (XX)
22	1246	AO2 PK WND 04032/1811 P0000 T10831100 (XX)
22	1253	AO2 PK WND 04036/1850 SLP307 P0000 T10891106 (XX)
22	1315	AO2 PK WND 35033/1902 P0000 T10891106 (XX)
22	1329	AO2 PK WND 35033/1902 P0000 T10891106 (XX)
22	1353	AO2 PK WND 35033/1902 SLP305 P0000 T10891106 (XX)
22	1413	AO2 PK WND 02027/1957 VIS 1 1/2V3 P0000 T10831106 (XX)
22	1421	AO2 PK WND 02027/1957 P0000 T10831106 (XX)
22	1432	AO2 PK WND 02027/1957 P0000 T10891106 (XX)
22	1451	AO2 PK WND 02027/1957 SFC VIS 3 P0000 (XX)
22	1453	AO2 PK WND 02027/1957 SFC VIS 2 1/2 SLP300 P0000 60000 T10831100 56004 (XX)
22	1504	AO2 SFC VIS 2 VIS 1 1/4V2 1/2 P0000 T10831100 (XX)
22	1526	AO2 P0000 T10831100 (ATC)
22	1531	AO2 P0000 T10831106 (ATC)
22	1537	AO2 P0000 T10831106 (ATC)
22	1546	AO2 P0000 T10891106 (ATC)
22	1551	AO2 P0000 FIBI (ATC)
22	1553	AO2 SLP305 P0000 T10891106 (ATC)
22	1619	AO2 P0000 T10891106 (ATC)
22	1653	AO2 PK WND 03026/2250 SFC VIS 2 1/2 SLP310 P0000 T10941117 (ATC)
22	1751	AO2 PK WND 03027/2321 P0000 FIBI (ATC)
22	1753	AO2 PK WND 03027/2321 SLP324 P0000 60000 T10941117 11078 21094 53013 (ATC)
22	1825	AO2 SFC VIS 4 P0000 T10941111
22	1835	AO2 CIG 008V011 P0000 T10941111
22	1839	AO2 SFC VIS 2 1/2 P0000 T10941111 FIBI (ATC)
22	1853	AO2 SFC VIS 2 1/2 SLP334 P0000 T10941117
22	1932	AO2 P0000 T11001117
22	1953	AO2 CIG 009V014 SLP349 P0000 T11001117
22	2032	AO2 P0000 T11001117
22	2039	AO2 CIG 008V014 P0000 T11001117
22	2049	AO2 P0000
22	2053	AO2 SLP355 P0000 60000 T11001117 53017
22	2102	AO2 P0000 T11001117
22	2109	AO2 P0000 T11001117
22	2153	AO2 SFC VIS 2 1/2 SLP366 P0000 T11001117
22	2253	AO2 SLP374 P0000 T11061122
22	2301	AO2 P0000 T11061122
22	2326	AO2 P0000 T11061122
22	2341	AO2 P0000 T11061122
22	2348	AO2 P0000
22	2353	AO2 SLP377 P0000 60000 T11061122 11094 21106 400441106 51009

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Table B.7 Storm 3-4, Hourly Precipitation, 22 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
22						T	0.01	T	0.01	T	T	T	22	T	T	0.01	T	T	T	0.01	T	T	T	T	T	22

Table B.8 Storm 3-4, Hourly Observations, 23 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
23	0011	11	BKN010 OVC018	4.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	16	040		26.75			M	SP		30.51
23	0022	11	SCT010 OVC020	4.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	14	040		26.75			M	SP		30.51
23	0035	11	FEW009 OVC018	2.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	11	040		26.76			M	SP		30.52
23	0043	11	BKN013 OVC020	2.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	17	030		26.75			M	SP		30.51
23	0051	11	BKN013 OVC018	3.00	-SN BR	12	-11.0	11	-11.5	9	-13.0	88	14	030		26.75			M	SP		30.51
23	0053	11	BKN012 OVC018	4.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	11	030	23	26.76			30.65	AA	T	30.52
23	0153	11	BKN012 OVC020	7.00	-SN	12	-11.1	11	-11.5	9	-12.8	88	15	030		26.75			30.64	AA	T	30.50
23	0216	11	OVC012	2.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	17	020		26.75			M	SP		30.51
23	0228	11	OVC010	1.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	17	020		26.75			M	SP		30.50
23	0253	11	OVC010	1.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	16	020		26.75			30.64	AA	0.01	30.51
23	0309	11	FEW012 OVC017	2.50	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	16	030		26.73			M	SP		30.49
23	0323	11	SCT012 OVC019	3.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	21	030	26	26.72			M	SP		30.48
23	0337	11	BKN012 OVC019	3.00	-SN BR	11	-11.7	10	-12.0	8	-13.3	88	20	030	26	26.73			M	SP		30.49
23	0353	11	BKN012 OVC019	5.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	18	030		26.75			30.64	AA	T	30.50
23	0430	11	BKN010 OVC020	2.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	13	020		26.75			M	SP		30.50
23	0451	11	BKN010 OVC017	3.00	-SN BR	12	-11.0	11	-11.5	9	-13.0	88	14	030		26.75			M	SP		30.50
23	0453	11	BKN010 OVC017	3.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	15	020		26.75			30.64	AA	T	30.51
23	0501	11	BKN010 OVC017	2.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	13	020		26.75			M	SP		30.50
23	0508	11	SCT010 OVC017	1.75	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	14	020		26.73			M	SP		30.49
23	0537	11	FEW009 OVC018	2.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	13	010		26.73			M	SP		30.49
23	0553	11	FEW009 OVC016	2.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	15	020		26.72			30.61	AA	T	30.48
23	0601	11	OVC014	3.00	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	14	010		26.75			M	SP		30.50
23	0653	11	BKN010 OVC017	6.00	-SN BR	11	-11.7	10	-12.2	7	-13.9	84	15	040		26.73			30.63	AA	T	30.49
23	0740	11	BKN011 OVC017	1.75	-SN BR	11	-11.7	10	-12.0	8	-13.3	88	13	030		26.75			M	SP		30.50
23	0751	11	BKN013 OVC029	1.00	-SN BR	10	-12.0	10	-12.3	9	-13.0	96	14	030		26.75			M	SP		30.50
23	0753	11	BKN013 OVC029	1.00	-SN BR	11	-11.7	10	-12.0	8	-13.3	88	14	030		26.75			30.64	AA	T	30.50
23	0800	11	BKN013 OVC029	0.75	-SN BR	11	-11.7	10	-12.0	8	-13.3	88	11	040		26.75			M	SP		30.50
23	0816	11	BKN013 OVC037	1.25	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	17	030		26.75			M	SP		30.50
23	0827	11	BKN017 OVC040	1.50	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	14	040		26.75			M	SP		30.50
23	0836	11	FEW017 OVC042	1.75	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	13	050		26.75			M	SP		30.50
23	0846	11	FEW023 OVC041	3.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	13	040		26.75			M	SP		30.51
23	0853	11	OVC041	5.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	13	040		26.75			30.65	AA	0.01	30.51
23	0944	11	FEW012 BKN036 OVC050	1.75	-SN	12	-11.1	11	-11.8	7	-13.9	80	13	030		26.75			M	SP		30.50

Table B.8 Storm 3-4, Hourly Observations, 23 FEB 2015, National Climatic Data Center, continued

23	0949	11	BKN029 BKN050 OVC055	1.00	-SN BR	12	-11.0	11	-11.5	9	-13.0	88	10	040		26.75			M	SP		30.51
23	0953	11	BKN027 OVC055	1.00	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	10	040		26.75			30.66	AA	0.01	30.51
23	1002	11	VV019	0.50	SN FZFG	12	-11.1	11	-11.6	8	-13.3	84	9	040		26.76			M	SP		30.52
23	1013	11	VV010	0.25	+SN FZFG	12	-11.1	11	-11.5	9	-12.8	88	10	040		26.75			M	SP		30.50
23	1017	11	VV008	0.25	+SN FZFG	13	-10.6	12	-11.1	9	-12.8	84	10	040		26.75			M	SP		30.50
23	1029	11	VV005	0.25	+SN FZFG	13	-10.6	12	-11.1	9	-12.8	84	10	030		26.75			M	SP		30.50
23	1036	11	VV006	0.25	+SN FZFG	13	-10.6	12	-11.1	9	-12.8	84	9	040		26.75			M	SP		30.50
23	1046	11	VV009	0.50	SN FZFG	13	-10.6	12	-11.1	9	-12.8	84	9	050		26.75			M	SP		30.51
23	1051	11	VV010	0.50	SN FZFG	12	-11.0	11	-11.5	9	-13.0	88	9	050		26.75			M	SP		30.51
23	1053	11	VV010	0.50	SN FZFG	13	-10.6	12	-11.1	9	-12.8	84	9	050		26.75			30.65	AA	0.09	30.51
23	1112	11	VV014	1.00	-SN	14	-10.0	13	-10.7	9	-12.8	80	9	040		26.75			M	SP		30.51
23	1123	11	BKN015 OVC030	1.25	-SN	14	-10.0	13	-10.7	9	-12.8	80	9	030		26.75			M	SP		30.51
23	1138	11	BKN018 OVC030	1.00	-SN BR	14	-10.0	13	-10.6	10	-12.2	84	7	040		26.75			M	SP		30.51
23	1151	11	BKN018 BKN022 OVC028	0.75	-SN	16	-9.0	14	-9.8	10	-12.0	77	7	050		26.73			M	SP		30.49
23	1153	11	BKN018 OVC028	0.75	-SN	15	-9.4	14	-10.2	10	-12.2	80	8	060		26.73			30.63	AA	0.03	30.49
23	1200	11	BKN017 OVC028	1.25	-SN	15	-9.4	14	-10.2	10	-12.2	80	6	060		26.72			M	SP		30.48
23	1205	11	FEW008 BKN019 OVC028	2.00	-SN	15	-9.4	14	-10.2	10	-12.2	80	7	060		26.72			M	SP		30.48
23	1215	11	FEW010 BKN019 OVC033	4.00	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	6	070		26.72			M	SP		30.47
23	1251	11	BKN014 OVC027	4.00	-SN	16	-9.0	14	-9.8	10	-12.0	77	5	070		26.70			M	SP		30.45
23	1253	11	OVC014	4.00	-SN	16	-8.9	15	-9.6	11	-11.7	81	3	050		26.70			30.58	AA	T	30.45
23	1329	11	BKN014 BKN022 OVC049	2.00	-SN	17	-8.3	15	-9.2	11	-11.7	77	5	VR		26.68			M	SP		30.43
23	1339	11	SCT014 BKN023 OVC049	3.00	-SN	17	-8.3	15	-9.4	10	-12.2	74	6	040		26.66			M	SP		30.41
23	1346	11	SCT014 OVC047	4.00	-SN	17	-8.3	15	-9.2	11	-11.7	77	5	040		26.66			M	SP		30.41
23	1351	11	BKN013 OVC047	3.00	-SN	18	-8.0	16	-9.0	10	-12.0	71	5	030		26.66			M	SP		30.41
23	1353	11	BKN013 OVC047	2.50	-SN	18	-7.8	16	-8.8	11	-11.7	74	5	VR		26.67			30.54	AA	T	30.42
23	1406	11	BKN016 OVC045	6.00	HZ	18	-7.8	16	-8.8	11	-11.7	74	5	010		26.66			M	SP		30.41
23	1453	11	BKN016 OVC036	9.00		17	-8.3	16	-9.1	12	-11.1	81	5	090		26.63			30.49	AA	T	30.37
23	1501	11	BKN014 OVC036	6.00	HZ	18	-7.8	16	-8.8	11	-11.7	74	3	010		26.62			M	SP		30.36
23	1525	11	OVC015	9.00		19	-7.2	17	-8.3	12	-11.1	74	3	VR		26.60			M	SP		30.34
23	1553	11	BKN015 OVC037	10.00		18	-7.8	16	-8.8	11	-11.7	74	0	000		26.60			30.46	AA		30.34
23	1651	11	SCT016 OVC033	10.00		18	-8.0	16	-9.0	10	-12.0	71	3	140		26.58			M	SP		30.32
23	1653	11	SCT016 OVC033	10.00		17	-8.3	15	-9.2	11	-11.7	77	0	000		26.58			30.45	AA		30.32
23	1753	11	OVC028	10.00		18	-7.8	16	-8.7	12	-11.1	77	6	170		26.57			30.43	AA		30.31
23	1853	11	OVC027	10.00		17	-8.3	16	-9.1	12	-11.1	81	8	180		26.56			30.42	AA		30.29
23	1953	11	SCT024 OVC029	10.00		17	-8.3	16	-9.1	12	-11.1	81	9	180		26.55			30.41	AA		30.28
23	2053	11	BKN022 OVC028	10.00		17	-8.3	16	-8.9	13	-10.6	84	8	190		26.55			30.40	AA		30.28
23	2153	11	OVC022	10.00		17	-8.3	16	-9.1	12	-11.1	81	9	190		26.55			30.40	AA		30.28
23	2253	11	OVC025	10.00		18	-7.8	17	-8.5	13	-10.6	81	7	210		26.54			30.39	AA		30.27
23	2353	11	OVC021	10.00		18	-7.8	17	-8.4	14	-10.0	84	6	220		26.52			30.36	AA		30.25

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Table B.9 Storm 3-4, Hourly Remarks, 23 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
23	0011	AO2 P0000 T11111128
23	0022	AO2 P0000 T11111128
23	0035	AO2 P0000 T11111128
23	0043	AO2 P0000 T11111128
23	0051	AO2 P0000 FIBI
23	0053	AO2 SLP380 P0000 T11111128
23	0153	AO2 SLP375 P0000 T11111128
23	0216	AO2 P0000 T11111128
23	0228	AO2 P0000 T11111128
23	0253	AO2 SLP377 P0001 60001 T11111128 55001
23	0309	AO2 P0000 T11111133
23	0323	AO2 P0000 T11111133
23	0337	AO2 P0000 T11171133
23	0353	AO2 SLP376 P0000 T11111133
23	0430	AO2 P0000 T11111128
23	0451	AO2 P0000
23	0453	AO2 SLP377 P0000 T11111128
23	0501	AO2 P0000 T11111128
23	0508	AO2 P0000 T11111128
23	0537	AO2 P0000 T11111128
23	0553	AO2 SLP367 P0000 60001 70001 T11111128 11106 21117 58008 (XX)
23	0601	AO2 P0000 T11111128 (XX)
23	0653	AO2 SLP371 P0000 T11171139 (XX)
23	0740	AO2 P0000 T11171133 (XX)
23	0751	AO2 P0000 FIBI (XX)
23	0753	AO2 SLP377 P0000 T11171133 (XX)
23	0800	AO2 P0000 T11171133 (XX)
23	0816	AO2 P0001 T11111133 (XX)
23	0827	AO2 P0001 T11111133 (XX)
23	0836	AO2 P0001 T11111133 (XX)
23	0846	AO2 P0001 T11111133 (XX)
23	0853	AO2 SLP378 P0001 60001 T11111133 51009 (XX)
23	0944	AO2 VIS 1V5 SNE1456B19 P0000 T11111139 (XX)
23	0949	AO2 SNE1456B19 P0000 (XX)
23	0953	AO2 SNE1456B19 SLP382 P0001 T11111133 (XX)
23	1002	AO2 P0000 T11111133 (XX)
23	1013	AO2 P0002 T11111128 (XX)

Table B.9 Storm 3-4, Hourly Remarks, 23 FEB 2015, National Climatic Data Center, continued

23	1017	AO2 PRESFR P0003 T11061128 (XX)
23	1029	AO2 P0006 T11061128 (XX)
23	1036	AO2 P0008 T11061128 (XX)
23	1046	AO2 P0008 T11061128 (XX)
23	1051	AO2 P0009 FIBI (XX)
23	1053	AO2 SLP378 P0009 T11061128 (XX)
23	1112	AO2 P0001 T11001128 (XX)
23	1123	AO2 P0001 T11001128 (XX)
23	1138	AO2 P0002 T11001122 (XX)
23	1151	AO2 P0002 FIBI (XX)
23	1153	AO2 SLP371 P0002 60013 T10941122 11094 21117 58005 (XX)
23	1200	AO2 P0001 T10941122 (XX)
23	1205	AO2 P0001 T10941122 (XX)
23	1215	AO2 P0001 T10941117 (XX)
23	1251	AO2 P0001 FIBI (XX)
23	1253	AO2 SLP356 P0001 T10891117 (XX)
23	1329	AO2 P0000 T10831117 (XX)
23	1339	AO2 PRESFR P0000 T10831122 (XX)
23	1346	AO2 P0000 T10831117 (XX)
23	1351	AO2 P0000 FIBI (XX)
23	1353	AO2 VIS 2V5 SLP343 P0000 T10781117 (XX)
23	1406	AO2 SNE06 P0000 T10781117 (XX)
23	1453	AO2 SNE06B17E32 SLP326 P0000 60001 T10831111 58038 (XX)
23	1501	AO2 T10781117 (XX)
23	1525	AO2 T10721111 (XX)
23	1553	AO2 SLP316 T10781117 (XX)
23	1651	AO2 FIBI (XX)
23	1653	AO2 SLP310 T10831117 (XX)
23	1753	AO2 SLP305 60001 T10781111 11072 21100 56018 (XX)
23	1853	AO2 SLP300 T10831111
23	1953	AO2 SLP298 T10831111
23	2053	AO2 SLP296 T10831106 56008
23	2153	AO2 SLP295 T10831111
23	2253	AO2 SLP290 T10781106
23	2353	AO2 SLP281 T10781100 11078 21083 410721117 58010

Dynamically generated Mon Mar 27 08:20:43 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table B.10 Storm 3-4, Hourly Precipitation, 23 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
23	T	T	0.01	T	T	T	T	T	0.01	0.01	0.09	0.03	23	T	T	T										23

Table B.11 Storm 3-4, Hourly Observations, FEB 21-23, 2015, WTAMU SchoolNET

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/21/2015	0:00	45.2	61	32.6	45.2	30.08	0.02	0	0	- -	11	2	23
2/21/2015	1:00	43.2	70	34.2	43.2	30.1	0.08	0	0	- -	19	2	19
2/21/2015	2:00	42.1	73	34.1	42.1	30.1	0.12	0	0	- -	8	1	7
2/21/2015	3:00	39.9	72	31.7	39.9	30.13	0.14	0	0	- -	10	16	9
2/21/2015	4:00	38.5	74	31	38.5	30.14	0.17	0	0	- -	7	16	8
2/21/2015	5:00	37.5	73	29.7	37.5	30.16	0.19	0	0	- -	3	15	3
2/21/2015	6:00	35	80	29.5	35	30.17	0.22	0	0	- -	5	16	5
2/21/2015	7:00	34.6	87	31.1	34.6	30.19	0.13	0	0	- -	5	16	6
2/21/2015	8:00	33.2	89	30.3	33.2	30.21	0.07	0	0	- -	1	1	3
2/21/2015	9:00	34.3	86	30.5	34.3	30.25	0.06	0	0	- -	2	15	1
2/21/2015	10:00	41.4	72	33.1	41.4	30.27	0.06	0	0	- -	3	8	9
2/21/2015	11:00	45.1	62	32.9	45.1	30.26	0.07	0	0	- -	5	8	11
2/21/2015	12:00	47.1	57	32.7	47.1	30.25	0.08	0	0	- -	6	2	11
2/21/2015	13:00	49.3	52	32.4	49.3	30.22	0.07	0	0	- -	5	9	9
2/21/2015	14:00	51	48	31.9	51	30.19	0.06	0	0	- -	10	5	10
2/21/2015	15:00	53.4	44	31.9	53.4	30.18	0.05	0	0	- -	3	2	7
2/21/2015	16:00	53.5	45	32.6	53.5	30.17	0.01	0	0	- -	4	7	5
2/21/2015	17:00	53	45	32.1	53	30.16	-0.02	0	0	- -	8	7	8
2/21/2015	18:00	51.8	48	32.7	51.8	30.18	-0.05	0	0	- -	14	7	13
2/21/2015	19:00	47.4	55	32.1	47.4	30.21	-0.06	0	0	- -	8	7	13
2/21/2015	20:00	44.6	60	31.6	44.6	30.23	-0.06	0	0	- -	5	4	7
2/21/2015	21:00	43	65	32.1	43	30.27	-0.04	0	0	- -	6	7	9
2/21/2015	22:00	42.1	69	32.7	42.1	30.29	0	0	0	- -	12	6	12
2/21/2015	23:00	41.4	73	33.5	41.4	30.28	0.04	0	0	- -	10	6	13

Table B.11 Storm 3-4, Hourly Observations, FEB 21-23, 2015, WTAMU SchoolNET, continued

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/22/2015	0:00	40.4	75	33.2	40.4	30.3	0.07	0	0	- -	6	12	9
2/22/2015	1:00	40.2	75	33	40.2	30.32	0.07	0	0	- -	4	8	8
2/22/2015	2:00	40.5	74	32.9	40.5	30.34	0.1	0	0	- -	5	6	8
2/22/2015	3:00	40.2	75	33	40.2	30.36	0.09	0	0	- -	9	5	13
2/22/2015	4:00	39.9	76	33	39.9	30.4	0.08	0	0	- -	4	9	9
2/22/2015	5:00	39.8	77	33.2	39.8	30.42	0.07	0	0	- -	9	3	11
2/22/2015	6:00	39.1	77	32.5	39.1	30.47	0.07	0	0	- -	7	2	10
2/22/2015	7:00	29.1	90	26.5	29.1	30.53	0.09	0	0	- -	18	1	23
2/22/2015	8:00	22.8	91	20.5	22.8	30.57	0.11	0	0	- -	25	4	25
2/22/2015	9:00	20.4	90	17.9	20.4	30.62	0.13	0	0	- -	14	3	27
2/22/2015	10:00	19.5	90	17	19.5	30.66	0.14	0	0	- -	20	2	21
2/22/2015	11:00	18.8	89	16	18.8	30.68	0.16	0	0	- -	20	1	20
2/22/2015	12:00	18.8	89	16	18.8	30.7	0.17	0	0	- -	18	2	18
2/22/2015	13:00	18.2	89	15.5	18.2	30.71	0.17	0	0	- -	21	2	24
2/22/2015	14:00	17.4	89	14.7	17.4	30.72	0.18	0	0	- -	11	1	15
2/22/2015	15:00	17.3	89	14.6	17.3	30.72	0.15	0	0	- -	12	2	16
2/22/2015	16:00	17.2	89	14.5	17.2	30.76	0.12	0	0	- -	11	2	11
2/22/2015	17:00	17	89	14.3	17	30.75	0.1	0	0	- -	9	2	8
2/22/2015	18:00	15.9	89	13.2	15.9	30.81	0.07	0	0	- -	13	3	16
2/22/2015	19:00	15.6	89	12.9	15.6	30.82	0.08	0	0	- -	8	2	8
2/22/2015	20:00	15.3	89	12.6	15.3	30.85	0.06	0	0	- -	8	3	8
2/22/2015	21:00	14.6	89	11.9	14.6	30.91	0.07	0	0	- -	9	3	9
2/22/2015	22:00	14.9	90	12.5	14.9	30.94	0.08	0	0	- -	11	2	11
2/22/2015	23:00	14.4	89	11.7	14.4	30.96	0.11	0	0	- -	7	2	7

Table B.11 Storm 3-4, Hourly Observations, FEB 21-23, 2015, WTAMU SchoolNET, continued

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/23/2015	0:00	14.3	90	11.9	14.3	30.97	0.12	0	0	- -	10	2	13
2/23/2015	1:00	13.1	89	10.4	13.1	30.98	0.13	0	0	- -	20	3	20
2/23/2015	2:00	13.1	89	10.4	13.1	30.99	0.12	0	0	- -	8	2	8
2/23/2015	3:00	12.8	89	10.1	12.8	30.99	0.12	0	0	- -	9	2	12
2/23/2015	4:00	12.8	90	10.4	12.8	31	0.09	0	0	- -	8	1	9
2/23/2015	5:00	12.1	89	9.4	12.1	31.01	0.09	0	0	- -	7	2	11
2/23/2015	6:00	12.3	89	9.6	12.3	30.96	0.05	0	0	- -	11	2	15
2/23/2015	7:00	12.7	89	10	12.7	31.02	0.04	0	0	- -	7	4	10
2/23/2015	8:00	11.9	89	9.2	11.9	31.03	0.03	0	0	- -	8	2	8
2/23/2015	9:00	12.8	89	10.1	12.8	31.05	0.01	0	0	- -	4	2	5
2/23/2015	10:00	11.9	89	9.2	11.9	31.06	0.02	0	0	- -	9	3	13
2/23/2015	11:00	15.2	91	13	15.2	31.07	0.03	0	0	- -	5	3	5
2/23/2015	12:00	14	90	11.6	14	31.04	0.03	0	0	- -	5	3	8
2/23/2015	13:00	16.1	90	13.6	16.1	31.01	0.03	0	0	- -	2	8	3
2/23/2015	14:00	18.2	89	15.5	18.2	30.97	0.04	0	0	- -	3	3	4
2/23/2015	15:00	18.7	90	16.2	18.7	30.91	0.01	0.03	0	- -	3	7	2
2/23/2015	16:00	19.6	89	16.8	19.6	30.88	-0.03	0.06	0	- -	3	3	5
2/23/2015	17:00	18.5	86	15	18.5	30.87	-0.06	0.08	0	- -	2	1	3
2/23/2015	18:00	18.2	87	14.9	18.2	30.85	-0.09	0.08	0	- -	1	7	0
2/23/2015	19:00	17.3	87	14.1	17.3	30.84	-0.11	0.08	0	- -	3	9	4
2/23/2015	20:00	17.1	86	13.6	17.1	30.83	-0.15	0.08	0	- -	2	11	4
2/23/2015	21:00	17.6	87	14.4	17.6	30.82	-0.13	0.08	0	- -	5	9	6
2/23/2015	22:00	18.1	87	14.8	18.1	30.82	-0.12	0.08	0	- -	4	11	4
2/23/2015	23:00	18.4	88	15.4	18.4	30.82	-0.09	0.08	0	- -	1	11	2

APPENDIX B

Storm 3-4

VIDEO DATA

Table B-12. Statistical Comparison of De-icing Videos for Storm 3-4

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	85.4	8.3	2/23, After first snowfall
	2	C	0.0	0.0	2/23, After >1 in snow
	3	C	35.0	10.6	2/23, After 1st plow
	4	C	61.3	9.9	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	C	82.9	8.6	2/23, After 2nd plow
	1	MD20	85.8	7.9	2/23, After first snowfall
	2	MD20	0.0	0.0	2/23, After >1 in snow
	3	MD20	37.5	12.9	2/23, After 1st plow
	4	MD20	70.0	7.4	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	MD20	83.3	8.9	2/23, After 2nd plow
	1	RS	82.5	10.6	2/23, After first snowfall
	2	RS	0.0	0.0	2/23, After >1 in snow
	3	RS	35.0	16.2	2/23, After 1st plow
	4	RS	61.7	9.4	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	RS	84.2	6.7	2/23, After 2nd plow

Table B-13. Raw Data from De-icing Videos for Storm 3-4

De-Icing Video No.	Date	Time	LANE	STATION	TREATMENT	KR % BARE	KR AASHTO	KR PSIC	FE % BARE	FE AASHTO	FE PSIC	WDL % BARE	WDL AASHTO	WDL PSIC
1	2/23/2015	9:31	NB	0-10	Control	80	4	2	80	4	2	80	4	1
				10-20	Meltdown-20	80	4	2	80	4	2	90	4	1
				20-30	Control	90	4	2	80	4	2	90	4	1
				30-40	Road Salt	90	4	2	80	4	2	90	4	1
				40-50	Control	90	4	2	90	4	2	90	4	1
				50-60	Meltdown-20	90	4	2	90	4	2	90	4	1
				60-70	Control	80	4	2	90	4	2	100	4	1
				70-80	Road Salt	90	4	2	90	4	2	90	4	1
			SB	80-70	Control	90	4	2	90	4	2	100	4	1
				70-60	Meltdown-20	90	4	2	90	4	2	100	4	1
				60-50	Control	90	4	2	70	4	2	90	4	1
				50-40	Road Salt	90	4	2	80	4	2	90	4	1
				40-30	Control	90	4	2	80	4	2	90	4	1
				30-20	Meltdown-20	80	4	2	70	4	2	80	4	1
				20-10	Control	70	4	2	70	4	2	80	4	1
				10-0	Road Salt	70	4	2	60	7	2	70	4	1
2	2/23/2015	11:47	NB	0-10	Control	0	8	3	0	8	3	0	8	4
				10-20	Meltdown-20	0	8	3	0	8	3	0	8	4
				20-30	Control	0	8	3	0	8	3	0	8	4
				30-40	Road Salt	0	8	3	0	8	3	0	8	4
				40-50	Control	0	8	3	0	8	3	0	8	4
				50-60	Meltdown-20	0	8	3	0	8	3	0	8	4
				60-70	Control	0	8	3	0	8	3	0	8	4
				70-80	Road Salt	0	8	3	0	8	3	0	8	4
			SB	80-70	Control	0	8	3	0	8	3	0	8	4
				70-60	Meltdown-20	0	8	3	0	8	3	0	8	4
				60-50	Control	0	8	3	0	8	3	0	8	4
				50-40	Road Salt	0	8	3	0	8	3	0	8	4
				40-30	Control	0	8	3	0	8	3	0	8	4
				30-20	Meltdown-20	0	8	3	0	8	3	0	8	4
				20-10	Control	0	8	3	0	8	3	0	8	4
				10-0	Road Salt	0	8	3	0	8	3	0	8	4
3	2/23/2015	13:52	NB	0-10	Control	20	6	4	30	6	3	20	7	4
				10-20	Meltdown-20	20	6	4	30	7	3	20	7	4
				20-30	Control	20	5	4	40	6	3	40	6	3
				30-40	Road Salt	30	5	4	30	6	3	40	7	3
				40-50	Control	30	5	4	30	6	3	30	6	3
				50-60	Meltdown-20	30	5	4	30	6	3	30	6	3
				60-70	Control	20	5	4	30	6	3	20	6	3
				70-80	Road Salt	10	5	4	10	6	3	20	6	3
			SB	80-70	Control	40	5	4	50	6	3	40	6	3
				70-60	Meltdown-20	40	5	4	60	6	3	50	6	3
				60-50	Control	40	5	4	40	6	3	50	5	3
				50-40	Road Salt	30	5	4	50	6	3	60	5	3
				40-30	Control	30	5	4	50	6	3	50	6	3
				30-20	Meltdown-20	40	5	4	50	7	3	50	5	3
				20-10	Control	30	5	4	50	6	3	40	6	3
				10-0	Road Salt	40	5	4	50	7	3	50	5	3

Table B-13. Raw Data from De-icing Videos for Storm 3-4 Continued

De-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
4	2/23/2015	15:07	NB	0-10	Control	70	5	3	60	7	2	60	5	3
				10-20	Meltdown-20	80	5	3	60	7	2	80	5	2
				20-30	Control	70	5	3	70	4	2	80	5	3
				30-40	Road Salt	60	5	3	50	7	2	60	5	3
				40-50	Control	60	5	3	60	6	2	60	5	3
				50-60	Meltdown-20	70	5	3	60	4	2	70	5	2
				60-70	Control	40	5	3	50	5	2	40	5	3
				70-80	Road Salt	60	5	3	50	6	2	50	5	2
			SB	80-70	Control	70	5	3	60	4	2	70	5	3
				70-60	Meltdown-20	80	5	3	70	4	2	60	5	3
				60-50	Control	70	5	3	60	5	2	50	5	3
				50-40	Road Salt	70	5	3	60	4	2	60	5	3
				40-30	Control	60	5	3	60	5	2	50	5	3
				30-20	Meltdown-20	70	5	3	70	5	2	70	5	3
				20-10	Control	70	5	3	70	4	2	60	5	3
				10-0	Road Salt	80	5	3	70	5	2	70	5	3
5	2/23/2015	16:48	NB	0-10	Control	90	4	2	80	4	2	100	3	1
				10-20	Meltdown-20	90	4	2	70	4	2	90	5	1
				20-30	Control	90	4	2	80	4	2	100	3	1
				30-40	Road Salt	80	4	2	80	4	2	90	3	1
				40-50	Control	80	4	2	70	4	2	90	5	1
				50-60	Meltdown-20	90	4	2	70	4	2	90	5	1
				60-70	Control	80	4	2	70	4	2	90	5	1
				70-80	Road Salt	90	4	2	70	4	2	90	4	1
			SB	80-70	Control	80	4	2	80	4	2	80	3	2
				70-60	Meltdown-20	90	4	2	80	4	2	70	5	2
				60-50	Control	80	4	2	70	5	2	80	5	2
				50-40	Road Salt	80	4	2	80	4	2	90	3	1
				40-30	Control	90	4	2	90	4	2	90	4	1
				30-20	Meltdown-20	90	4	2	80	4	2	90	3	1
				20-10	Control	80	4	2	80	5	2	70	5	2
				10-0	Road Salt	90	4	2	80	4	2	90	3	1

Table B-14. Statistical Comparison of Anti-icing Videos for Storm 3-4

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
Anti-icing	1	C	63.3	14.4	2/23, After first snowfall
	2	C	0.0	0.0	2/23, After >1 in snow
	3	C	15.0	5.2	2/23, After 1st plow
	4	C	48.3	10.3	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	C	71.7	15.3	2/23, After 2nd plow
	1	MDA	60.0	6.3	2/23, After first snowfall
	2	MDA	0.0	0.0	2/23, After >1 in snow
	3	MDA	23.3	8.2	2/23, After 1st plow
	4	MDA	53.3	16.3	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	MDA	76.7	19.7	2/23, After 2nd plow
	1	RSB	58.3	21.4	2/23, After first snowfall
	2	RSB	0.0	0.0	2/23, After >1 in snow
	3	RSB	21.7	4.1	2/23, After 1st plow
	4	RSB	55.0	18.7	2/23, After 1st de-icing, 2nd anti-icing, slushing
	5	RSB	83.3	8.2	2/23, After 2nd plow

Table B-15. Raw Data from Anti-icing Videos for Storm 3-4

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
1	2/23/2015	9:13	SB	0-10	Control	70	4	2	60	4	2	80	4	1
				10-20	Meltdown Apex	70	4	2	60	7	2	60	6	2
				20-30	Control	60	4	2	40	7	2	50	6	2
				30-40	Road Salt Brine	50	4	2	30	7	2	40	7	2
			NB	40-30	Control	70	4	2	40	7	2	70	6	2
				30-20	Meltdown Apex	60	4	2	50	7	2	60	6	2
				20-10	Control	80	4	2	60	7	2	80	4	1
				10-10	Road Salt Brine	80	4	2	70	4	2	80	4	1
2	2/23/2015	11:39	SB	0-10	Control	0	8	3	0	8	3	0	8	4
				10-20	Meltdown Apex	0	8	3	0	8	3	0	8	4
				20-30	Control	0	8	3	0	8	3	0	8	4
				30-40	Road Salt Brine	0	8	3	0	8	3	0	8	4
			NB	40-30	Control	0	8	3	0	8	3	0	8	4
				30-20	Meltdown Apex	0	8	3	0	8	3	0	8	4
				20-10	Control	0	8	3	0	8	3	0	8	4
				10-10	Road Salt Brine	0	8	3	0	8	3	0	8	4
3	2/23/2015	13:45	SB	0-10	Control	20	6	4	20	6	4	20	6	4
				10-20	Meltdown Apex	20	6	4	30	7	4	30	6	3
				20-30	Control	10	6	4	10	9	4	20	7	4
				30-40	Road Salt Brine	20	6	4	20	6	4	20	7	4
			NB	40-30	Control	10	6	4	20	9	4	10	9	4
				30-20	Meltdown Apex	10	6	4	30	7	4	20	7	3
				20-10	Control	10	6	4	20	6	4	10	9	4
				10-10	Road Salt Brine	20	6	4	30	6	4	20	6	3
4	2/23/2015	15:12	SB	0-10	Control	50	5	3	50	5	3	50	5	3
				10-20	Meltdown Apex	70	5	3	60	5	3	70	5	3
				20-30	Control	60	5	3	60	5	3	60	5	3
				30-40	Road Salt Brine	80	5	3	60	7	3	70	5	3
			NB	40-30	Control	30	5	3	30	7	4	40	5	3
				30-20	Meltdown Apex	40	5	3	30	7	4	50	5	3
				20-10	Control	50	5	3	50	5	3	50	5	3
				10-10	Road Salt Brine	30	5	3	40	5	3	50	5	3
5	2/23/2015	16:48	SB	0-10	Control	70	4	2	80	4	2	80	4	2
				10-20	Meltdown Apex	90	4	2	90	3	2	100	3	1
				20-30	Control	80	4	2	90	4	2	90	5	1
				30-40	Road Salt Brine	90	4	2	90	4	2	90	5	2
			NB	40-30	Control	50	5	3	50	7	4	50	5	2
				30-20	Meltdown Apex	70	5	3	50	7	3	60	5	2
				20-10	Control	80	5	3	60	5	2	80	5	2
				10-10	Road Salt Brine	80	5	3	70	5	2	80	5	2

APPENDIX B

Storm 3-4

IMAGE DATA

Table B-16. Statistical Comparison of De-icing Photos for Storm 3-4

Type	Photoset	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	100.0	0.0	2/21, Before 1st anti-icing
	2	C	100.0	0.0	2/21, After 1st anti-Icing, slushing
	3	C	100.0	0.0	2/22, After first snowfall
	4	C	13.4	13.5	2/23, After >1 in snow
	5	C	93.9	11.3	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	MD	100.0	0.0	2/21, Before 1st anti-icing
	2	MD	100.0	0.0	2/21, After 1st anti-Icing, slushing
	3	MD	100.0	0.0	2/22, After first snowfall
	4	MD	14.8	22.2	2/23, After >1 in snow
	5	MD	100.0	0.0	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	RS	100.0	0.0	2/21, Before 1st anti-icing
	2	RS	100.0	0.0	2/21, After 1st anti-Icing, slushing
	3	RS	100.0	0.0	2/22, After first snowfall
	4	RS	11.5	17.6	2/23, After >1 in snow
	5	RS	95.6	5.8	2/23, After 1st de-icing, 2nd anti-icing, slushing

Table B-17. Raw Data from De-icing Photos for Storm 3-4

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
1	2/21/2015	16:14	NB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	Road Salt	0	0	100	0	0	100	0	0	100
				34	Road Salt	0	0	100	0	0	100	0	0	100
				38	Road Salt	0	0	100	0	0	100	0	0	100
				44	Control	0	0	100	0	0	100	0	0	100
				46	Control	0	0	100	0	0	100	0	0	100
				48	Control	0	0	100	0	0	100	0	0	100
				52	MD 20	0	0	100	0	0	100	0	0	100
				54	MD 20	0	0	100	0	0	100	0	0	100
				58	MD 20	0	0	100	0	0	100	0	0	100
				64	Control	0	0	100	0	0	100	0	0	100
				66	Control	0	0	100	0	0	100	0	0	100
				68	Control	0	0	100	0	0	100	0	0	100
				72	Road Salt	0	0	100	0	0	100	0	0	100
				74	Road Salt	0	0	100	0	0	100	0	0	100
				78	Road Salt	0	0	100	0	0	100	0	0	100
			SB	76	Control	0	0	100	0	0	100	0	0	100
				74	Control	0	0	100	0	0	100	0	0	100
				72	Control	0	0	100	0	0	100	0	0	100
				68	MD 20	0	0	100	0	0	100	0	0	100
				64	MD 20	0	0	100	0	0	100	0	0	100
				62	MD 20	0	0	100	0	0	100	0	0	100
				56	Control	0	0	100	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	0	0	100	0	0	100	0	0	100
				48	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	Road Salt	0	0	100	0	0	100	0	0	100
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	0	0	100	0	0	100	0	0	100

Table B-17. Raw Data from De-icing Photos for Storm 3-4 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
2	2/21/2015	20:08	NB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	Road Salt	0	0	100	0	0	100	0	0	100
				34	Road Salt	0	0	100	0	0	100	0	0	100
				38	Road Salt	0	0	100	0	0	100	0	0	100
				44	Control	0	0	100	0	0	100	0	0	100
				46	Control	0	0	100	0	0	100	0	0	100
				48	Control	0	0	100	0	0	100	0	0	100
				52	MD 20	0	0	100	0	0	100	0	0	100
				54	MD 20	0	0	100	0	0	100	0	0	100
				58	MD 20	0	0	100	0	0	100	0	0	100
				64	Control	0	0	100	0	0	100	0	0	100
				66	Control	0	0	100	0	0	100	0	0	100
				68	Control	0	0	100	0	0	100	0	0	100
				72	Road Salt	0	0	100	0	0	100	0	0	100
				74	Road Salt	0	0	100	0	0	100	0	0	100
				78	Road Salt	0	0	100	0	0	100	0	0	100
			SB	76	Control	0	0	100	0	0	100	0	0	100
				74	Control	0	0	100	0	0	100	0	0	100
				72	Control	0	0	100	0	0	100	0	0	100
				68	MD 20	0	0	100	0	0	100	0	0	100
				64	MD 20	0	0	100	0	0	100	0	0	100
				62	MD 20	0	0	100	0	0	100	0	0	100
				56	Control	0	0	100	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	0	0	100	0	0	100	0	0	100
				48	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	Road Salt	0	0	100	0	0	100	0	0	100
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	0	0	100	0	0	100	0	0	100

Table B-17. Raw Data from De-icing Photos for Storm 3-4 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
3	2/22/2015	15;12	NB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	Road Salt	0	0	100	0	0	100	0	0	100
				34	Road Salt	0	0	100	0	0	100	0	0	100
				38	Road Salt	0	0	100	0	0	100	0	0	100
				44	Control	0	0	100	0	0	100	0	0	100
				46	Control	0	0	100	0	0	100	0	0	100
				48	Control	0	0	100	0	0	100	0	0	100
				52	MD 20	0	0	100	0	0	100	0	0	100
				54	MD 20	0	0	100	0	0	100	0	0	100
				58	MD 20	0	0	100	0	0	100	0	0	100
				64	Control	0	0	100	0	0	100	0	0	100
				66	Control	0	0	100	0	0	100	0	0	100
				68	Control	0	0	100	0	0	100	0	0	100
				72	Road Salt	0	0	100	0	0	100	0	0	100
				74	Road Salt	0	0	100	0	0	100	0	0	100
				78	Road Salt	0	0	100	0	0	100	0	0	100
			SB	76	Control	0	0	100	0	0	100	0	0	100
				74	Control	0	0	100	0	0	100	0	0	100
				72	Control	0	0	100	0	0	100	0	0	100
				68	MD 20	0	0	100	0	0	100	0	0	100
				64	MD 20	0	0	100	0	0	100	0	0	100
				62	MD 20	0	0	100	0	0	100	0	0	100
				56	Control	0	0	100	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	0	0	100	0	0	100	0	0	100
				48	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	Road Salt	0	0	100	0	0	100	0	0	100
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	0	0	100	0	0	100	0	0	100

Table B-17. Raw Data from De-icing Photos for Storm 3-4 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
4	2/23/2015	12:50	NB	4	Control	90	0	10	100	0	0	97	0	3
				6	Control	90	0	10	98	0	2	97	0	3
				8	Control	90	0	10	99	0	1	97	0	3
				12	MD 20	100	0	0	100	0	0	100	0	0
				14	MD 20	90	0	10	100	0	0	96	0	4
				18	MD 20	90	0	10	99	0	1	96	0	4
				24	Control	90	0	10	100	0	0	99	0	1
				26	Control	100	0	0	100	0	0	100	0	0
				28	Control	90	0	10	98	0	2	97	0	3
				32	Road Salt	90	0	10	98	0	2	99	0	1
				34	Road Salt	90	0	10	96	0	4	97	0	3
				38	Road Salt	80	0	20	88	0	12	90	0	10
				44	Control	90	0	10	99	0	1	99	0	1
				46	Control	90	0	10	99	0	1	98	0	2
				48	Control	90	0	10	87	0	13	96	0	4
				52	MD 20	90	0	10	99	0	1	100	0	0
				54	MD 20	80	0	20	94	0	6	97	0	3
				58	MD 20	90	0	10	99	0	1	96	0	4
				64	Control	80	0	20	92	0	8	95	0	5
				66	Control	100	0	0	100	0	0	100	0	0
				68	Control	100	0	0	100	0	0	100	0	0
				72	Road Salt	100	0	0	100	0	0	100	0	0
				74	Road Salt	100	0	0	100	0	0	100	0	0
				78	Road Salt	90	0	10	99	0	1	97	0	3
			SB	76	Control	100	0	0	100	0	0	100	0	0
				74	Control	72	0	28	68	0	32	67	0	33
				72	Control	63	0	37	64	0	36	64	0	36
				68	MD 20	90	0	10	100	0	0	100	0	0
				64	MD 20	100	0	0	100	0	0	100	0	0
				62	MD 20	70	0	30	78	0	22	74	0	26
				56	Control	80	0	20	96	0	4	94	0	6
				54	Control	70	0	30	75	0	25	54	0	46
				52	Control	90	0	10	92	0	8	84	0	16
				48	Road Salt	90	0	10	98	0	2	98	0	2
				44	Road Salt	90	0	10	100	0	0	100	0	0
				42	Road Salt	100	0	0	100	0	0	100	0	0
				36	Control	90	0	10	97	0	3	97	0	3
				34	Control	63	0	37	64	0	36	58	0	42
				32	Control	72	0	28	66	0	34	64	0	36
				28	MD 20	100	0	0	100	0	0	100	0	0
				24	MD 20	40	0	60	42	0	58	34	0	66
				22	MD 20	40	0	60	45	0	55	40	0	60
				16	Control	78	0	22	69	0	31	68	0	32
				14	Control	80	0	20	91	0	9	83	0	17
				12	Control	76	0	24	71	0	29	68	0	32
				8	Road Salt	90	0	10	99	0	1	94	0	6
				6	Road Salt	44	0	56	54	10	36	41	0	59
				2	Road Salt	52	0	48	67	0	33	54	0	46

Table B-17. Raw Data from De-icing Photos for Storm 3-4 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
5	2/23/2015	15:24	NB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	5	5	90	10	10	80	5	5	90
				8	Control	0	0	100	5	5	90	0	0	100
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	5	5	90	5	5	90	0	0	100
				28	Control	10	10	80	10	10	80	5	5	90
				32	Road Salt	5	5	90	5	5	90	5	5	90
				34	Road Salt	10	10	80	10	10	80	5	5	90
				38	Road Salt	5	5	90	10	10	80	5	5	90
				44	Control	15	15	70	10	10	80	5	5	90
				46	Control	15	15	70	15	15	70	5	5	90
				48	Control	0	0	100	0	0	100	0	0	100
				52	MD 20	0	0	100	0	0	100	0	0	100
				54	MD 20	0	0	100	0	0	100	0	0	100
				58	MD 20	0	0	100	0	0	100	0	0	100
				64	Control	0	0	100	0	0	100	0	0	100
				66	Control	30	30	40	30	30	40	30	30	40
				68	Control	35	35	30	35	35	30	35	35	30
				72	Road Salt	15	15	70	20	20	60	15	15	70
				74	Road Salt	5	5	90	5	5	90	0	0	100
				78	Road Salt	15	15	70	15	15	70	10	10	80
			SB	76	Control	40	40	20	35	35	30	30	30	40
				74	Control	0	0	100	0	0	100	0	0	100
				72	Control	0	0	100	0	0	100	0	0	100
				68	MD 20	0	0	100	0	0	100	0	0	100
				64	MD 20	0	0	100	0	0	100	0	0	100
				62	MD 20	0	0	100	0	0	100	0	0	100
				56	Control	5	5	90	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	5	5	90	5	5	90	0	0	100
				48	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	Road Salt	0	0	100	0	0	100	0	0	100
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	0	0	100	0	0	100	0	0	100

Table B-18. Statistical Comparison of Anti-icing Photos for Storm 3-4

Type	Photoset	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
Anti-icing	1	C	100.0	0.00	2/21, Before 1st anti-icing
	2	C	100.0	0.00	2/21, After 1st anti-icing, slushing
	3	C	99.4	1.30	2/22, After first snowfall
	4	C	4.5	3.39	2/23, After >1 in snow
	5	C	84.6	17.65	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	MDA	100.0	0.00	2/21, Before 1st anti-icing
	2	MDA	100.0	0.00	2/21, After 1st anti-icing, slushing
	3	MDA	95.6	3.44	2/22, After first snowfall
	4	MDA	10.8	13.17	2/23, After >1 in snow
	5	MDA	88.6	13.17	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	RSB	100.0	0.00	2/21, Before 1st anti-icing
	2	RSB	100.0	0.00	2/21, After 1st anti-icing, slushing
	3	RSB	91.6	6.77	2/22, After first snowfall
	4	RSB	0.0	0.00	2/23, After >1 in snow
	5	RSB	84.4	11.48	2/23, After 1st de-icing, 2nd anti-icing, slushing

Table B-19. Raw Data from Anti-icing Photos for Storm 3-4

Anti-Icing Video No.	Date	Time	LANE	STATION	TREATMENT	KR Snowy	KR Slush	KR Clear	FE Snowy	FE Slush	FE Clear	WDL Snowy	WDL Slush	WDL Clear
1	2/21/2015	16:14	SB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MDA	0	0	100	0	0	100	0	0	100
				14	MDA	0	0	100	0	0	100	0	0	100
				18	MDA	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	RSB	0	0	100	0	0	100	0	0	100
				34	RSB	0	0	100	0	0	100	0	0	100
				38	RSB	0	0	100	0	0	100	0	0	100
			NB	36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MDA	0	0	100	0	0	100	0	0	100
				24	MDA	0	0	100	0	0	100	0	0	100
				22	MDA	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	RSB	0	0	100	0	0	100	0	0	100
				6	RSB	0	0	100	0	0	100	0	0	100
				2	RSB	0	0	100	0	0	100	0	0	100
2	2/21/2015	20:08	SB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MDA	0	0	100	0	0	100	0	0	100
				14	MDA	0	0	100	0	0	100	0	0	100
				18	MDA	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	0	0	100	0	0	100	0	0	100
				32	RSB	0	0	100	0	0	100	0	0	100
				34	RSB	0	0	100	0	0	100	0	0	100
				38	RSB	0	0	100	0	0	100	0	0	100
			NB	36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MDA	0	0	100	0	0	100	0	0	100
				24	MDA	0	0	100	0	0	100	0	0	100
				22	MDA	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	RSB	0	0	100	0	0	100	0	0	100
				6	RSB	0	0	100	0	0	100	0	0	100
				2	RSB	0	0	100	0	0	100	0	0	100

Table B-19. Raw Data from Anti-icing Photos for Storm 3-4 Continued

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
3	2/22/2015	15:12	SB	4	Control	0	0	100	0	0	100	0	0	100
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	0	0	100	0	0	100	0	0	100
				12	MDA	10	0	90	5	0	95	15	0	85
				14	MDA	0	0	100	0	0	100	10	0	90
				18	MDA	0	0	100	0	0	100	0	0	100
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	0	0	100	10	0	90	0	0	100
				28	Control	0	0	100	10	0	90	0	0	100
				32	RSB	10	0	90	10	0	90	10	0	90
				34	RSB	10	0	90	15	0	85	15	0	85
				38	RSB	10	0	90	16	0	84	10	0	90
			NB	36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MDA	0	0	100	0	0	100	10	0	90
				24	MDA	0	0	100	10	0	90	10	0	90
				22	MDA	0	0	100	0	0	100	10	0	90
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	0	0	100
				8	RSB	0	0	100	0	0	100	0	0	100
				6	RSB	19	0	81	11	0	89	16	0	84
				2	RSB	0	0	100	0	0	100	0	0	100
4	2/23/2015	12:50	SB	4	Control	90	0	10	98	0	2	97	0	3
				6	Control	80	0	20	94	0	6	92	0	8
				8	Control	90	0	10	99	0	1	97	0	3
				12	MDA	80	0	20	96	0	4	91	0	9
				14	MDA	90	0	10	90	0	10	98	0	2
				18	MDA	18	0	82	88	0	12	84	0	16
				24	Control	90	0	10	100	0	0	97	0	3
				26	Control	100	0	0	100	0	0	100	0	0
				28	Control	90	0	10	100	0	0	100	0	0
				32	RSB	100	0	0	100	0	0	100	0	0
				34	RSB	100	0	0	100	0	0	100	0	0
				38	RSB	100	0	0	100	0	0	100	0	0
			NB	36	Control	90	0	10	97	0	3	97	0	3
				34	Control	90	0	10	97	0	3	96	0	4
				32	Control	90	0	10	97	0	3	94	0	6
				28	MDA	90	0	10	98	0	2	94	0	6
				24	MDA	90	0	10	99	0	1	99	0	1
				22	MDA	100	0	0	100	0	0	100	0	0
				16	Control	90	0	10	90	0	10	96	0	4
				14	Control	100	0	0	100	0	0	100	0	0
				12	Control	100	0	0	100	0	0	100	0	0
				8	RSB	100	0	0	100	0	0	100	0	0
				6	RSB	100	0	0	100	0	0	100	0	0
				2	RSB	100	0	0	100	0	0	100	0	0

Table B-19. Raw Data from Anti-icing Photos for Storm 3-4 Continued

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
5	2/23/2015	15:24	SB	4	Control	5	5	90	5	5	90	5	5	90
				6	Control	0	0	100	0	0	100	0	0	100
				8	Control	5	5	90	10	10	80	5	5	90
				12	MDA	0	0	100	0	0	100	0	0	100
				14	MDA	0	0	100	0	0	100	0	0	100
				18	MDA	5	5	90	5	5	90	5	5	90
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	5	5	90	0	0	100	0	0	100
				28	Control	5	5	90	5	5	90	5	5	90
				32	RSB	10	10	80	15	15	70	5	5	90
				34	RSB	10	10	80	10	10	80	5	5	90
				38	RSB	0	0	100	0	0	100	0	0	100
			NB	36	Control	30	10	60	30	10	60	25	5	70
				34	Control	25	25	50	35	25	40	35	25	40
				32	Control	30	30	40	60	0	40	60	10	30
				28	MDA	20	20	60	35	15	50	30	10	60
				24	MDA	20	20	60	25	15	60	20	10	70
				22	MDA	15	15	70	15	15	70	10	10	80
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	15	15	70	20	20	60	15	15	70
				12	Control	35	35	30	45	25	30	40	30	30
				8	RSB	25	25	50	20	20	60	20	20	60
				6	RSB	25	25	50	20	20	60	20	20	60
				2	RSB	30	30	40	35	25	40	30	20	50

APPENDIX B

Storm 3-4

DECELEROMETER DATA

Table B-20. Statistical Comparison of De-icing Decelerometer Data for Storm 3-4

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	106.5	9.4	2/21, Before 1st anti-icing
	2	C	79.5	7.7	2/23, After >1 in snow
	3	C	54.9	19.0	2/23, After >1 in snow
	4	C	94.5	6.6	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	MD20	106.8	6.5	2/21, Before 1st anti-icing
	2	MD20	81.3	11.7	2/23, After >1 in snow
	3	MD20	51.9	15.9	2/23, After >1 in snow
	4	MD20	99.5	3.1	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	RS	107.3	7.0	2/21, Before 1st anti-icing
	2	RS	80.6	7.0	2/23, After >1 in snow
	3	RS	49.2	11.1	2/23, After >1 in snow
	4	RS	96.1	6.4	2/23, After 1st de-icing, 2nd anti-icing, slushing

Table B-21. De-icing Raw Decelerometer Data for Storm 3-4

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
1	2/21, Before 1st anti-icing	NB	6:23 PM	2	Control	83%	Clear Road
			6:24 PM	4	Control	85%	Clear Road
			6:25 PM	6	Control	102%	Clear Road
			6:39 PM	12	M-20	101%	Clear Road
			6:39 PM	14	M-20	114%	Clear Road
			6:40 PM	16	M-20	106%	Clear Road
			6:27 PM	22	Control	110%	Clear Road
			6:28 PM	24	Control	121%	Clear Road
			6:28 PM	26	Control	106%	Clear Road
			6:50 PM	32	Road Salt	97%	Clear Road
			6:50 PM	34	Road Salt	111%	Clear Road
			6:51 PM	36	Road Salt	102%	Clear Road
			6:30 PM	42	Control	98%	Clear Road
			6:30 PM	44	Control	107%	Clear Road
			6:31 PM	46	Control	115%	Clear Road
			6:42 PM	52	M-20	112%	Clear Road
			6:43 PM	54	M-20	109%	Clear Road
			6:44 PM	56	M-20	110%	Clear Road
			6:34 PM	62	Control	101%	Clear Road
			6:35 PM	64	Control	110%	Clear Road
			6:35 PM	66	Control	104%	Clear Road
			6:54 PM	72	Road Salt	111%	Clear Road
			6:54 PM	74	Road Salt	120%	Clear Road
			6:55 PM	76	Road Salt	113%	Clear Road
	2/21, Before 1st anti-icing	SB	6:47 PM	78	Control	115%	Clear Road
			6:48 PM	76	Control	105%	Clear Road
			6:48 PM	74	Control	125%	Clear Road
			6:25 PM	68	M-20	107%	Clear Road
			6:26 PM	66	M-20	100%	Clear Road
			6:26 PM	64	M-20	109%	Clear Road
			6:40 PM	58	Control	103%	Clear Road
			6:41 PM	56	Control	113%	Clear Road
			6:41 PM	54	Control	107%	Clear Road
			6:29 PM	48	Road Salt	104%	Clear Road
			6:29 PM	46	Road Salt	101%	Clear Road
			6:29 PM	44	Road Salt	98%	Clear Road
			6:51 PM	38	Control	112%	Clear Road
			6:52 PM	36	Control	104%	Clear Road
			6:52 PM	34	Control	110%	Clear Road
			6:31 PM	28	M-20	118%	Clear Road
			6:32 PM	26	M-20	100%	Clear Road
			6:32 PM	24	M-20	96%	Clear Road
			6:45 PM	18	Control	101%	Clear Road
			6:45 PM	16	Control	106%	Clear Road
			6:46 PM	14	Control	113%	Clear Road
			6:36 PM	8	Road Salt	110%	Clear Road
			6:37 PM	6	Road Salt	107%	Clear Road
			6:37 PM	4	Road Salt	113%	Clear Road

Table B-21. De-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
2	2/23, After >1 in snow	NB	2:16 PM	2	Control	85%	Patchy Ice
			2:16 PM	4	Control	83%	Patchy Ice
			2:17 PM	6	Control	87%	Patchy Ice
			2:18 PM	12	M-20	94%	Patchy Ice
			2:18 PM	14	M-20	97%	Patchy Ice
			2:19 PM	16	M-20	95%	Patchy Ice
			2:20 PM	22	Control	92%	Patchy Ice
			2:21 PM	24	Control	87%	Patchy Ice
			2:21 PM	26	Control	92%	Patchy Ice
			2:22 PM	32	Road Salt	88%	Patchy Ice
			2:22 PM	34	Road Salt	87%	Patchy Ice
			2:23 PM	36	Road Salt	88%	Patchy Ice
			2:23 PM	42	Control	85%	Patchy Ice
			2:24 PM	44	Control	79%	Patchy Ice
			2:24 PM	46	Control	83%	Patchy Ice
			2:25 PM	52	M-20	78%	Patchy Ice
			2:26 PM	54	M-20	90%	Patchy Ice
			2:26 PM	56	M-20	83%	Patchy Ice
			2:27 PM	62	Control	86%	Patchy Ice
			2:28 PM	64	Control	79%	Patchy Ice
			2:28 PM	66	Control	81%	Patchy Ice
			2:29 PM	72	Road Salt	89%	Patchy Ice
			2:29 PM	74	Road Salt	69%	Patchy Ice
			2:30 PM	76	Road Salt	83%	Patchy Ice
	2/23, After >1 in snow	SB	2:32 PM	78	Control	69%	Patchy Ice
			2:33 PM	76	Control	68%	Patchy Ice
			2:33 PM	74	Control	67%	Patchy Ice
			2:34 PM	68	M-20	58%	Patchy Ice
			2:35 PM	66	M-20	76%	Patchy Ice
			2:35 PM	64	M-20	76%	Patchy Ice
			2:36 PM	58	Control	67%	Patchy Ice
			2:36 PM	56	Control	74%	Patchy Ice
			2:37 PM	54	Control	78%	Patchy Ice
			2:38 PM	48	Road Salt	69%	Patchy Ice
			2:38 PM	46	Road Salt	77%	Patchy Ice
			2:38 PM	44	Road Salt	77%	Patchy Ice
			2:39 PM	38	Control	71%	Patchy Ice
			2:40 PM	36	Control	74%	Patchy Ice
			2:40 PM	34	Control	71%	Patchy Ice
			2:41 PM	28	M-20	69%	Patchy Ice
			2:41 PM	26	M-20	74%	Patchy Ice
			2:42 PM	24	M-20	86%	Patchy Ice
			2:42 PM	18	Control	84%	Patchy Ice
			2:43 PM	16	Control	80%	Patchy Ice
			2:43 PM	14	Control	85%	Patchy Ice
			2:44 PM	8	Road Salt	78%	Patchy Ice
			2:44 PM	6	Road Salt	83%	Patchy Ice
			2:45 PM	4	Road Salt	79%	Patchy Ice

Table B-21. De-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
3	2/23, After 1st plow	NB	1:16 PM	2	Control	43%	Loose Snow
			1:16 PM	4	Control	44%	Loose Snow
			1:17 PM	6	Control	29%	Loose Snow
			1:18 PM	12	M-20	42%	Loose Snow
			1:18 PM	14	M-20	40%	Loose Snow
			1:19 PM	16	M-20	42%	Loose Snow
			1:19 PM	22	Control	45%	Loose Snow
			1:20 PM	24	Control	61%	Loose Snow
			1:20 PM	26	Control	45%	Loose Snow
			1:21 PM	32	Road Salt	43%	Loose Snow
			1:21 PM	34	Road Salt	42%	Loose Snow
			1:22 PM	36	Road Salt	43%	Loose Snow
			1:23 PM	42	Control	42%	Loose Snow
			1:23 PM	44	Control	37%	Loose Snow
			1:24 PM	46	Control	46%	Loose Snow
			1:24 PM	52	M-20	47%	Loose Snow
			1:25 PM	54	M-20	40%	Loose Snow
			1:25 PM	56	M-20	44%	Loose Snow
			1:26 PM	62	Control	37%	Loose Snow
			1:27 PM	64	Control	42%	Loose Snow
			1:27 PM	66	Control	40%	Loose Snow
			1:31 PM	72	Road Salt	29%	Loose Snow
			1:31 PM	74	Road Salt	46%	Loose Snow
			1:29 PM	76	Road Salt	43%	Loose Snow
	2/23, After 1st plow	SB	1:34 PM	78	Control	58%	Loose Snow
			1:35 PM	76	Control	40%	Loose Snow
			1:35 PM	74	Control	47%	Loose Snow
			1:36 PM	68	M-20	45%	Loose Snow
			1:37 PM	66	M-20	43%	Loose Snow
			1:38 PM	64	M-20	93%	Patchy Loose Snow
			1:38 PM	58	Control	94%	Patchy Loose Snow
			1:39 PM	56	Control	93%	Patchy Loose Snow
			1:40 PM	54	Control	66%	Patchy Loose Snow
			1:40 PM	48	Road Salt	58%	Patchy Loose Snow
			1:41 PM	46	Road Salt	65%	Patchy Loose Snow
			1:41 PM	44	Road Salt	59%	Patchy Loose Snow
			1:43 PM	38	Control	62%	Patchy Loose Snow
			1:43 PM	36	Control	66%	Patchy Loose Snow
			1:43 PM	34	Control	90%	Patchy Loose Snow
			1:44 PM	28	M-20	56%	Patchy Loose Snow
			1:45 PM	26	M-20	66%	Patchy Loose Snow
			1:45 PM	24	M-20	65%	Patchy Loose Snow
			1:46 PM	18	Control	86%	Patchy Loose Snow
			1:47 PM	16	Control	48%	Patchy Loose Snow
			1:47 PM	14	Control	57%	Patchy Loose Snow
			1:48 PM	8	Road Salt	45%	Patchy Loose Snow
			1:49 PM	6	Road Salt	67%	Patchy Loose Snow
			1:49 PM	4	Road Salt	50%	Patchy Loose Snow

Table B-21. De-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
4	2/23, After 1st de-icing, 2nd anti-icing, slushing	NB	3:47 PM	2	Control	92%	Patchy Slush
			3:48 PM	4	Control	87%	Patchy Slush
			3:48 PM	6	Control	78%	Patchy Slush
			3:49 PM	12	M-20	98%	Patchy Wet
			3:50 PM	14	M-20	100%	Patchy Wet
			3:50 PM	16	M-20	102%	Patchy Wet
			3:51 PM	22	Control	99%	Patchy Wet
			3:51 PM	24	Control	99%	Patchy Wet
			3:52 PM	26	Control	99%	Patchy Wet
			3:53 PM	32	Road Salt	96%	Patchy Wet
			3:53 PM	34	Road Salt	94%	Patchy Wet
			3:54 PM	36	Road Salt	96%	Patchy Wet
			3:55 PM	42	Control	94%	Patchy Wet
			3:55 PM	44	Control	93%	Patchy Wet
			3:55 PM	46	Control	102%	Patchy Wet
			3:56 PM	52	M-20	95%	Patchy Wet
			3:57 PM	54	M-20	97%	Patchy Wet
			3:57 PM	56	M-20	101%	Patchy Wet
			3:58 PM	62	Control	102%	Patchy Wet
			3:59 PM	64	Control	94%	Patchy Packed Snow
			3:59 PM	66	Control	86%	Patchy Packed Snow
			4:00 PM	72	Road Salt	84%	Patchy Wet
			4:01 PM	74	Road Salt	99%	Patchy Wet
			4:02 PM	76	Road Salt	103%	Patchy Wet
	2/23, After 1st de-icing, 2nd anti-icing, slushing	SB	4:05 PM	78	Control	92%	Patchy Wet
			4:05 PM	76	Control	100%	Patchy Wet
			4:06 PM	74	Control	96%	Patchy Wet
			4:07 PM	68	M-20	102%	Patchy Wet
			4:07 PM	66	M-20	100%	Patchy Wet
			4:07 PM	64	M-20	99%	Patchy Wet
			4:08 PM	58	Control	97%	Patchy Wet
			4:09 PM	56	Control	88%	Patchy Wet
			4:09 PM	54	Control	96%	Patchy Wet
			4:10 PM	48	Road Salt	101%	Patchy Wet
			4:12 PM	46	Road Salt	87%	Patchy Wet
			4:11 PM	44	Road Salt	94%	Patchy Wet
			4:13 PM	38	Control	95%	Patchy Wet
			4:13 PM	36	Control	95%	Patchy Wet
			4:14 PM	34	Control	81%	Patchy Wet
			4:14 PM	28	M-20	106%	Patchy Wet
			4:15 PM	26	M-20	99%	Patchy Wet
			4:15 PM	24	M-20	95%	Patchy Wet
			4:16 PM	18	Control	102%	Patchy Wet
			4:16 PM	16	Control	99%	Patchy Wet
			4:17 PM	14	Control	103%	Patchy Wet
			4:17 PM	8	Road Salt	94%	Patchy Wet
			4:18 PM	6	Road Salt	107%	Patchy Wet
			4:18 PM	4	Road Salt	98%	Patchy Wet

Table B-22. Statistical Comparison of Anti-icing Decelerometer Data for Storm 3-4

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
Anti-icing	1	C	99.4	7.4	2/21, Before 1st anti-icing
	2	C	97.8	5.2	2/21, After 1st anti-icing, slushing
	3	C	91.3	7.9	2/22, After first snowfall
	4	C	78.2	12.0	2/22, After more snow
	5	C	46.8	1.7	2/23, After >1 in snow
	6	C	45.2	5.6	2/23, After 1st plow
	7	C	81.3	8.1	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	MDA	99.0	8.1	2/21, Before 1st anti-icing
	2	MDA	86.0	6.8	2/21, After 1st anti-icing, slushing
	3	MDA	83.3	8.4	2/22, After first snowfall
	4	MDA	81.0	5.9	2/22, After more snow
	5	MDA	49.7	2.0	2/23, After >1 in snow
	6	MDA	46.2	4.0	2/23, After 1st plow
	7	MDA	77.3	10.1	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	RSB	105.0	7.6	2/21, Before 1st anti-icing
	2	RSB	103.7	3.9	2/21, After 1st anti-icing, slushing
	3	RSB	95.8	5.7	2/22, After first snowfall
	4	RSB	82.0	4.3	2/22, After more snow
	5	RSB	53.2	6.6	2/23, After >1 in snow
	6	RSB	47.7	4.0	2/23, After 1st plow
	7	RSB	93.7	6.6	2/23, After 1st de-icing, 2nd anti-icing, slushing

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
1	2/21, Before 1st anti-icing	SB	5:38 PM	2	Control	95%	Clear Road
			5:39 PM	4	Control	98%	Clear Road
			5:39 PM	6	Control	100%	Clear Road
			6:09 PM	12	M-Apex	100%	Clear Road
			6:09 PM	14	M-Apex	87%	Clear Road
			6:10 PM	16	M-Apex	98%	Clear Road
			5:41 PM	22	Control	99%	Clear Road
			5:42 PM	24	Control	105%	Clear Road
			5:42 PM	26	Control	103%	Clear Road
			6:14 PM	32	Salt Brine	90%	Clear Road
			6:15 PM	34	Salt Brine	107%	Clear Road
			6:15 PM	36	Salt Brine	111%	Clear Road
		NB	5:44 PM	38	Control	96%	Clear Road
			5:44 PM	36	Control	82%	Clear Road
			5:45 PM	34	Control	113%	Clear Road
			6:11 PM	28	M-Apex	112%	Clear Road
			6:11 PM	26	M-Apex	101%	Clear Road
			6:12 PM	24	M-Apex	96%	Clear Road
			5:47 PM	18	Control	97%	Clear Road
			5:48 PM	16	Control	105%	Clear Road
			5:48 PM	14	Control	100%	Clear Road
			6:17 PM	8	Salt Brine	109%	Clear Road
			6:17 PM	6	Salt Brine	108%	Clear Road
			6:18 PM	4	Salt Brine	105%	Clear Road

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
2	2/21, After 1st anti-icing, slushing	SB	8:32 PM	2	Control	91%	Clear Road
			8:33 PM	4	Control	103%	Clear Road
			8:33 PM	6	Control	100%	Clear Road
			8:45 PM	12	M-Apex	81%	Wet
			8:45 PM	14	M-Apex	87%	Wet
			8:46 PM	16	M-Apex	81%	Wet
			8:35 PM	22	Control	88%	Clear Road
			8:36 PM	24	Control	94%	Clear Road
			8:36 PM	26	Control	101%	Clear Road
			8:40 PM	32	Salt Brine	104%	Wet
			8:41 PM	34	Salt Brine	104%	Wet
			8:41 PM	36	Salt Brine	102%	Wet
		NB	8:38 PM	38	Control	100%	Clear Road
			8:37 PM	36	Control	102%	Clear Road
			8:37 PM	34	Control	103%	Clear Road
			8:48 PM	28	M-Apex	83%	Wet
			8:47 PM	26	M-Apex	85%	Wet
			8:46 PM	24	M-Apex	99%	Wet
			8:35 PM	18	Control	92%	Clear Road
			8:34 PM	16	Control	101%	Clear Road
			8:34 PM	14	Control	98%	Clear Road
			8:42 PM	8	Salt Brine	101%	Wet
			8:43 PM	6	Salt Brine	100%	Wet
			8:43 PM	4	Salt Brine	111%	Wet

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
3	2/22, After first snowfall	SB	10:40 AM	2	Control	72%	Patchy Ice
			10:41 AM	4	Control	82%	Patchy Ice
			10:41 AM	6	Control	90%	Patchy Ice
			10:54 AM	12	M-Apex	83%	Patchy Ice
			10:54 AM	14	M-Apex	71%	Patchy Ice
			10:55 AM	16	M-Apex	76%	Patchy Ice
			10:44 AM	22	Control	102%	Patchy Ice
			10:44 AM	24	Control	96%	Patchy Ice
			10:45 AM	26	Control	99%	Patchy Ice
			10:49 AM	32	Salt Brine	94%	Patchy Ice
			10:49 AM	34	Salt Brine	87%	Patchy Ice
			10:48 AM	36	Salt Brine	97%	Patchy Ice
		NB	10:46 AM	38	Control	93%	Patchy Ice
			10:46 AM	36	Control	94%	Patchy Ice
			10:45 AM	34	Control	95%	Patchy Ice
			10:56 AM	28	M-Apex	87%	Patchy Ice
			10:56 AM	26	M-Apex	91%	Patchy Ice
			10:55 AM	24	M-Apex	92%	Patchy Ice
			10:43 AM	18	Control	90%	Patchy Ice
			10:42 AM	16	Control	93%	Patchy Ice
			10:42 AM	14	Control	89%	Patchy Ice
			10:51 AM	8	Salt Brine	94%	Patchy Ice
			10:51 AM	6	Salt Brine	99%	Patchy Ice
			10:52 AM	4	Salt Brine	104%	Patchy Ice

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
4	2/22, After more snow	SB	1:23 PM	2	Control	60%	Patchy Ice
			1:24 PM	4	Control	56%	Patchy Ice
			1:25 PM	6	Control	66%	Patchy Ice
			1:26 PM	12	M-Apex	76%	Patchy Ice
			1:28 PM	14	M-Apex	78%	Patchy Ice
			1:28 PM	16	M-Apex	74%	Patchy Ice
			1:29 PM	22	Control	80%	Patchy Ice
			1:30 PM	24	Control	78%	Patchy Ice
			1:30 PM	26	Control	73%	Patchy Ice
			1:32 PM	32	Salt Brine	84%	Patchy Ice
			1:33 PM	34	Salt Brine	79%	Patchy Ice
			1:33 PM	36	Salt Brine	76%	Patchy Ice
		NB	1:48 PM	38	Control	82%	Patchy Ice
			1:48 PM	36	Control	91%	Patchy Ice
			1:49 PM	34	Control	90%	Patchy Ice
			1:52 PM	28	M-Apex	87%	Patchy Ice
			1:53 PM	26	M-Apex	88%	Patchy Ice
			1:53 PM	24	M-Apex	83%	Patchy Ice
			1:54 PM	18	Control	86%	Patchy Ice
			1:55 PM	16	Control	88%	Patchy Ice
			1:55 PM	14	Control	88%	Patchy Ice
			1:56 PM	8	Salt Brine	87%	Patchy Ice
			1:57 PM	6	Salt Brine	86%	Patchy Ice
			1:58 PM	4	Salt Brine	80%	Patchy Ice

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
5	2/23, After >1 in snow	SB	11:57 AM	2	Control	45%	Loose Snow
			11:58 AM	4	Control	46%	Loose Snow
			11:58 AM	6	Control	44%	Loose Snow
			11:59 AM	12	M-Apex	46%	Loose Snow
			12:00 PM	14	M-Apex	51%	Loose Snow
			12:01 PM	16	M-Apex	51%	Loose Snow
			12:03 PM	22	Control	49%	Loose Snow
			12:03 PM	24	Control	47%	Loose Snow
			12:04 PM	26	Control	49%	Loose Snow
			12:05 PM	32	Salt Brine	48%	Loose Snow
			12:06 PM	34	Salt Brine	66%	Loose Snow
			12:07 PM	36	Salt Brine	49%	Loose Snow
		NB	12:09 PM	38	Control	48%	Loose Snow
			12:09 PM	36	Control	48%	Loose Snow
			12:10 PM	34	Control	45%	Loose Snow
			12:11 PM	28	M-Apex	50%	Loose Snow
			12:12 PM	26	M-Apex	51%	Loose Snow
			12:13 PM	24	M-Apex	49%	Loose Snow
			12:14 PM	18	Control	48%	Loose Snow
			12:15 PM	16	Control	45%	Loose Snow
			12:16 PM	14	Control	48%	Loose Snow
			12:17 PM	8	Salt Brine	51%	Loose Snow
			12:18 PM	6	Salt Brine	51%	Loose Snow
			12:19 PM	4	Salt Brine	54%	Loose Snow

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
6	2/23, After 1st plow	SB	12:54 PM	2	Control	55%	Loose Snow
			12:55 PM	4	Control	49%	Loose Snow
			12:55 PM	6	Control	48%	Loose Snow
			12:56 PM	12	M-Apex	52%	Loose Snow
			12:57 PM	14	M-Apex	43%	Loose Snow
			12:57 PM	16	M-Apex	43%	Loose Snow
			12:59 PM	22	Control	54%	Loose Snow
			1:00 PM	24	Control	45%	Loose Snow
			1:00 PM	26	Control	39%	Loose Snow
			1:02 PM	32	Salt Brine	45%	Loose Snow
			1:02 PM	34	Salt Brine	52%	Loose Snow
			1:03 PM	36	Salt Brine	46%	Loose Snow
		NB	1:06 PM	38	Control	36%	Loose Snow
			1:06 PM	36	Control	43%	Loose Snow
			1:07 PM	34	Control	45%	Loose Snow
			1:08 PM	28	M-Apex	50%	Loose Snow
			1:09 PM	26	M-Apex	43%	Loose Snow
			1:09 PM	24	M-Apex	46%	Loose Snow
			1:10 PM	18	Control	42%	Loose Snow
			1:11 PM	16	Control	42%	Loose Snow
			1:11 PM	14	Control	44%	Loose Snow
			1:12 PM	8	Salt Brine	53%	Loose Snow
			1:12 PM	6	Salt Brine	43%	Loose Snow
			1:13 PM	4	Salt Brine	47%	Loose Snow

Table B-23. Anti-icing Raw Decelerometer Data for Storm 3-4 Continued

Test Set	Date, Conditions	Lane	Time	Section	Section Type	Percent G	Comments
7	2/23, After 1st de-icing, 2nd anti-icing, slushing	SB	3:26 PM	2	Control	91%	Patchy Slush
			3:27 PM	4	Control	84%	Patchy Slush
			3:28 PM	6	Control	79%	Patchy Slush
			3:29 PM	12	M-Apex	94%	Patchy Wet
			3:30 PM	14	M-Apex	83%	Patchy Wet
			3:31 PM	16	M-Apex	77%	Patchy Slush
			3:32 PM	22	Control	89%	Patchy Slush
			3:32 PM	24	Control	92%	Patchy Slush
			3:33 PM	26	Control	86%	Patchy Slush
			3:34 PM	32	Salt Brine	99%	Patchy Wet
			3:35 PM	34	Salt Brine	98%	Patchy Wet
			3:35 PM	36	Salt Brine	91%	Patchy Wet
		NB	3:38 PM	38	Control	73%	Patchy Packed Snow
			3:38 PM	36	Control	68%	Patchy Packed Snow
			3:39 PM	34	Control	76%	Patchy Packed Snow
			3:40 PM	28	M-Apex	69%	Patchy Packed Snow
			3:40 PM	26	M-Apex	75%	Patchy Packed Snow
			3:41 PM	24	M-Apex	66%	Patchy Packed Snow
			3:42 PM	18	Control	72%	Patchy Packed Snow
			3:43 PM	16	Control	78%	Patchy Slush
			3:44 PM	14	Control	88%	Patchy Slush
			3:44 PM	8	Salt Brine	100%	Patchy Slush
			3:45 PM	6	Salt Brine	91%	Patchy Slush
			3:46 PM	4	Salt Brine	83%	Patchy Slush

APPENDIX C

Winter 2014/15

Storm 3-5

02-25-2015

APPENDIX C

Storm 3-5

WEATHER DATA

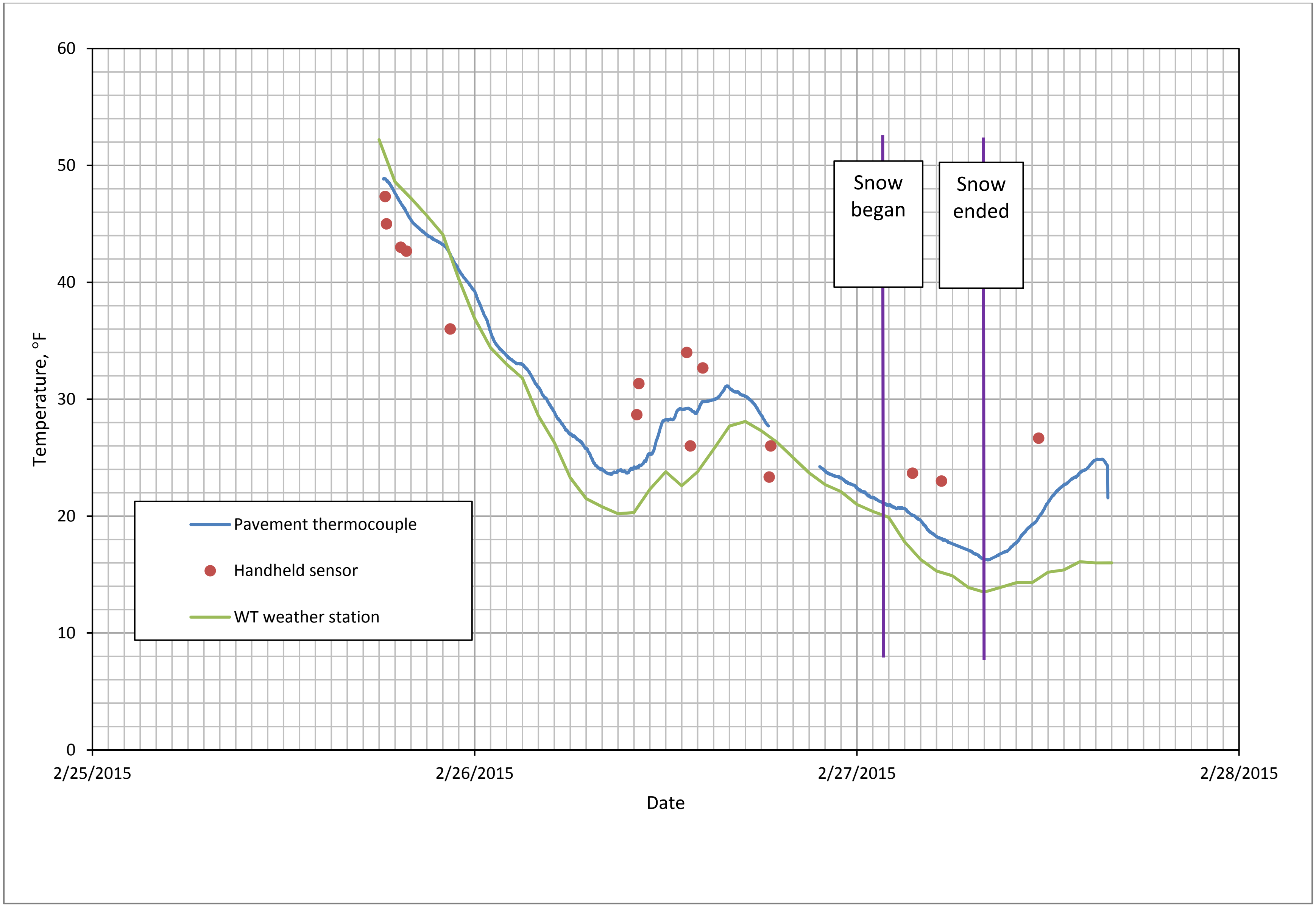

Figure C.1. Temperature Data at Field Test Site, Storm Event 3-5, FEB 25-27, 2015

Table C.1 On-Site Temperature Readings, Storm 3-5

Date	Time		Location (N/S)	Temperature R1	R2	R3	Average	Snow Thickness	Comments	Initials
02/25/15	18:23	2/25/2015 18:23	S	48	47	47	47.3	0	Sunny	AJ
02/25/15	18:28	2/25/2015 18:28	N	45	45	45	45.0	0	Sunny	AJ
02/25/15	19:22	2/25/2015 19:22	N	44	43	42	43.0	0	Cloudy	KR
02/25/15	19:43	2/25/2015 19:43	S	43	42	43	42.7	0	Cloudy	KR
02/25/15	22:28	2/25/2015 22:28	S	36	36	36	36.0	0	Rain	AJ
02/26/15	10:11	2/26/2015 10:11	N	29	28	29	28.7	0	Cloudy	AJ,KR
02/26/15	10:19	2/26/2015 10:19	S	31	31	32	31.3	0	Cloudy	AJ,KR
02/26/15	13:19	2/26/2015 13:19	S	36	34	32	34.0	0	Cloudy	KR,RM,TW
02/26/15	13:33	2/26/2015 13:33	N	28	26	24	26.0	0	Cloudy	KR,RM,TW
02/26/15	14:20	2/26/2015 14:20	N	33	33	32	32.7	0	Partly cloudy	AJ
02/26/15	18:30	2/26/2015 18:30	N	24	23	23	23.3	0	Cloudy 26º	KR
02/26/15	18:36	2/26/2015 18:36	S	26	26	26	26.0	0	Cloudy	KR
02/27/15	3:30	2/27/2015 3:30	N	24	24	23	23.7	trace	Cloudy, snow	AJ
02/27/15	5:19	2/27/2015 5:19	S	22	23	24	23.0	0.5	Cloudy, snow	AJ
02/27/15	5:27	2/27/2015 5:27	N					0.5	Cloudy, snow	KR
02/27/15	11:25	2/27/2015 11:25	S	27	26	27	26.7	0	Cloudy	AJ

Table C.2 Storm 3-5, Hourly Observations, 25 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
25	0053	11	OVC085	10.00		34	1.1	30	-0.8	25	-3.9	70	5	310		26.23			29.93	AA		29.93
25	0153	11	CLR	10.00		30	-1.1	28	-2.3	24	-4.4	78	6	270		26.21			29.92	AA		29.91
25	0253	11	CLR	10.00		30	-1.1	28	-2.3	24	-4.4	78	3	250		26.18			29.88	AA		29.87
25	0353	11	CLR	10.00		26	-3.3	24	-4.3	21	-6.1	81	6	260		26.18			29.88	AA		29.87
25	0453	11	CLR	10.00		29	-1.7	27	-2.8	23	-5.0	78	10	290		26.17			29.87	AA		29.86
25	0553	11	CLR	10.00		26	-3.3	24	-4.4	20	-6.7	78	8	280		26.16			29.87	AA		29.85
25	0653	11	CLR	10.00		25	-3.9	24	-4.6	21	-6.1	85	7	280		26.16			29.88	AA		29.85
25	0753	11	CLR	10.00		28	-2.2	26	-3.4	22	-5.6	78	6	220		26.14			29.86	AA		29.83
25	0853	11	CLR	10.00		39	3.9	34	1.1	27	-2.8	62	5	270		26.13			29.83	AA		29.82
25	0953	11	CLR	10.00		43	6.1	36	2.3	27	-2.8	53	16	300		26.14			29.83	AA		29.83
25	1053	11	CLR	10.00		47	8.3	39	3.7	28	-2.2	48	16	300		26.14			29.82	AA		29.83
25	1153	11	CLR	10.00		52	11.1	40	4.2	23	-5.0	32	17	320	21	26.14			29.81	AA		29.83
25	1253	11	CLR	10.00		57	13.9s	41	5.1	20	-6.7	24	16	350	23	26.13			29.77	AA		29.81
25	1353	11	CLR	10.00		57	13.9	42	5.2	21	-6.1	25	22	350	30	26.13			29.78	AA		29.81
25	1453	11	CLR	10.00		56	13.3	44	6.4	29	-1.7	36	22	350	28	26.11			29.78	AA		29.80
25	1553	11	CLR	10.00		55	12.8	44	6.7	32	0.0	42	21	360	29	26.13			29.80	AA		29.81
25	1653	11	FEW046	10.00		53	11.7	43	6.2	32	0.0	45	18	010	25	26.13			29.81	AA		29.82
25	1753	11	FEW120	10.00		49	9.4	42	5.5	34	1.1	56	17	010	26	26.16			29.85	AA		29.85
25	1853	11	OVC110	10.00		47	8.3	41	4.7	33	0.6	58	17	010		26.19			29.89	AA		29.88
25	1953	11	FEW041 BKN100 BKN120	10.00		45	7.2	40	4.2	33	0.6	63	15	010		26.21			29.92	AA		29.91
25	2053	11	OVC095	10.00		44	6.7	39	3.9	33	0.6	65	15	010		26.25			29.93	AA		29.95
25	2153	11	FEW028 BKN034 OVC045	10.00		43	6.1	39	3.8	34	1.1	71	20	020		26.28			29.96	AA		29.98
25	2236	11	BKN024 BKN031 OVC035	10.00	-RA	40	4.4	37	2.9	34	1.1	79	16	020		26.29			M	SP		30.00
25	2253	11	OVC022	10.00	-RA	39	3.9	37	2.8	35	1.7	86	18	030		26.29			29.98	AA	T	30.00
25	2353	11	FEW010 BKN025 OVC037	8.00	UP	36	2.2	35	1.7	34	1.1	92	16	030	24	26.31			30.00	AA	0.01	30.02

Dynamically generated Mon Mar 27 08:51:40 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table C.3 Storm 3-5, Hourly Remarks, 25 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
25	0053	AO2 SLP137 T00111039
25	0153	AO2 SLP131 T10111044
25	0253	AO2 SLP119 T10111044 58019
25	0353	AO2 SLP120 T10331061
25	0453	AO2 SLP114 T10171050
25	0553	AO2 SLP116 T10331067 10011 21033 57005 (XX)
25	0653	AO2 SLP120 T10391061 (XX)
25	0753	AO2 SLP111 T10221056 (XX)
25	0853	AO2 SLP100 T00391028 58010 (XX)
25	0953	AO2 SLP101 T00611028 (XX)
25	1053	AO2 SLP097 T00831022 (XX)
25	1153	AO2 SLP094 T01111050 10111 21044 51004 (XX)
25	1253	AO2 SLP081 T01391067 (XX)
25	1353	AO2 PK WND 36026/1939 SLP083 T01391061 (XX)
25	1453	AO2 PK WND 36028/2009 SLP084 T01331017 56009 (XX)
25	1553	AO2 PK WND 36027/2059 SLP090 T01280000 (XX)
25	1653	AO2 SLP094 T01170000 (XX)
25	1753	AO2 SLP108 T00940011 10144 20094 53014 (XX)
25	1853	AO2 SLP122 T00830006
25	1953	AO2 SLP131 T00720006
25	2053	AO2 SLP135 T00670006 52029
25	2153	AO2 SLP144 T00610011
25	2236	AO2 RAB29 P0000 T00440011
25	2253	AO2 PK WND 02026/0443 RAB29 SLP153 P0000 T00390017
25	2353	AO2 PK WND 04028/0509 RAE16UPB16 SLP158 P0000 60000 T00220011 10094 20022 401441044 51023

Dynamically generated Mon Mar 27 08:52:25 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table C.4 Storm 3-5, Hourly Precipitation, 25 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
25													25											T	0.01	25

Table C.5 Storm 3.5, Hourly Observations, 26 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
26	0008	11	BKN012 BKN017 OVC025	5.00	-SN BR	35	1.7	34	0.9	32	0.0	89	17	030	25	26.32			M	SP		30.03
26	0020	11	SCT014 OVC037	9.00	UP	35	1.7	34	1.1	33	0.6	92	15	030		26.32			M	SP		30.03
26	0053	11	FEW028 OVC039	10.00		35	1.7	33	0.7	31	-0.6	85	21	030	29	26.34			30.02	AA	T	30.05
26	0128	11	SCT015 BKN023 OVC035	2.50	-SN BR	34	1.1	32	0.1	30	-1.1	85	17	030		26.36			M	SP		30.07
26	0135	11	BKN013 BKN019 OVC035	1.75	-SN BR	33	0.6	32	-0.1	30	-1.1	89	18	030	25	26.36			M	SP		30.07
26	0142	11	SCT009 BKN013 OVC026	2.00	-SN BR	33	0.6	32	0.0	31	-0.6	92	15	030		26.36			M	SP		30.07
26	0151	11	SCT009 BKN015 OVC036	6.00	-SN BR	34	1.0	32	-0.2	28	-2.0	79	23	020	30	26.37			M	SP		30.08
26	0152	11	SCT009 BKN015 OVC038	7.00	-SN	33	0.6	31	-0.3	29	-1.7	85	23	020	30	26.37			30.05	AA	T	30.08
26	0207	11	FEW009 SCT016 OVC042	10.00		32	0.0	30	-0.8	28	-2.2	85	20	020	30	26.38			M	SP		30.09
26	0226	11	SCT014 BKN026 OVC050	10.00		30	-1.1	29	-1.7	27	-2.8	89	23	030	30	26.39			M	SP		30.10
26	0233	11	SCT015 OVC060	10.00		30	-1.1	28	-1.9	26	-3.3	85	21	020	30	26.39			M	SP		30.10
26	0253	11	FEW012 OVC065	10.00		29	-1.7	27	-2.5	25	-3.9	85	18	020		26.39			30.09	AA		30.11
26	0338	11	BKN013 OVC070	10.00		27	-2.8	26	-3.5	23	-5.0	85	22	020	29	26.40			M	SP		30.12
26	0353	11	OVC013	10.00		26	-3.3	25	-4.1	22	-5.6	85	20	020	26	26.40			30.11	AA		30.12
26	0423	11	BKN016 OVC070	10.00		25	-3.9	23	-4.8	20	-6.7	81	20	010	29	26.41			M	SP		30.13
26	0434	11	OVC014	10.00		24	-4.4	23	-5.2	20	-6.7	85	18	010	26	26.41			M	SP		30.13
26	0453	11	OVC014	10.00		24	-4.4	22	-5.3	19	-7.2	81	18	010	28	26.42			30.14	AA		30.14
26	0553	11	OVC012	10.00		21	-6.1	20	-6.8	17	-8.3	84	21	010	26	26.45			30.19	AA		30.17
26	0653	11	BKN012 OVC080	10.00		20	-6.7	19	-7.3	16	-8.9	84	24	020	31	26.48			30.24	AA		30.21
26	0716	11	SCT014 OVC085	10.00		20	-6.7	18	-7.5	15	-9.4	81	17	020		26.49			M	SP		30.22
26	0729	11	BKN014 OVC085	10.00		19	-7.2	18	-7.9	15	-9.4	84	20	010	26	26.50			M	SP		30.23
26	0753	11	OVC013	10.00		19	-7.2	17	-8.0	14	-10.0	81	22	020	28	26.52			30.29	AA		30.25
26	0824	11	SCT015 OVC090	10.00		19	-7.2	17	-8.2	13	-10.6	77	24	020	28	26.53			M	SP		30.26
26	0853	11	FEW017 OVC090	10.00		19	-7.2	17	-8.2	13	-10.6	77	22	020		26.55			30.32	AA		30.28
26	0909	11	BKN016 OVC085	10.00		19	-7.2	17	-8.2	13	-10.6	77	18	030		26.55			M	SP		30.28
26	0932	11	SCT016 BKN080 OVC100	10.00		20	-6.7	18	-7.6	14	-10.0	77	20	030	25	26.55			M	SP		30.28
26	0953	11	FEW016 OVC090	10.00		21	-6.1	19	-7.3	14	-10.0	74	17	020		26.57			30.35	AA		30.31
26	1053	11	SCT022 BKN065 OVC085	10.00		22	-5.6	19	-7.0	13	-10.6	68	15	020		26.58			30.37	AA		30.32
26	1119	11	BKN023 OVC035	8.00		23	-5.0	20	-6.4	15	-9.4	71	18	050		26.57			M	SP		30.30
26	1153	11	OVC018	9.00	-SN	21	-6.1	18	-7.6	12	-11.1	68	16	050		26.57			30.36	AA	T	30.30
26	1253	11	OVC022	10.00		22	-5.6	19	-7.2	12	-11.1	65	13	030	25	26.57			30.36	AA		30.30
26	1353	11	BKN026	10.00		26	-3.3	22	-5.6	13	-10.6	58	14	360	21	26.55			30.33	AA		30.28
26	1438	11	SCT029	10.00		28	-2.2	23	-5.0	12	-11.1	51	14	020	21	26.53			M	SP		30.26

Table C.5 Storm 3-5, Hourly Observations, 26 FEB 2015, National Climatic Data Center, continued

26	1453	11	SCT030	10.00		29	-1.7	24	-4.7	12	-11.1	49	15	020	21	26.53			30.32	AA		30.26
26	1553	11	FEW035	10.00		30	-1.1	24	-4.4	11	-11.7	45	13	050		26.52			30.31	AA		30.25
26	1653	11	SCT043	10.00		28	-2.2	22	-5.3	10	-12.2	47	9	070		26.51			30.31	AA		30.24
26	1753	11	OVC065	10.00		26	-3.3	21	-6.1	9	-12.8	48	13	050		26.52			30.33	AA		30.25
26	1853	11	OVC060	10.00		24	-4.4	20	-6.9	9	-12.8	53	13	070		26.54			30.35	AA		30.27
26	1953	11	OVC060	10.00		23	-5.0	19	-7.4	8	-13.3	52	14	070		26.56			30.38	AA		30.29
26	2053	11	OVC055	10.00		22	-5.6	18	-8.0	6	-14.4	50	14	080		26.57			30.40	AA		30.30
26	2153	11	OVC055	10.00		21	-6.1	17	-8.5	5	-15.0	50	13	070		26.57			30.39	AA		30.30
26	2253	11	OVC050	10.00		21	-6.1	17	-8.5	5	-15.0	50	15	080		26.57			30.39	AA		30.30
26	2353	11	OVC046	10.00		20	-6.7	16	-8.9	5	-15.0	52	16	100		26.56			30.38	AA		30.29

Dynamically generated Mon Mar 27 08:53:10 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table C.6 Storm 3-5, Hourly Remarks, 26 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
26	0008	AO2 UPE0557SNB0557 P0001 T00170000
26	0020	AO2 UPE0557B19SNB0557E19 P0001 T00170006
26	0053	AO2 UPE0557B19E21SNB0557E19 SLP165 P0001 T00171006
26	0128	AO2 SNB21 P0000 T00111011
26	0135	AO2 SNB21 P0000 T00061011
26	0142	AO2 SNB21 P0000 T00061006
26	0151	AO2 PK WND 02026/0749 SNB21 P0000
26	0152	AO2 PK WND 02026/0749 SNB21 SLP177 P0000 T00061017
26	0207	AO2 PK WND 02026/0758 SNE0756 P0000 T00001022
26	0226	AO2 PK WND 03028/0816 SNE0756 P0000 T10111028
26	0233	AO2 PK WND 03028/0816 SNE0756 P0000 T10111033
26	0253	AO2 PK WND 03028/0816 SNE0756 SLP190 P0000 60001 T10171039 53026
26	0338	AO2 PK WND 02026/0856 T10281050
26	0353	AO2 PK WND 02026/0856 SLP196 T10331056
26	0423	AO2 PK WND 02026/1002 T10391067
26	0434	AO2 PK WND 02026/1002 T10441067
26	0453	AO2 PK WND 02026/1002 SLP207 T10441072
26	0553	AO2 SLP223 60001 70001 T10611083 10022 21061 53018
26	0653	AO2 PK WND 02027/1252 SLP240 T10671089 (XX)
26	0716	AO2 PK WND 02027/1256 T10671094 (XX)
26	0729	AO2 PK WND 02027/1256 T10721094 (XX)
26	0753	AO2 PK WND 02027/1256 SLP258 T10721100 (XX)
26	0824	AO2 PK WND 02027/1412 T10721106 (XX)
26	0853	AO2 PK WND 02027/1412 SLP267 T10721106 51034 (XX)
26	0909	AO2 T10721106 (XX)
26	0932	AO2 T10671100 (XX)
26	0953	AO2 SLP276 T10611100 (XX)
26	1053	AO2 SLP283 T10561106 (XX)
26	1119	AO2 SNB07E19 P0000 T10501094 (XX)
26	1153	AO2 SNB07E19B25 SLP280 P0000 60000 T10611111 11044 21072 50008 (XX)
26	1253	AO2 SNE1754 SLP280 P0000 T10561111 (XX)
26	1353	AO2 SLP270 T10331106 (XX)
26	1438	AO2 T10221111 (XX)
26	1453	AO2 SLP266 60000 T10171111 58013 (XX)
26	1553	AO2 SLP264 T10111117 (XX)
26	1653	AO2 SLP265 T10221122 (XX)
26	1753	AO2 SLP271 60000 T10331128 11006 21061 55004 (XX)

Table C.6 Storm 3-5, Hourly Remarks, 26 FEB 2015, National Climatic Data Center, continued

26	1853	AO2 SLP279 T10441128
26	1953	AO2 SLP288 T10501133
26	2053	AO2 SLP293 T10561144 51015
26	2153	AO2 SLP291 T10611150
26	2253	AO2 SLP292 T10611150
26	2353	AO2 SLP289 T10671150 11033 21067 400221072 58003

Dynamically generated Mon Mar 27 08:53:33 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table C.7 Storm 3-5, Hourly Precipitation, 26 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
26	T	T										T	26													26

Table C.8 Storm 3-5, Hourly Observations, 27 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
27	0053	11	OVC047	10.00		19	-7.2	15	-9.2	5	-15.0	54	14	100		26.55			30.37	AA		30.28
27	0153	11	OVC044	10.00		19	-7.2	15	-9.5	3	-16.1	49	13	090		26.53			30.34	AA		30.26
27	0253	11	OVC034	6.00	-SN	18	-7.8	15	-9.5	6	-14.4	59	11	110		26.56			30.37	AA	T	30.29
27	0305	11	OVC026	2.50	-SN	17	-8.3	15	-9.6	8	-13.3	68	10	120		26.56			M	SP		30.29
27	0341	11	OVC020	1.50	-SN	16	-8.9	15	-9.6	11	-11.7	81	13	120		26.54			M	SP		30.27
27	0353	11	OVC018	1.25	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	13	110		26.52			30.33	AA	0.02	30.25
27	0424	11	VV014	1.00	-SN BR	15	-9.4	14	-9.9	12	-11.1	88	13	110		26.53			M	SP		30.26
27	0445	11	OVC013	1.25	-SN BR	15	-9.4	14	-10.0	11	-11.7	84	13	110		26.52			M	SP		30.25
27	0453	11	VV013	1.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	13	100		26.53			30.35	AA	0.03	30.26
27	0508	11	OVC014	1.25	-SN BR	14	-10.0	13	-10.6	10	-12.2	84	9	110		26.54			M	SP		30.27
27	0519	11	VV012	1.00	-SN BR	14	-10.0	13	-10.4	11	-11.7	88	9	100		26.55			M	SP		30.28
27	0531	11	VV010	0.75	-SN BR	14	-10.0	13	-10.6	10	-12.2	84	8	100		26.56			M	SP		30.29
27	0548	11	VV009	0.75	-SN BR	14	-10.0	13	-10.6	10	-12.0	84	11	080		26.56			M	SP		30.29
27	0553	11	VV009	0.75	-SN BR	14	-10.0	13	-10.6	10	-12.2	84	10	080		26.55			30.38	AA	0.05	30.28
27	0628	11	VV007	0.50	SN FZFG	13	-10.6	12	-11.0	10	-12.2	88	9	110		26.57			M	SP		30.31
27	0653	11	VV008	0.50	-SN BR	13	-10.6	12	-11.1	9	-12.8	84	13	110		26.57			30.40	AA	0.07	30.30
27	0701	11	VV008	0.75	-SN BR	13	-10.6	12	-11.0	10	-12.2	88	11	100		26.56			M	SP		30.29
27	0712	11	OVC011	0.75	-SN BR	13	-10.6	12	-11.1	9	-12.8	84	14	110		26.56			M	SP		30.29
27	0729	11	OVC017	1.50	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	14	110		26.55			M	SP		30.28
27	0737	11	VV015	0.75	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	14	100		26.55			M	SP		30.28
27	0740	11	VV014	0.50	SN FZFG	12	-11.1	11	-11.5	9	-12.8	88	14	100		26.55			M	SP		30.28
27	0753	11	VV014	0.50	SN FZFG	12	-11.1	11	-11.5	9	-12.8	88	14	110		26.56			30.40	AA	0.04	30.29
27	0804	11	VV012	0.75	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	15	120		26.57			M	SP		30.30
27	0836	11	VV017	0.75	-SN BR	12	-11.1	11	-11.5	9	-12.8	88	15	100		26.56			M	SP		30.29
27	0853	11	BKN024 OVC038	0.75	-SN BR	12	-11.1	11	-11.6	8	-13.3	84	14	110		26.56			30.40	AA	0.01	30.29
27	0953	11	FEW011 BKN017 OVC035	1.00	-SN	12	-11.1	11	-11.8	7	-13.9	80	17	120		26.57			30.42	AA	0.01	30.30
27	1010	11	SCT021 SCT035 OVC070	2.00	-SN	12	-11.1	11	-11.8	7	-13.9	80	16	110		26.57			M	SP		30.31
27	1024	11	FEW015 BKN021 OVC070	2.00	-SN	13	-10.6	12	-11.2	8	-13.3	80	14	120		26.57			M	SP		30.31
27	1031	11	SCT019 BKN032 OVC070	2.00	-SN	13	-10.6	11	-11.4	7	-13.9	77	15	120		26.57			M	SP		30.31
27	1035	11	FEW013 BKN019 OVC070	3.00	-SN	13	-10.6	12	-11.2	8	-13.3	80	14	120		26.57			M	SP		30.30
27	1046	11	FEW013 BKN019 OVC050	2.50	-SN	13	-10.6	12	-11.2	8	-13.3	80	14	130		26.57			M	SP		30.30
27	1053	11	SCT013 BKN019 OVC050	3.00	-SN	13	-10.6	11	-11.4	7	-13.9	77	15	120		26.57			30.42	AA	T	30.31
27	1128	11	BKN018 OVC047	5.00	-SN	13	-10.6	11	-11.4	7	-13.9	77	15	120		26.57			M	SP		30.31

Table C.8 Storm 3-5, Hourly Observations, 27 FEB 2015, National Climatic Data Center, continued

27	1153	11	OVC018	4.00	-SN	14	-10.0	12	-10.8	8	-13.3	77	14	120		26.56			30.40	AA	T	30.29
27	1200	11	OVC017	1.75	-SN	14	-10.0	12	-10.8	8	-13.3	77	13	120		26.57			M	SP		30.30
27	1213	11	OVC017	4.00	-SN	14	-10.0	12	-11.0	7	-13.9	74	16	140		26.56			M	SP		30.29
27	1218	11	OVC017	7.00	-SN	14	-10.0	12	-11.0	7	-13.9	74	15	150		26.56			M	SP		30.29
27	1253	11	OVC019	9.00	-SN	14	-10.0	12	-10.8	8	-13.3	77	13	140		26.55			30.40	AA	T	30.28
27	1353	11	OVC018	4.00	-SN	15	-9.4	13	-10.3	9	-12.8	77	13	150		26.51			30.35	AA	T	30.24
27	1405	11	OVC018	2.50	-SN	15	-9.4	13	-10.3	9	-12.8	77	11	130		26.50			M	SP		30.23
27	1428	11	OVC017	4.00	-SN	16	-8.9	14	-9.9	9	-12.8	74	11	140		26.49			M	SP		30.22
27	1453	11	OVC017	4.00	-SN	15	-9.4	13	-10.3	9	-12.8	77	9	140		26.49			30.33	AA	T	30.22
27	1551	11	BKN017 OVC022	2.50	-SN	16	-9.0	14	-9.9	9	-13.0	74	10	130		26.49			M	SP		30.22
27	1553	11	BKN017 OVC022	2.50	-SN	15	-9.4	14	-10.2	10	-12.2	80	13	130		26.49			30.34	AA	T	30.22
27	1603	11	OVC017	1.75	-SN	15	-9.4	14	-10.2	10	-12.2	80	13	120		26.48			M	SP		30.21
27	1612	11	OVC017	2.00	-SN	15	-9.4	14	-10.2	10	-12.2	80	13	120		26.48			M	SP		30.21
27	1620	11	OVC017	1.75	-SN	15	-9.4	14	-10.2	10	-12.2	80	14	130		26.48			M	SP		30.21
27	1625	11	BKN014 OVC019	2.00	-SN	15	-9.4	14	-10.2	10	-12.2	80	13	140		26.49			M	SP		30.22
27	1632	11	OVC016	2.00	-SN	15	-9.4	14	-10.2	10	-12.2	80	10	130		26.49			M	SP		30.22
27	1653	11	BKN016 OVC022	2.00	-SN	15	-9.4	13	-10.3	9	-12.8	77	13	140		26.48			30.33	AA	T	30.21
27	1734	11	BKN013 BKN020 OVC041	2.00	-SN	14	-10.0	13	-10.7	9	-12.8	80	15	130		26.46			M	SP		30.19
27	1753	11	BKN015 OVC040	2.00	-SN	14	-10.0	13	-10.7	9	-12.8	80	15	130		26.46			30.31	AA	T	30.18
27	1810	11	BKN015 OVC039	3.00	-SN	14	-10.0	13	-10.7	9	-12.8	80	14	130		26.46			M	SP		30.19
27	1830	11	OVC014	3.00	-SN	14	-10.0	13	-10.7	9	-12.8	80	10	140		26.49			M	SP		30.22
27	1853	11	OVC012	5.00	-SN BR	13	-10.6	12	-11.1	9	-12.8	84	13	130		26.48			30.35	AA	T	30.21
27	1917	11	FEW010 OVC037	6.00	-SN BR	13	-10.6	12	-11.1	9	-12.8	84	14	150		26.47			M	SP		30.20
27	1948	11	BKN010 OVC038	7.00	-SN	12	-11.0	11	-11.5	9	-13.0	88	14	140		26.47			M	SP		30.20
27	1953	11	BKN010 OVC038	9.00	-SN	13	-10.6	12	-11.1	9	-12.8	84	14	150		26.47			30.33	AA	T	30.20
27	2017	11	SCT010 OVC037	9.00	-SN	13	-10.6	12	-11.1	9	-12.8	84	10	140		26.48			M	SP		30.21
27	2034	11	FEW009 OVC038	10.00		13	-10.6	12	-11.1	9	-12.8	84	13	140		26.49			M	SP		30.22
27	2051	11	BKN009 OVC038	9.00		12	-11.0	11	-11.5	9	-13.0	88	13	140		26.49			M	SP		30.22
27	2053	11	BKN009 OVC038	9.00	-SN	12	-11.1	11	-11.6	8	-13.3	84	13	150		26.49			30.36	AA	T	30.22
27	2104	11	SCT010 OVC036	9.00		12	-11.1	11	-11.6	8	-13.3	84	16	150		26.49			M	SP		30.22
27	2153	11	FEW010 OVC038	8.00	-SN	11	-11.7	10	-12.0	8	-13.3	88	13	150		26.48			30.35	AA	T	30.21
27	2248	11	FEW009 OVC033	10.00		10	-12.0	10	-12.3	9	-13.0	96	11	160		26.48			M	SP		30.21
27	2253	11	FEW009 OVC032	10.00		11	-11.7	10	-12.0	8	-13.3	88	13	160		26.48			30.36	AA		30.21
27	2337	11	BKN008 OVC031	10.00		11	-11.7	10	-11.9	9	-12.8	92	14	150		26.48			M	SP		30.21
27	2353	11	CLR	7.00		11	-11.7	M	M	9	-12.8	M	13	160		M			30.34	AA	T	30.21

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Table C.9 Storm 3-5, Hourly Remarks, 27 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY REMARKS OBSERVATIONS TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 3604 ft. above sea level
Latitude: 35.229
Longitude: -101.704
Data Version: VER3

Date	Time	Remarks
27	0053	AO2 SLP285 T10721150
27	0153	AO2 SLP275 T10721161
27	0253	AO2 SNB31 SLP283 P0000 60000 T10781144 55002
27	0305	AO2 VIS 1 3/4V4 P0000 T10831133
27	0341	AO2 P0001 T10891117
27	0353	AO2 PRESFR SLP272 P0002 T10941117
27	0424	AO2 P0001 T10941111
27	0445	AO2 P0002 T10941117
27	0453	AO2 SLP278 P0003 T11001117
27	0508	AO2 P0001 T11001122
27	0519	AO2 P0001 T11001117
27	0531	AO2 P0002 T11001122
27	0548	AO2 P0004
27	0553	AO2 SLP289 P0005 60010 70010 T11001122 11067 21100 50010
27	0628	AO2 TWR VIS 3/4 P0004 T11061122 (XX)
27	0653	AO2 SFC VIS 1 SLP296 P0007 T11061128 (XX)
27	0701	AO2 P0001 T11061122 (XX)
27	0712	AO2 SFC VIS 1 1/4 P0002 T11061128 (XX)
27	0729	AO2 P0002 T11111128 (XX)
27	0737	AO2 TWR VIS 1 1/2 P0002 T11111128 (XX)
27	0740	AO2 TWR VIS 3/4 P0002 T11111128 (XX)
27	0753	AO2 TWR VIS 3/4 SLP294 P0004 T11111128 (XX)
27	0804	AO2 P0000 T11111128 (XX)
27	0836	AO2 SFC VIS 1 P0001 T11111128 (XX)
27	0853	AO2 SFC VIS 1 3/4 SLP296 P0001 60012 T11111133 51002 (XX)
27	0953	AO2 SFC VIS 1 1/2 SLP300 P0001 T11111139 (XX)
27	1010	AO2 SFC VIS 2 1/2 P0000 T11111139 (XX)
27	1024	AO2 SFC VIS 4 P0000 T11061133 (XX)
27	1031	AO2 SFC VIS 4 P0000 T11061139 (XX)
27	1035	AO2 P0000 T11061133 (XX)
27	1046	AO2 VIS 1 3/4V4 P0000 T11061133 (XX)
27	1053	AO2 SLP303 P0000 T11061139 (XX)
27	1128	AO2 P0000 T11061139 (XX)
27	1153	AO2 SLP296 P0000 60013 T11001133 11100 21111 58000 (XX)
27	1200	AO2 TWR VIS 2 P0000 T11001133 (XX)
27	1213	AO2 P0000 T11001139 (XX)
27	1218	AO2 P0000 T11001139 (XX)

Table C.9 Storm 3-5, Hourly Remarks, 27 FEB 2015, National Climatic Data Center, continued

27	1253	AO2 SLP294 P0000 T11001133 (XX)
27	1353	AO2 SLP279 P0000 T10941128 (XX)
27	1405	AO2 P0000 T10941128 (XX)
27	1428	AO2 P0000 T10891128 (XX)
27	1453	AO2 SLP272 P0000 60000 T10941128 58021 (XX)
27	1551	AO2 TWR VIS 3 VIS 2V3 P0000 FIBI (XX)
27	1553	AO2 SLP274 P0000 T10941122 (XX)
27	1603	AO2 TWR VIS 2 P0000 T10941122 (XX)
27	1612	AO2 P0000 T10941122 (XX)
27	1620	AO2 TWR VIS 2 P0000 T10941122 (XX)
27	1625	AO2 P0000 T10941122 (XX)
27	1632	AO2 SFC VIS 2 1/2 P0000 T10941122 (XX)
27	1653	AO2 SFC VIS 3 SLP270 P0000 T10941128 (XX)
27	1734	AO2 SFC VIS 4 P0000 T11001128 (XX)
27	1753	AO2 SFC VIS 4 SLP263 P0000 60000 T11001128 11089 21100 58013 (XX)
27	1810	AO2 P0000 T11001128 (XX)
27	1830	AO2 PRESRR P0000 T11001128 (XX)
27	1853	AO2 SLP276 P0000 T11061128 (XX)
27	1917	AO2 P0000 T11061128 (XX)
27	1948	AO2 P0000 (XX)
27	1953	AO2 SLP270 P0000 T11061128 (XX)
27	2017	AO2 P0000 T11061128 (XX)
27	2034	AO2 SNE27 P0000 T11061128 (XX)
27	2051	AO2 SNE27 P0000 FIBI (XX)
27	2053	AO2 SNE27B52 SLP282 P0000 60000 T11111133 53003 (XX)
27	2104	AO2 SNE01 P0000 T11111133 (XX)
27	2153	AO2 SNE01B28 SLP276 P0000 T11171133 (XX)
27	2248	AO2 SNE0355 P0000 (XX)
27	2253	AO2 SNE0355 SLP280 P0000 T11171133 (XX)
27	2337	AO2 T11171128 (XX)
27	2353	AO2 SNB46 SLP274 P0000 60000 T11171128 11100 21117 410671117 50001=

Dynamically generated Mon Mar 27 08:54:45 EDT 2017 via http://www.ncdc.noaa.gov/qclcd/QCLCD

Table C.10 Storm 3-5, Hourly Precipitation, 27 FEB 2015, National Climatic Data Center

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
Data Version: VER3

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

QUALITY CONTROLLED LOCAL
CLIMATOLOGICAL DATA
(final)
HOURLY PRECIPITATION TABLE
AMARILLO RICK HUSBAND INTL AIRPORT (23047)
AMARILLO, TX
(02/2015)

	A.M. HOUR(L.S.T) ENDING AT													P.M. HOUR(L.S.T) ENDING AT												
DT	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--	--1--	--2--	--3--	--4--	--5--	--6--	--7--	--8--	--9--	--10--	--11--	--12--	--DT--
27			T	0.02	0.03	0.05	0.07	0.04	0.01	0.01	T	T	27	T	T	T	T	T	T	T	T	T	T		T	27

Table C.11 Storm 3-5, Hourly Observations, FEB 25-27, 2015, WTAMU SchoolNET

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/25/2015	0:00	34.5	77	28.1	34.5	30.35	-0.06	0.07	0	- -	3	15	3
2/25/2015	1:00	34.8	76	28	34.8	30.34	-0.04	0	0	- -	1	15	1
2/25/2015	2:00	34.1	77	27.7	34.1	30.3	-0.04	0	0	- -	0	14	4
2/25/2015	3:00	31.4	80	26	31.4	30.27	-0.07	0	0	- -	1	13	2
2/25/2015	4:00	28.5	83	24	28.5	30.26	-0.05	0	0	- -	2	14	3
2/25/2015	5:00	27.1	84	22.9	27.1	30.26	-0.05	0	0	- -	2	15	4
2/25/2015	6:00	26.7	85	22.8	26.7	30.25	-0.09	0	0	- -	1	13	2
2/25/2015	7:00	26	85	22.1	26	30.24	-0.08	0	0	- -	2	12	3
2/25/2015	8:00	25.7	86	22.1	25.7	30.22	-0.07	0	0	- -	2	12	2
2/25/2015	9:00	32.4	81	27.2	32.4	30.21	-0.07	0	0	- -	5	12	5
2/25/2015	10:00	41.5	69	32.2	41.5	30.21	-0.06	0	0	- -	6	1	3
2/25/2015	11:00	48.6	52	31.8	48.6	30.19	-0.05	0	0	- -	6	1	16
2/25/2015	12:00	53.1	35	25.9	53.1	30.18	-0.03	0	0	- -	9	16	10
2/25/2015	13:00	54.1	30	23.1	54.1	30.16	-0.05	0	0	- -	10	1	13
2/25/2015	14:00	56.2	35	28.7	56.2	30.13	-0.04	0	0	- -	13	3	15
2/25/2015	15:00	56.1	37	30	56.1	30.14	-0.06	0	0	- -	10	2	15
2/25/2015	16:00	55.4	41	31.9	55.4	30.14	-0.05	0	0	- -	11	1	15
2/25/2015	17:00	54.8	47	34.9	54.8	30.14	-0.04	0	0	- -	14	1	12
2/25/2015	18:00	52.2	53	35.6	52.2	30.16	-0.05	0	0	- -	11	2	15
2/25/2015	19:00	48.6	64	37.1	48.6	30.2	-0.03	0	0	- -	10	3	8
2/25/2015	20:00	47.2	63	35.3	47.2	30.23	-0.03	0	0	- -	9	16	10
2/25/2015	21:00	45.7	68	35.8	45.7	30.26	-0.01	0	0	- -	7	3	13
2/25/2015	22:00	44.1	73	36.1	44.1	30.29	0.02	0	0	- -	12	1	14
2/25/2015	23:00	40.3	84	35.8	40.3	30.3	0.06	0.01	0	- -	14	3	18

Table C.11 Storm 3-5, Hourly Observations, FEB 25-27, 2015, WTAMU SchoolNET, continued

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/26/2015	0:00	36.9	89	33.9	36.9	30.32	0.09	0.04	0	- -	17	3	19
2/26/2015	1:00	34.4	91	32	34.4	30.35	0.11	0.03	0	- -	14	3	15
2/26/2015	2:00	33	93	31.1	33	30.39	0.12	0.04	0	- -	16	2	20
2/26/2015	3:00	31.8	92	29.7	31.8	30.41	0.11	0.04	0	- -	18	2	20
2/26/2015	4:00	28.6	90	26	28.6	30.43	0.11	0.04	0	- -	15	3	15
2/26/2015	5:00	26.3	88	23.2	26.3	30.45	0.09	0.04	0	- -	18	3	18
2/26/2015	6:00	23.3	87	20	23.3	30.5	0.09	0.04	0	- -	19	2	20
2/26/2015	7:00	21.5	85	17.7	21.5	30.54	0.11	0.04	0	- -	16	3	17
2/26/2015	8:00	20.8	86	17.2	20.8	30.58	0.12	0.04	0	- -	11	1	12
2/26/2015	9:00	20.2	84	16.1	20.2	30.61	0.13	0.04	0	- -	19	4	22
2/26/2015	10:00	20.3	81	15.4	20.3	30.66	0.12	0.04	0	- -	10	2	18
2/26/2015	11:00	22.3	78	16.5	22.3	30.64	0.12	0.04	0	- -	21	3	23
2/26/2015	12:00	23.8	77	17.7	23.8	30.64	0.13	0.04	0	- -	14	3	20
2/26/2015	13:00	22.6	73	15.3	22.6	30.64	0.14	0.04	0	- -	15	1	15
2/26/2015	14:00	23.8	74	16.8	23.8	30.63	0.14	0.04	0	- -	7	3	10
2/26/2015	15:00	25.7	72	18	25.7	30.63	0.08	0.04	0	- -	13	2	14
2/26/2015	16:00	27.7	63	16.8	27.7	30.63	0.06	0.04	0	- -	4	4	10
2/26/2015	17:00	28.1	58	15.2	28.1	30.63	0.04	0.04	0	- -	3	6	13
2/26/2015	18:00	27.3	58	14.5	27.3	30.64	0.01	0.04	0	- -	3	5	6
2/26/2015	19:00	26.3	59	13.9	26.3	30.66	-0.01	0.04	0	- -	14	4	16
2/26/2015	20:00	25	58	12.3	25	30.7	0	0.04	0	- -	7	3	15
2/26/2015	21:00	23.7	61	12.3	23.7	30.71	0	0.04	0	- -	7	3	9
2/26/2015	22:00	22.7	56	9.3	22.7	30.73	0.01	0.04	0	- -	9	5	9
2/26/2015	23:00	22.1	57	9.2	22.1	30.74	0.04	0.04	0	- -	2	9	12

Table C.11 Storm 3-5, Hourly Observations, FEB 25-27, 2015, WTAMU SchoolNET, continued

Date mm/dd/yyyy	Time hh:mm	Temperature ºF	Relative Humidity %	Dewpoint ºF	Heat Index ºF	Barometric Pressure in Hg	Trend in Hg	Rainfall in	Rain Rate in/hr	Water Level cm	Wind Speed mph	Peak Wind Speed mph	Average Wind Speed mph
2/27/2015	0:00	21	57	8.2	21	30.73	0.05	0.04	0	- -	4	1	10
2/27/2015	1:00	20.4	58	8	20.4	30.7	0.06	0	0	- -	5	7	7
2/27/2015	2:00	19.9	55	6.3	19.9	30.73	0.07	0	0	- -	5	6	14
2/27/2015	3:00	17.8	72	10.3	17.8	30.74	0.06	0	0	- -	3	5	5
2/27/2015	4:00	16.3	84	12.3	16.3	30.72	0.03	0	0	- -	2	9	5
2/27/2015	5:00	15.3	86	11.8	15.3	30.74	0.01	0	0	- -	3	6	8
2/27/2015	6:00	14.9	88	11.9	14.9	30.76	0.01	0	0	- -	1	9	2
2/27/2015	7:00	13.9	88	11	13.9	30.76	0	0	0	- -	3	9	3
2/27/2015	8:00	13.5	88	10.6	13.5	30.77	0	0	0	- -	8	4	11
2/27/2015	9:00	13.9	87	10.7	13.9	30.79	0.02	0	0	- -	3	12	4
2/27/2015	10:00	14.3	85	10.6	14.3	30.8	0.05	0	0	- -	7	7	14
2/27/2015	11:00	14.3	83	10.1	14.3	30.8	0.01	0	0	- -	8	6	8
2/27/2015	12:00	15.2	79	9.9	15.2	30.79	0.03	0	0	- -	7	9	11
2/27/2015	13:00	15.4	80	10.3	15.4	30.78	0.06	0	0	- -	4	6	9
2/27/2015	14:00	16.1	79	10.7	16.1	30.73	0.03	0	0	- -	4	10	13
2/27/2015	15:00	16	79	10.6	16	30.72	-0.01	0	0	- -	5	7	10
2/27/2015	16:00	16	80	10.9	16	30.72	0.01	0	0	- -	9	7	10
2/27/2015	17:00	15.3	81	10.5	15.3	30.7	-0.01	0	0	- -	11	6	15
2/27/2015	18:00	14.5	82	10	14.5	30.7	-0.04	0	0	- -	10	7	10
2/27/2015	19:00	13.7	83	9.5	13.7	30.73	-0.06	0	0	- -	6	7	11
2/27/2015	20:00	13.4	85	9.7	13.4	30.72	-0.06	0	0	- -	5	9	11
2/27/2015	21:00	13.1	85	9.4	13.1	30.74	-0.05	0	0	- -	7	8	10
2/27/2015	22:00	12.8	85	9.1	12.8	30.74	-0.03	0	0	- -	7	6	12
2/27/2015	23:00	12.2	87	9	12.2	30.74	0.01	0	0	- -	1	9	2

APPENDIX C

Storm 3-5

VIDEO DATA

Table C-12. Statistical Comparison of De-icing Videos for Storm 3-5

Type	Video	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	C	98.8	3.4	2/26, After overnight rain
	3	C	99.6	2.0	2/27, Still waiting for snow
	4	C	52.5	22.5	2/27, After first snowfall
	5	C	1.3	3.4	2/27, After >1 in snow
	6	C	9.6	7.5	2/27, After 1st plow
	7	C	26.7	6.4	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	C	56.3	19.3	2/27, After 2nd de-icing, slushing
	9	C	66.3	14.4	2/27, After 3rd plow
	1	MD20	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	MD20	98.3	3.9	2/26, After overnight rain
	3	MD20	99.2	2.9	2/27, Still waiting for snow
	4	MD20	55.0	19.8	2/27, After first snowfall
	5	MD20	0.0	0.0	2/27, After >1 in snow
	6	MD20	10.8	5.1	2/27, After 1st plow
	7	MD20	20.0	8.5	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	MD20	75.0	9.0	2/27, After 2nd de-icing, slushing
	9	MD20	84.2	6.7	2/27, After 3rd plow
	1	RS	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	RS	98.3	3.9	2/26, After overnight rain
	3	RS	98.3	3.9	2/27, Still waiting for snow
	4	RS	48.3	23.7	2/27, After first snowfall
	5	RS	0.0	0.0	2/27, After >1 in snow
	6	RS	7.5	4.5	2/27, After 1st plow
	7	RS	20.8	5.1	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	RS	76.7	9.8	2/27, After 2nd de-icing, slushing
	9	RS	80.8	9.0	2/27, After 3rd plow

Table C-13. Raw Data from De-icing Videos for Storm 3-5

De-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
1	2/25/2015	20:32	NB	0-10	Control	100	1	1	100	1	1	100	1	1
				10-20	Meltdown-20	100	1	1	100	1	1	100	1	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt	100	1	1	100	1	1	100	1	1
				40-50	Control	100	1	1	100	1	1	100	1	1
				50-60	Meltdown-20	100	1	1	100	1	1	100	1	1
				60-70	Control	100	1	1	100	1	1	100	1	1
				70-80	Road Salt	100	1	1	100	1	1	100	1	1
			SB	80-70	Control	100	1	1	100	1	1	100	1	1
				70-60	Meltdown-20	100	1	1	100	1	1	100	1	1
				60-50	Control	100	1	1	100	1	1	100	1	1
				50-40	Road Salt	100	1	1	100	1	1	100	1	1
				40-30	Control	100	1	1	100	1	1	100	1	1
				30-20	Meltdown-20	100	1	1	100	1	1	100	1	1
				20-10	Control	100	1	1	100	1	1	100	1	1
				10-0	Road Salt	100	1	1	100	1	1	100	1	1
2	2/26/2015	10:26	NB	0-10	Control	90	1	2	100	1	1	100	1	1
				10-20	Meltdown-20	100	1	1	100	1	1	100	1	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt	90	1	2	100	1	1	100	1	1
				40-50	Control	100	1	1	100	1	2	100	1	1
				50-60	Meltdown-20	90	1	2	100	1	1	100	1	1
				60-70	Control	90	1	2	100	1	1	100	1	1
				70-80	Road Salt	90	1	2	100	1	2	100	1	1
			SB	80-70	Control	90	1	2	100	1	2	100	1	1
				70-60	Meltdown-20	90	1	2	100	1	1	100	1	1
				60-50	Control	100	1	1	100	1	1	100	1	1
				50-40	Road Salt	100	1	1	100	1	1	100	1	1
				40-30	Control	100	1	1	100	1	1	100	1	1
				30-20	Meltdown-20	100	1	2	100	1	1	100	1	1
				20-10	Control	100	1	1	100	1	1	100	1	1
				10-0	Road Salt	100	1	1	100	1	1	100	1	1
3	2/26/2015	15:42	NB	0-10	Control	100	1	2	100	1	1	100	1	1
				10-20	Meltdown-20	100	1	1	100	1	1	100	1	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt	100	1	2	100	1	1	100	1	1
				40-50	Control	100	1	1	100	1	1	100	1	1
				50-60	Meltdown-20	100	1	1	100	1	1	100	1	1
				60-70	Control	100	1	1	100	1	1	100	1	1
				70-80	Road Salt	100	1	1	100	1	1	100	1	1
			SB	80-70	Control	100	1	1	100	1	1	100	1	1
				70-60	Meltdown-20	100	1	1	100	1	1	100	1	1
				60-50	Control	100	1	1	100	1	1	100	1	1
				50-40	Road Salt	90	1	2	100	1	1	100	1	1
				40-30	Control	90	1	2	100	1	1	100	1	1
				30-20	Meltdown-20	90	1	2	100	1	1	100	1	1
				20-10	Control	100	1	1	100	1	1	100	1	1
				10-0	Road Salt	90	1	2	100	1	1	100	1	1

Table C-13. Raw Data from De-icing Videos for Storm 3-5 Continued

De-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
4	2/27/2015	3:48	NB	0-10	Control	60	7	2	80	7	2	60	6	2
				10-20	Meltdown-20	50	7	2	80	7	2	50	6	2
				20-30	Control	40	7	2	80	7	2	40	6	2
				30-40	Road Salt	30	7	2	80	7	2	30	7	2
				40-50	Control	20	7	2	80	7	2	30	7	2
				50-60	Meltdown-20	30	7	2	80	7	2	40	6	2
				60-70	Control	30	7	2	80	7	2	20	7	2
				70-80	Road Salt	20	7	2	80	7	2	20	7	2
			SB	80-70	Control	30	7	2	90	7	2	50	7	2
				70-60	Meltdown-20	40	7	2	90	7	2	40	7	2
				60-50	Control	30	7	2	80	7	2	40	7	2
				50-40	Road Salt	40	7	2	80	7	2	50	7	2
				40-30	Control	40	7	2	70	7	2	50	7	2
				30-20	Meltdown-20	40	7	2	70	7	2	50	7	2
				20-10	Control	30	7	2	80	7	2	50	7	2
				10-0	Road Salt	30	7	2	70	7	2	50	7	2
5	2/27/2015	7:13	NB	0-10	Control	10	9	4	10	9	4	10	9	4
				10-20	Meltdown-20	0	9	4	0	9	4	0	9	4
				20-30	Control	0	9	4	0	9	4	0	9	4
				30-40	Road Salt	0	9	4	0	9	4	0	9	4
				40-50	Control	0	9	4	0	9	4	0	9	4
				50-60	Meltdown-20	0	9	4	0	9	4	0	9	4
				60-70	Control	0	9	4	0	9	4	0	9	4
				70-80	Road Salt	0	9	4	0	9	4	0	9	4
			SB	80-70	Control	0	9	4	0	9	4	0	9	4
				70-60	Meltdown-20	0	9	4	0	9	4	0	9	4
				60-50	Control	0	9	4	0	9	4	0	9	4
				50-40	Road Salt	0	9	4	0	9	4	0	9	4
				40-30	Control	0	9	4	0	9	4	0	9	4
				30-20	Meltdown-20	0	9	4	0	9	4	0	9	4
				20-10	Control	0	9	4	0	9	4	0	9	4
				10-0	Road Salt	0	9	4	0	9	4	0	9	4
6	2/27/2015	7:32	NB	0-10	Control	20	9	4	30	7	4	20	7	4
				10-20	Meltdown-20	0	9	4	10	9	4	10	9	4
				20-30	Control	0	9	4	10	9	4	10	9	4
				30-40	Road Salt	0	9	4	10	9	4	10	9	4
				40-50	Control	0	9	4	10	6	4	10	9	4
				50-60	Meltdown-20	10	9	4	10	6	4	20	9	4
				60-70	Control	0	9	4	0	6	4	10	9	4
				70-80	Road Salt	0	9	4	0	6	4	10	9	4
			SB	80-70	Control	0	9	4	10	9	4	10	9	4
				70-60	Meltdown-20	10	9	4	10	7	4	10	9	4
				60-50	Control	10	9	4	10	7	4	10	9	4
				50-40	Road Salt	10	9	4	10	76	4	10	9	4
				40-30	Control	10	9	4	10	6	4	10	9	4
				30-20	Meltdown-20	10	9	4	20	9	4	10	9	4
				20-10	Control	0	9	4	20	7	4	10	9	4
				10-0	Road Salt	10	9	4	10	9	4	10	9	4

Table C-13. Raw Data from De-icing Videos for Storm 3-5 Continued

De-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
7	2/27/2015	10:12	NB	0-10	Control	30	9	4	30	7	4	30	7	4
				10-20	Meltdown-20	20	9	4	40	7	4	30	7	4
				20-30	Control	30	9	4	30	7	4	30	7	4
				30-40	Road Salt	20	9	4	20	9	4	20	7	4
				40-50	Control	10	9	4	20	9	4	20	7	4
				50-60	Meltdown-20	20	9	4	10	7	4	20	7	4
				60-70	Control	30	9	4	20	7	4	30	7	4
				70-80	Road Salt	20	9	4	10	9	4	20	7	4
			SB	80-70	Control	30	9	4	20	7	4	30	7	4
				70-60	Meltdown-20	10	9	4	10	9	4	20	7	4
				60-50	Control	20	9	4	20	7	4	20	7	4
				50-40	Road Salt	30	9	4	20	7	4	20	7	4
				40-30	Control	30	9	4	30	7	4	30	7	4
				30-20	Meltdown-20	20	9	4	20	7	4	20	7	4
				20-10	Control	30	9	4	40	7	4	30	7	4
				10-0	Road Salt	30	9	4	20	7	4	20	7	4

Table C-14. Statistical Comparison of Anti-icing Videos for Storm 3-5

Type	Video	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
Anti-icing	1	C	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	C	99.2	2.9	2/26, After overnight rain
	3	C	100.0	0.0	2/27, Still waiting for snow
	4	C	32.5	9.7	2/27, After first snowfall
	5	C	0.8	2.9	2/27, After >1 in snow
	6	C	9.3	2.6	2/27, After 1st plow
	7	C	26.7	4.9	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	C	52.5	6.2	2/27, After 2nd de-icing, slushing
	9	C	66.7	10.7	2/27, After 3rd plow
	1	MDA	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	MDA	100.0	0.0	2/26, After overnight rain
	3	MDA	100.0	0.0	2/27, Still waiting for snow
	4	MDA	20.0	6.3	2/27, After first snowfall
	5	MDA	0.0	0.0	2/27, After >1 in snow
	6	MDA	18.3	4.1	2/27, After 1st plow
	7	MDA	26.7	5.2	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	MDA	63.3	15.1	2/27, After 2nd de-icing, slushing
	9	MDA	70.0	19.0	2/27, After 3rd plow
	1	RSB	100.0	0.0	2/25, After 1st anti-icing, slushing
	2	RSB	98.3	2.9	2/26, After overnight rain
	3	RSB	100.0	0.0	2/27, Still waiting for snow
	4	RSB	21.7	4.1	2/27, After first snowfall
	5	RSB	1.7	4.1	2/27, After >1 in snow
	6	RSB	23.3	5.2	2/27, After 1st plow
	7	RSB	18.3	7.5	2/27, After 1st de-icing, 2nd anti-icing, slushing
	8	RSB	78.3	7.5	2/27, After 2nd de-icing, slushing
	9	RSB	85.0	5.5	2/27, After 3rd plow

Table C-15. Raw Data from Anti-icing Videos for Storm 3-5

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
1	2/25/2015	20:28	SB	0-10	Control	100	1	1	100	1	1	100	1	1
				10-20	Meltdown Apex	100	2	1	100	1	1	100	2	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt Brine	100	2	1	100	1	1	100	1	1
			NB	40-30	Control	100	1	1	100	1	1	100	1	1
				30-20	Meltdown Apex	100	2	1	100	1	1	100	2	1
				20-10	Control	100	1	1	100	1	1	100	1	1
				10-10	Road Salt Brine	100	2	1	100	1	1	100	1	1
2	2/26/2015	10:26	SB	0-10	Control	100	1	1	100	1	1	100	1	1
				10-20	Meltdown Apex	100	1	2	100	2	1	100	2	1
				20-30	Control	100	1	1	100	1	1	100	2	1
				30-40	Road Salt Brine	100	1	1	100	1	1	100	1	1
			NB	40-30	Control	100	1	2	100	1	1	100	1	1
				30-20	Meltdown Apex	100	1	2	100	2	1	100	2	1
				20-10	Control	90	1	2	100	1	1	100	2	1
				10-10	Road Salt Brine	90	1	2	100	1	1	100	2	1
3	2/26/2015	15:42	SB	0-10	Control	100	1	1	100	1	1	100	1	1
				10-20	Meltdown Apex	100	1	1	100	2	1	100	2	1
				20-30	Control	100	1	1	100	1	1	100	1	1
				30-40	Road Salt Brine	100	1	1	100	1	1	100	1	1
			NB	40-30	Control	100	1	1	100	1	1	100	1	1
				30-20	Meltdown Apex	100	2	1	100	2	1	100	2	1
				20-10	Control	100	1	1	100	1	1	100	1	1
				10-10	Road Salt Brine	100	2	1	100	1	1	100	1	1
4	2/27/2015	3:57	SB	0-10	Control	40	7	2	30	7	2	50	6	2
				10-20	Meltdown Apex	20	7	2	20	7	2	20	7	2
				20-30	Control	20	7	2	20	7	2	30	7	2
				30-40	Road Salt Brine	20	7	2	20	7	2	20	7	2
			NB	40-30	Control	20	7	2	30	7	2	40	7	2
				30-20	Meltdown Apex	20	7	2	30	7	2	10	7	2
				20-10	Control	40	7	2	30	7	2	40	7	2
				10-10	Road Salt Brine	30	7	2	20	7	2	20	7	2
5	2/27/2015	7:13	SB	0-10	Control	0	9	4	10	8	4	0	8	4
				10-20	Meltdown Apex	0	9	4	0	8	4	0	8	4
				20-30	Control	0	9	4	0	8	4	0	8	4
				30-40	Road Salt Brine	0	9	4	0	8	4	0	8	4
			NB	40-30	Control	0	9	4	0	8	4	0	8	4
				30-20	Meltdown Apex	0	9	4	0	8	4	0	8	4
				20-10	Control	0	9	4	0	8	4	0	8	4
				10-10	Road Salt Brine	0	9	4	10	8	4	0	8	4

Table C-15. Raw Data from Anti-icing Videos for Storm 3-5 Continued

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC	% BARE	AASHTO	PSIC
6	2/27/2015	7:24	SB	0-10	Control	10	9	4	10	9	4	1	8	4
				10-20	Meltdown Apex	20	9	4	20	7	4	20	7	4
				20-30	Control	10	9	4	10	9	4	10	9	4
				30-40	Road Salt Brine	30	9	4	20	7	4	30	7	4
			NB	40-30	Control	10	9	4	10	9	4	10	9	4
				30-20	Meltdown Apex	20	9	4	10	9	4	20	7	4
				20-10	Control	10	9	4	10	9	4	10	8	4
				10-10	Road Salt Brine	20	9	4	20	9	4	20	7	4
7	2/27/2015	10:08	SB	0-10	Control	30	5	4	30	7	4	20	7	4
				10-20	Meltdown Apex	20	5	4	30	5	4	20	5	3
				20-30	Control	30	5	4	20	7	4	20	7	4
				30-40	Road Salt Brine	10	5	4	20	7	4	10	5	3
			NB	40-30	Control	30	5	4	30	5	4	30	7	4
				30-20	Meltdown Apex	30	5	4	30	5	4	30	5	3
				20-10	Control	30	5	4	30	5	4	20	7	4
				10-10	Road Salt Brine	20	5	4	30	5	4	20	5	3
8	2/27/2015	13:46	SB	0-10	Control	60	5	4	50	7	4	50	5	3
				10-20	Meltdown Apex	80	5	4	80	4	2	70	4	2
				20-30	Control	60	5	4	60	7	4	50	5	3
				30-40	Road Salt Brine	90	4	4	80	4	2	80	4	2
			NB	40-30	Control	50	5	4	50	7	4	40	7	3
				30-20	Meltdown Apex	50	7	4	50	7	4	50	5	3
				20-10	Control	60	7	4	50	7	4	50	7	3
				10-10	Road Salt Brine	80	5	4	70	5	3	70	4	2
9	2/27/2015	15:03	SB	0-10	Control	80	4	4	70	4	2	80	4	2
				10-20	Meltdown Apex	90	4	4	80	4	2	90	3	1
				20-30	Control	70	4	4	70	4	2	80	4	2
				30-40	Road Salt Brine	90	4	4	90	4	2	90	3	1
			NB	40-30	Control	60	7	4	50	7	2	50	5	3
				30-20	Meltdown Apex	60	7	4	50	7	2	50	4	3
				20-10	Control	70	4	4	60	4	2	60	4	2
				10-10	Road Salt Brine	80	4	4	80	4	2	80	4	1

APPENDIX C

Storm 3-5

IMAGE DATA

Table C-16. Statistical Comparison of De-icing Photos for Storm 3-5

Type	Photoset	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	9.6	10.0	2/27, After >1 in snow
	2	C	18.6	11.5	2/27, After 1st plow
	3	C	45.6	26.3	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	C	85.2	20.2	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow
	1	MD	9.8	5.1	2/27, After >1 in snow
	2	MD	8.9	7.6	2/27, After 1st plow
	3	MD	50.1	32.6	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	MD	99.9	0.5	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow
	1	RS	5.7	6.1	2/27, After >1 in snow
	2	RS	8.4	8.1	2/27, After 1st plow
	3	RS	64.5	28.2	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	RS	98.2	4.4	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow

Table C-17. Raw Data from De-icing Photos for Storm 3-5

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
1	2/27/2015	6:50	NB	4	Control	82	0	18	80	0	20	76	0	24
				6	Control	50	0	50	54	0	46	63	0	37
				8	Control	96	0	4	95	0	5	91	0	9
				12	MD 20	93	0	7	91	0	9	89	0	11
				14	MD 20	91	0	9	89	0	11	90	0	10
				18	MD 20	86	0	14	80	0	20	78	0	22
				24	Control	98	0	2	97	0	3	97	0	3
				26	Control	89	0	11	94	0	6	95	0	5
				28	Control	91	0	9	92	0	8	87	0	13
				32	Road Salt	92	0	8	94	0	6	91	0	9
				34	Road Salt	99	0	1	98	0	2	98	0	2
				38	Road Salt	99	0	1	98	0	2	98	0	2
				44	Control	98	0	2	97	0	3	97	0	3
				46	Control	94	0	6	97	0	3	94	0	6
				48	Control	99	0	1	98	0	2	98	0	2
				52	MD 20	90	0	10	86	0	14	90	0	10
				54	MD 20	91	0	9	89	0	11	88	0	12
				58	MD 20	89	0	11	89	0	11	87	0	13
				64	Control	97	0	3	96	0	4	95	0	5
				66	Control	97	0	3	97	0	3	93	0	7
				68	Control	99	0	1	98	0	2	96	0	4
				72	Road Salt	97	0	3	98	0	2	95	0	5
				74	Road Salt	98	0	2	98	0	2	96	0	4
				78	Road Salt	96	0	4	96	0	4	93	0	7
			SB	76	Control	100	0	0	100	0	0	100	0	0
				74	Control	86	0	14	88	0	12	89	0	11
				72	Control	78	0	22	76	0	24	80	0	20
				68	MD 20	92	0	8	92	0	8	89	0	11
				64	MD 20	98	0	2	99	0	1	98	0	2
				62	MD 20	90	0	10	89	0	11	90	0	10
				56	Control	95	0	5	95	0	5	95	0	5
				54	Control	80	0	20	78	0	22	74	0	26
				52	Control	99	0	1	99	0	1	99	0	1
				48	Road Salt	97	0	3	97	0	3	95	0	5
				44	Road Salt	97	0	3	97	0	3	95	0	5
				42	Road Salt	100	0	0	100	0	0	100	0	0
				36	Control	98	0	2	98	0	2	98	0	2
				34	Control	90	0	10	92	0	8	92	0	8
				32	Control	96	0	4	91	0	9	95	0	5
				28	MD 20	99	0	1	100	0	0	98	0	2
				24	MD 20	93	0	7	91	0	9	93	0	7
				22	MD 20	83	0	17	85	0	15	82	0	18
				16	Control	92	0	8	85	0	15	92	0	8
				14	Control	88	0	12	88	0	12	91	0	9
				12	Control	89	0	11	87	0	13	88	0	12
				8	Road Salt	97	0	3	96	0	4	97	0	3
				6	Road Salt	82	0	18	82	0	18	79	0	21
				2	Road Salt	80	0	20	84	0	16	85	0	15

Table C-17. Raw Data from De-icing Photos for Storm 3-5 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
2	2/27/2015	9:15	NB	4	Control	70	0	30	72	0	28	64	0	36
				6	Control	51	0	49	62	0	38	58	0	42
				8	Control	93	0	7	94	0	6	94	0	6
				12	MD 20	93	0	7	94	0	6	91	0	9
				14	MD 20	82	0	18	73	0	27	77	0	23
				18	MD 20	87	0	13	78	0	22	86	0	14
				24	Control	78	0	22	66	0	34	82	0	18
				26	Control	82	0	18	78	0	22	84	0	16
				28	Control	77	0	23	70	0	30	78	0	22
				32	Road Salt	87	0	13	82	0	18	85	0	15
				34	Road Salt	88	0	12	91	0	9	91	0	9
				38	Road Salt	99	0	1	98	0	2	96	0	4
				44	Control	98	0	2	96	0	4	97	0	3
				46	Control	96	0	4	99	0	1	99	0	1
				48	Control	96	0	4	93	0	7	95	0	5
				52	MD 20	98	0	2	99	0	1	99	0	1
				54	MD 20	80	0	20	82	0	18	82	0	18
				58	MD 20	86	0	14	85	0	15	87	0	13
				64	Control	76	0	24	71	0	29	74	0	26
				66	Control	89	0	11	89	0	11	81	0	19
				68	Control	87	0	13	86	0	14	87	0	13
				72	Road Salt	97	0	3	97	0	3	97	0	3
				74	Road Salt	97	0	3	97	0	3	97	0	3
				78	Road Salt	98	0	2	94	0	6	96	0	4
			SB	76	Control	99	0	1	99	0	1	98	0	2
				74	Control	85	0	15	78	0	22	84	0	16
				72	Control	72	0	28	76	0	24	82	0	18
				68	MD 20	98	0	2	98	0	2	98	0	2
				64	MD 20	98	0	2	96	0	4	96	0	4
				62	MD 20	98	0	2	94	0	6	94	0	6
				56	Control	84	0	16	87	0	13	84	0	16
				54	Control	52	0	48	71	0	29	51	0	49
				52	Control	96	0	4	94	0	6	92	0	8
				48	Road Salt	92	0	8	89	0	11	85	0	15
				44	Road Salt	99	0	1	99	0	1	99	0	1
				42	Road Salt	96	0	4	95	0	5	91	0	9
				36	Control	90	0	10	94	0	6	90	0	10
				34	Control	80	0	20	84	0	16	83	0	17
				32	Control	93	0	7	89	0	11	87	0	13
				28	MD 20	98	0	2	98	0	2	96	0	4
				24	MD 20	99	0	1	99	0	1	98	0	2
				22	MD 20	87	0	13	87	0	13	90	0	10
				16	Control	74	0	26	73	0	27	70	0	30
				14	Control	80	0	20	72	0	28	68	0	32
				12	Control	77	0	23	75	0	25	74	0	26
				8	Road Salt	98	0	2	94	0	6	95	0	5
				6	Road Salt	98	0	2	97	0	3	95	0	5
				2	Road Salt	75	0	25	72	0	28	66	0	34

Table C-17. Raw Data from De-icing Photos for Storm 3-5 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
3	2/27/2015	10:48	NB	4	Control	9	0	91	27	0	73	18	0	82
				6	Control	51	0	49	49	0	51	52	0	48
				8	Control	83	0	17	78	0	22	84	0	16
				12	MD 20	77	15	8	76	15	9	76	15	9
				14	MD 20	72	15	13	74	20	6	76	15	9
				18	MD 20	100	0	0	100	0	0	98	0	2
				24	Control	49	0	51	63	0	37	53	5	42
				26	Control	88	10	2	88	10	2	87	10	3
				28	Control	65	0	35	42	0	58	57	0	43
				32	Road Salt	5	5	90	10	10	80	15	15	70
				34	Road Salt	57	10	33	68	10	22	69	10	21
				38	Road Salt	45	15	40	40	10	50	45	15	40
				44	Control	86	0	14	84	0	16	82	0	18
				46	Control	78	0	22	68	0	32	78	0	22
				48	Control	90	0	10	89	0	11	76	0	24
				52	MD 20	25	25	50	25	25	50	20	20	60
				54	MD 20	74	20	6	81	15	4	84	10	6
				58	MD 20	90	0	10	98	0	2	95	5	0
				64	Control	24	0	76	41	0	59	44	5	51
				66	Control	92	0	8	84	0	16	88	0	12
				68	Control	86	0	14	86	0	14	88	0	12
				72	Road Salt	80	20	0	81	15	4	80	20	0
				74	Road Salt	20	20	60	47	10	43	33	15	52
				78	Road Salt	10	10	80	25	15	60	15	15	70
			SB	76	Control	99	0	1	94	0	6	98	0	2
				74	Control	53	5	42	56	5	39	53	5	42
				72	Control	41	5	54	37	5	58	41	5	54
				68	MD 20	10	10	80	20	20	60	20	20	60
				64	MD 20	0	0	100	15	15	70	10	10	80
				62	MD 20	30	30	40	15	15	70	15	15	70
				56	Control	66	0	34	42	0	58	49	5	46
				54	Control	15	5	80	10	0	90	21	5	74
				52	Control	76	0	24	77	0	23	74	0	26
				48	Road Salt	30	30	40	29	20	51	10	10	80
				44	Road Salt	80	20	0	79	20	1	80	20	0
				42	Road Salt	54	45	1	51	25	24	49	25	26
				36	Control	54	0	46	50	5	45	57	0	43
				34	Control	5	5	90	9	0	91	10	0	90
				32	Control	41	5	54	47	5	48	41	5	54
				28	MD 20	35	5	60	30	10	60	50	30	20
				24	MD 20	25	25	50	24	15	61	40	20	40
				22	MD 20	35	0	65	46	0	54	37	0	63
				16	Control	20	20	60	24	15	61	30	10	60
				14	Control	20	20	60	24	15	61	25	15	60
				12	Control	47	0	53	44	0	56	48	0	52
				8	Road Salt	0	0	100	5	5	90	10	10	80
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	20	20	60	15	15	70	20	20	60

Table C-17. Raw Data from De-icing Photos for Storm 3-5 Continued

De-Icing Photos			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
4	2/27/2015	13:17	NB	4	Control	5	5	90	5	5	90	5	5	90
				6	Control	10	10	80	15	15	70	10	10	80
				8	Control	20	20	60	35	15	50	25	25	50
				12	MD 20	0	0	100	0	0	100	0	0	100
				14	MD 20	0	0	100	0	0	100	0	0	100
				18	MD 20	0	0	100	0	0	100	0	0	100
				24	Control	5	5	90	5	5	90	5	5	90
				26	Control	0	0	100	0	0	100	0	0	100
				28	Control	5	5	90	5	5	90	5	5	90
				32	Road Salt	0	0	100	0	0	100	5	5	90
				34	Road Salt	0	0	100	0	0	100	0	0	100
				38	Road Salt	0	0	100	0	0	100	0	0	100
				44	Control	40	20	40	45	15	40	40	20	40
				46	Control	50	10	40	50	10	40	45	15	40
				48	Control	20	10	70	30	10	60	25	15	60
				52	MD 20	0	0	100	0	0	100	0	0	100
				54	MD 20	0	0	100	0	0	100	0	0	100
				58	MD 20	0	0	100	0	0	100	5	5	90
				64	Control	20	10	70	20	10	70	15	15	70
				66	Control	55	5	40	50	10	40	50	10	40
				68	Control	55	5	40	57	0	43	68	0	32
				72	Road Salt	10	10	80	25	5	70	10	10	80
				74	Road Salt	5	5	90	5	5	90	5	5	90
				78	Road Salt	0	0	100	0	0	100	0	0	100
			SB	76	Control	55	15	30	55	15	30	60	20	20
				74	Control	15	15	70	20	20	60	15	15	70
				72	Control	0	0	100	0	0	100	5	5	90
				68	MD 20	0	0	100	0	0	100	0	0	100
				64	MD 20	0	0	100	0	0	100	0	0	100
				62	MD 20	0	0	100	0	0	100	0	0	100
				56	Control	0	0	100	0	0	100	0	0	100
				54	Control	0	0	100	0	0	100	0	0	100
				52	Control	5	5	90	5	5	90	10	10	80
				48	Road Salt	0	0	100	0	0	100	0	0	100
				44	Road Salt	0	0	100	0	0	100	0	0	100
				42	Road Salt	0	0	100	0	0	100	0	0	100
				36	Control	0	0	100	0	0	100	0	0	100
				34	Control	0	0	100	0	0	100	0	0	100
				32	Control	0	0	100	0	0	100	0	0	100
				28	MD 20	0	0	100	0	0	100	0	0	100
				24	MD 20	0	0	100	0	0	100	0	0	100
				22	MD 20	0	0	100	0	0	100	0	0	100
				16	Control	0	0	100	0	0	100	0	0	100
				14	Control	0	0	100	0	0	100	0	0	100
				12	Control	0	0	100	0	0	100	5	5	90
				8	Road Salt	0	0	100	0	0	100	0	0	100
				6	Road Salt	0	0	100	0	0	100	0	0	100
				2	Road Salt	0	0	100	0	0	100	0	0	100

Table C-18. Statistical Comparison of Anti-icing Photos for Storm 3-5

Type	Photoset	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
Anti-icing	1	C	5.6	3.7	2/27, After >1 in snow
	2	C	13.5	3.8	2/27, After 1st plow
	3	C	31.1	10.3	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	C	78.9	23.3	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow
	1	MDA	9.4	1.5	2/27, After >1 in snow
	2	MDA	4.4	1.9	2/27, After 1st plow
	3	MDA	9.3	9.6	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	MDA	78.9	20.3	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow
	1	RSB	8.7	1.8	2/27, After >1 in snow
	2	RSB	4.5	6.0	2/27, After 1st plow
	3	RSB	22.2	18.7	2/27, After 1st de-icing, 2nd anti-icing, slushing
	4	RSB	98.3	2.6	2/27, After 2nd plow, 2nd de-icing, slushing, 3rd plow

Table C-19. Raw Data from Anti-icing Photos for Storm 3-5

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
1	2/27/2015	6:50	SB	4	Control	90	0	10	90	0	10	87	0	13
				6	Control	91	0	9	91	0	9	88	0	12
				8	Control	90	0	10	88	0	12	91	0	9
				12	MDA	94	0	6	93	0	7	91	0	9
				14	MDA	88	0	12	92	0	8	89	0	11
				18	MDA	88	0	12	91	0	9	88	0	12
				24	Control	92	0	8	92	0	8	93	0	7
				26	Control	96	0	4	98	0	2	98	0	2
				28	Control	90	0	10	96	0	4	93	0	7
				32	RSB	95	0	5	94	0	6	92	0	8
				34	RSB	91	0	9	90	0	10	89	0	11
				38	RSB	90	0	10	90	0	10	91	0	9
			NB	36	Control	96	0	4	95	0	5	95	0	5
				34	Control	99	0	1	100	0	0	99	0	1
				32	Control	94	0	6	94	0	6	93	0	7
				28	MDA	94	0	6	89	0	11	89	0	11
				24	MDA	92	0	8	94	0	6	90	0	10
				22	MDA	94	0	6	89	0	11	86	0	14
				16	Control	97	0	3	96	0	4	95	0	5
				14	Control	98	0	2	98	0	2	97	0	3
				12	Control	99	0	1	100	0	0	99	0	1
				8	RSB	88	0	12	95	0	5	85	0	15
				6	RSB	89	0	11	96	0	4	89	0	11
				2	RSB	94	0	6	96	0	4	90	0	10
2	2/27/2015	9:15	SB	4	Control	96	0	4	94	0	6	91	0	9
				6	Control	93	0	7	87	0	13	85	0	15
				8	Control	88	0	12	87	0	13	88	0	12
				12	MDA	96	0	4	96	0	4	97	0	3
				14	MDA	98	0	2	97	0	3	98	0	2
				18	MDA	94	0	6	98	0	2	96	0	4
				24	Control	88	0	12	79	0	21	86	0	14
				26	Control	92	0	8	84	0	16	84	0	16
				28	Control	88	0	12	81	0	19	84	0	16
				32	RSB	98	0	2	99	0	1	98	0	2
				34	RSB	98	0	2	98	0	2	94	0	6
				38	RSB	97	0	3	98	0	2	98	0	2
			NB	36	Control	88	0	12	85	0	15	87	0	13
				34	Control	88	0	12	90	0	10	85	0	15
				32	Control	83	0	17	85	0	15	81	0	19
				28	MDA	90	0	10	95	0	5	92	0	8
				24	MDA	96	0	4	96	0	4	98	0	2
				22	MDA	94	0	6	93	0	7	96	0	4
				16	Control	85	0	15	82	0	18	85	0	15
				14	Control	82	0	18	84	0	16	74	0	26
				12	Control	94	0	6	90	0	10	92	0	8
				8	RSB	98	0	2	98	0	2	99	0	1
				6	RSB	98	0	2	99	0	1	99	0	1
				2	RSB	83	15	2	84	10	6	83	15	2

Table C-19. Raw Data from Anti-icing Photos for Storm 3-5 Continued

Anti-Icing Video			LANE	STATION	TREATMENT	KR			FE			WDL		
No.	Date	Time				Snowy	Slush	Clear	Snowy	Slush	Clear	Snowy	Slush	Clear
3	2/27/2015	10:48	SB	4	Control	56	0	44	55	0	45	54	0	46
				6	Control	63	0	37	54	0	46	72	0	28
				8	Control	72	0	28	69	0	31	72	0	28
				12	MDA	99	0	1	100	0	0	99	0	1
				14	MDA	96	0	4	98	0	2	98	0	2
				18	MDA	98	0	2	96	0	4	98	0	2
				24	Control	76	0	24	66	0	34	79	0	21
				26	Control	87	0	13	82	0	18	87	0	13
				28	Control	62	0	38	58	0	42	64	0	36
				32	RSB	70	30	0	75	25	0	75	25	0
				34	RSB	83	15	2	76	15	9	78	20	2
				38	RSB	100	0	0	100	0	0	100	0	0
			NB	36	Control	80	0	20	68	0	32	64	0	36
				34	Control	91	0	9	81	0	19	82	0	18
				32	Control	75	0	25	58	0	42	77	0	23
				28	MDA	74	20	6	69	25	6	78	20	2
				24	MDA	90	0	10	85	0	15	92	0	8
				22	MDA	88	0	12	86	0	14	89	0	11
				16	Control	53	0	47	61	0	39	61	0	39
				14	Control	56	0	44	53	0	47	61	0	39
				12	Control	77	0	23	84	0	16	72	0	28
				8	RSB	90	10	0	85	15	0	85	15	0
				6	RSB	87	10	3	80	20	0	84	10	6
				2	RSB	40	5	55	49	10	41	44	20	36
4	2/27/2015	13:17	SB	4	Control	15	15	70	20	10	70	15	15	70
				6	Control	5	5	90	5	5	90	10	10	80
				8	Control	10	10	80	10	10	80	15	15	70
				12	MDA	0	0	100	0	0	100	0	0	100
				14	MDA	0	0	100	0	0	100	5	5	90
				18	MDA	5	5	90	5	5	90	10	10	80
				24	Control	0	0	100	0	0	100	0	0	100
				26	Control	5	5	90	5	5	90	5	5	90
				28	Control	5	5	90	10	10	80	10	10	80
				32	RSB	0	0	100	0	0	100	0	0	100
				34	RSB	0	0	100	0	0	100	0	0	100
				38	RSB	0	0	100	0	0	100	0	0	100
			NB	36	Control	40	10	50	35	15	50	40	10	50
				34	Control	90	0	10	90	0	10	79	0	21
				32	Control	30	20	50	30	20	50	34	25	41
				28	MDA	30	20	50	45	15	40	45	15	40
				24	MDA	30	20	50	50	20	30	45	15	40
				22	MDA	30	20	50	45	15	40	35	15	50
				16	Control	10	10	80	15	15	70	15	15	70
				14	Control	10	10	80	20	0	80	10	10	80
				12	Control	15	15	70	25	15	60	25	15	60
				8	RSB	0	0	100	0	0	100	0	0	100
				6	RSB	5	5	90	5	5	90	5	5	90
				2	RSB	5	5	90	5	5	90	5	5	90

APPENDIX C

Storm 3-5

DECELEROMETER DATA

Table C-20. Statistical Comparison of De-icing Decelerometer Data for Storm 3-5

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	35.3	3.8	2/27, After 1st Plow
	2	C	41.7	8.1	2/27, After 1st de-icing, 2nd anti-icing, slushing
	3	C	52.1	15.1	2/27, After 2nd Plow
	4	C	81.2	15.2	2/27, After 2nd de-icing, slushing, 3rd plow
	1	MD20	37.3	5.0	2/27, After 1st Plow
	2	MD20	47.8	4.6	2/27, After 1st de-icing, 2nd anti-icing, slushing
	3	MD20	76.6	13.5	2/27, After 2nd Plow
	4	MD20	96.9	2.8	2/27, After 2nd de-icing, slushing, 3rd plow
	1	RS	34.9	4.3	2/27, After 1st Plow
	2	RS	43.2	2.9	2/27, After 1st de-icing, 2nd anti-icing, slushing
	3	RS	85.1	16.0	2/27, After 2nd Plow
	4	RS	97.2	5.4	2/27, After 2nd de-icing, slushing, 3rd plow

Table C-21. De-icing Decelerometer Data for Storm 3-5

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
1	2/27, After 1st Plow	NB	7:51 AM	2	Control	41%	Packed Snow
			7:51 AM	4	Control	35%	Packed Snow
			7:51 AM	6	Control	31%	Packed Snow
			7:52 AM	12	M-20	36%	Packed Snow
			7:53 AM	14	M-20	39%	Packed Snow
			7:53 AM	16	M-20	42%	Packed Snow
			7:54 AM	22	Control	40%	Packed Snow
			7:54 AM	24	Control	36%	Packed Snow
			7:55 AM	26	Control	34%	Packed Snow
			7:56 AM	32	Road Salt	32%	Packed Snow
			7:56 AM	34	Road Salt	32%	Packed Snow
			7:57 AM	36	Road Salt	33%	Packed Snow
			7:58 AM	42	Control	38%	Packed Snow
			7:59 AM	44	Control	34%	Packed Snow
			7:59 AM	46	Control	26%	Packed Snow
			8:00 AM	52	M-20	32%	Packed Snow
			8:01 AM	54	M-20	36%	Packed Snow
			8:01 AM	56	M-20	49%	Packed Snow
			8:03 AM	62	Control	33%	Packed Snow
			8:04 AM	64	Control	39%	Packed Snow
			8:05 AM	66	Control	37%	Packed Snow
			8:05 AM	72	Road Salt	34%	Packed Snow
			8:06 AM	74	Road Salt	33%	Packed Snow
			8:06 AM	76	Road Salt	33%	Packed Snow
		SB	8:07 AM	78	Control	37%	Packed Snow
			8:08 AM	76	Control	29%	Packed Snow
			8:09 AM	74	Control	29%	Packed Snow
			8:10 AM	68	M-20	31%	Packed Snow
			8:10 AM	66	M-20	41%	Packed Snow
			8:11 AM	64	M-20	39%	Packed Snow
			8:12 AM	58	Control	38%	Packed Snow
			8:13 AM	56	Control	38%	Packed Snow
			8:13 AM	54	Control	38%	Packed Snow
			8:14 AM	48	Road Salt	43%	Packed Snow
			8:14 AM	46	Road Salt	32%	Packed Snow
			8:15 AM	44	Road Salt	33%	Packed Snow
			8:15 AM	38	Control	33%	Packed Snow
			8:16 AM	36	Control	33%	Packed Snow
			8:16 AM	34	Control	35%	Packed Snow
			8:17 AM	28	M-20	34%	Packed Snow
			8:18 AM	26	M-20	34%	Packed Snow
			8:18 AM	24	M-20	35%	Packed Snow
			8:19 AM	18	Control	36%	Packed Snow
			8:19 AM	16	Control	37%	Packed Snow
			8:20 AM	14	Control	39%	Packed Snow
			8:20 AM	8	Road Salt	32%	Packed Snow
			8:21 AM	6	Road Salt	38%	Packed Snow
			8:21 AM	4	Road Salt	44%	Packed Snow

Table C-21. De-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
2	2/27, After 1st de-icing, 2nd anti-icing, slushing	NB	10:37 AM	2	Control	51%	Packed Snow
			10:38 AM	4	Control	60%	Packed Snow
			10:38 AM	6	Control	43%	Packed Snow
			10:39 AM	12	M-20	55%	Packed Snow
			10:39 AM	14	M-20	54%	Packed Snow
			10:40 AM	16	M-20	51%	Packed Snow
			10:40 AM	22	Control	47%	Packed Snow
			10:41 AM	24	Control	46%	Packed Snow
			10:41 AM	26	Control	46%	Packed Snow
			10:42 AM	32	Road Salt	48%	Packed Snow
			10:42 AM	34	Road Salt	41%	Packed Snow
			10:43 AM	36	Road Salt	43%	Packed Snow
			10:44 AM	42	Control	28%	Packed Snow
			10:44 AM	44	Control	37%	Packed Snow
			10:45 AM	46	Control	34%	Packed Snow
			10:46 AM	52	M-20	45%	Packed Snow
			10:46 AM	54	M-20	44%	Packed Snow
			10:47 AM	56	M-20	45%	Packed Snow
			10:47 AM	62	Control	46%	Packed Snow
			10:48 AM	64	Control	29%	Packed Snow
			10:48 AM	66	Control	40%	Packed Snow
			10:49 AM	72	Road Salt	43%	Packed Snow
			10:50 AM	74	Road Salt	41%	Packed Snow
			10:50 AM	76	Road Salt	39%	Packed Snow
		SB	10:52 AM	78	Control	42%	Packed Snow
			10:53 AM	76	Control	40%	Packed Snow
			10:53 AM	74	Control	44%	Packed Snow
			10:54 AM	68	M-20	45%	Packed Snow
			10:54 AM	66	M-20	46%	Packed Snow
			10:55 AM	64	M-20	52%	Packed Snow
			10:55 AM	58	Control	37%	Packed Snow
			10:56 AM	56	Control	43%	Packed Snow
			10:56 AM	54	Control	38%	Packed Snow
			10:57 AM	48	Road Salt	39%	Packed Snow
			10:57 AM	46	Road Salt	45%	Packed Snow
			10:58 AM	44	Road Salt	44%	Packed Snow
			10:58 AM	38	Control	34%	Packed Snow
			10:59 AM	36	Control	34%	Packed Snow
			10:59 AM	34	Control	35%	Packed Snow
			11:00 AM	28	M-20	41%	Packed Snow
			11:00 AM	26	M-20	52%	Packed Snow
			11:01 AM	24	M-20	44%	Packed Snow
			11:02 AM	18	Control	39%	Packed Snow
			11:02 AM	16	Control	60%	Packed Snow
			11:03 AM	14	Control	47%	Packed Snow
			11:04 AM	8	Road Salt	45%	Packed Snow
			11:04 AM	6	Road Salt	43%	Packed Snow
			11:04 AM	4	Road Salt	47%	Packed Snow

Table C-21. De-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
3	2/27, After 2nd Plow	NB	12:09 PM	2	Control	69%	Patchy Packed Snow
			12:10 PM	4	Control	56%	Patchy Packed Snow
			12:10 PM	6	Control	58%	Patchy Packed Snow
			12:11 PM	12	M-20	91%	Patchy Packed Snow
			12:12 PM	14	M-20	91%	Patchy Packed Snow
			12:12 PM	16	M-20	60%	Patchy Packed Snow
			12:13 PM	22	Control	53%	Patchy Packed Snow
			12:14 PM	24	Control	47%	Patchy Packed Snow
			12:14 PM	26	Control	59%	Patchy Packed Snow
			12:15 PM	32	Road Salt	87%	Patchy Packed Snow
			12:15 PM	34	Road Salt	47%	Patchy Packed Snow
			12:16 PM	36	Road Salt	65%	Patchy Packed Snow
			12:19 PM	42	Control	27%	Patchy Packed Snow
			12:20 PM	44	Control	35%	Patchy Packed Snow
			12:23 PM	46	Control	42%	Patchy Packed Snow
			12:23 PM	52	M-20	77%	Patchy Packed Snow
			12:24 PM	54	M-20	85%	Patchy Packed Snow
			12:24 PM	56	M-20	63%	Patchy Packed Snow
			12:25 PM	62	Control	43%	Patchy Packed Snow
			12:26 PM	64	Control	40%	Patchy Packed Snow
			12:26 PM	66	Control	39%	Patchy Packed Snow
			12:27 PM	72	Road Salt	46%	Patchy Packed Snow
			12:28 PM	74	Road Salt	52%	Patchy Packed Snow
			12:28 PM	76	Road Salt	68%	Patchy Packed Snow
		SB	12:30 PM	78	Control	59%	Patchy Packed Snow
			12:30 PM	76	Control	48%	Patchy Packed Snow
			12:31 PM	74	Control	34%	Patchy Packed Snow
			12:32 PM	68	M-20	59%	Patchy Packed Snow
			12:33 PM	66	M-20	83%	Patchy Packed Snow
			12:33 PM	64	M-20	85%	Patchy Packed Snow
			12:34 PM	58	Control	46%	Patchy Packed Snow
			12:34 PM	56	Control	50%	Patchy Packed Snow
			12:35 PM	54	Control	41%	Patchy Packed Snow
			12:35 PM	48	Road Salt	64%	Patchy Packed Snow
			12:36 PM	46	Road Salt	61%	Patchy Packed Snow
			12:36 PM	44	Road Salt	64%	Patchy Packed Snow
			12:37 PM	38	Control	50%	Patchy Packed Snow
			12:37 PM	36	Control	77%	Patchy Packed Snow
			12:38 PM	34	Control	52%	Patchy Packed Snow
			12:38 PM	28	M-20	69%	Patchy Packed Snow
			12:39 PM	26	M-20	95%	Patchy Packed Snow
			12:40 PM	24	M-20	61%	Patchy Packed Snow
			12:40 PM	18	Control	80%	Patchy Packed Snow
			12:41 PM	16	Control	90%	Patchy Packed Snow
			12:41 PM	14	Control	56%	Patchy Packed Snow
			12:42 PM	8	Road Salt	77%	Patchy Packed Snow
			12:42 PM	6	Road Salt	83%	Patchy Packed Snow
			12:43 PM	4	Road Salt	80%	Patchy Packed Snow

Table C-21. De-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
4	2/27, After 2nd de-icing, slushing, 3rd plow	NB	2:34 PM	2	Control	85%	Wet
			2:34 PM	4	Control	64%	Patchy Packed Snow
			2:35 PM	6	Control	76%	Patchy Packed Snow
			2:35 PM	12	M-20	96%	Wet
			2:36 PM	14	M-20	99%	Wet
			2:36 PM	16	M-20	97%	Wet
			2:37 PM	22	Control	94%	Wet
			2:37 PM	24	Control	80%	Wet
			2:38 PM	26	Control	78%	Wet
			2:38 PM	32	Road Salt	96%	Wet
			2:39 PM	34	Road Salt	99%	Wet
			2:39 PM	36	Road Salt	103%	Wet
			2:40 PM	42	Control	64%	Patchy Packed Snow
			2:40 PM	44	Control	69%	Patchy Packed Snow
			2:41 PM	46	Control	61%	Patchy Packed Snow
			2:41 PM	52	M-20	96%	Wet
			2:42 PM	54	M-20	93%	Wet
			2:42 PM	56	M-20	99%	Wet
			2:43 PM	62	Control	64%	Patchy Packed Snow
			2:43 PM	64	Control	50%	Patchy Packed Snow
			2:44 PM	66	Control	69%	Patchy Packed Snow
			2:44 PM	72	Road Salt	102%	Wet
			2:45 PM	74	Road Salt	89%	Wet
			2:46 PM	76	Road Salt	103%	Wet
		SB	2:47 PM	78	Control	85%	Patchy Packed Snow
			2:48 PM	76	Control	83%	Patchy Packed Snow
			2:48 PM	74	Control	63%	Patchy Packed Snow
			2:49 PM	68	M-20	94%	Wet
			2:49 PM	66	M-20	92%	Wet
			2:50 PM	64	M-20	100%	Wet
			2:50 PM	58	Control	102%	Wet
			2:51 PM	56	Control	90%	Wet
			2:51 PM	54	Control	85%	Patchy Slush
			2:52 PM	48	Road Salt	88%	Wet
			2:52 PM	46	Road Salt	98%	Wet
			2:53 PM	44	Road Salt	90%	Wet
			2:53 PM	38	Control	94%	Wet
			2:54 PM	36	Control	98%	Wet
			2:54 PM	34	Control	95%	Wet
			2:55 PM	28	M-20	98%	Wet
			2:55 PM	26	M-20	101%	Wet
			2:55 PM	24	M-20	98%	Wet
			2:56 PM	18	Control	101%	Wet
			2:57 PM	16	Control	98%	Wet
			2:57 PM	14	Control	100%	Wet
			2:58 PM	8	Road Salt	100%	Wet
			2:58 PM	6	Road Salt	101%	Wet
			2:59 PM	4	Road Salt	97%	Wet

Table C-22. Statistical Comparison of Anti-icing Decelerometer Data for Storm 3-5

Type	Set	Treatment	Mean (%)	Standard Deviation (%)	Date, Conditions
De-icing	1	C	106.5	9.4	2/21, Before 1st anti-icing
	2	C	79.5	7.7	2/23, After >1 in snow
	3	C	54.9	19.0	2/23, After >1 in snow
	4	C	94.5	6.6	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	MD20	106.8	6.5	2/21, Before 1st anti-icing
	2	MD20	81.3	11.7	2/23, After >1 in snow
	3	MD20	51.9	15.9	2/23, After >1 in snow
	4	MD20	99.5	3.1	2/23, After 1st de-icing, 2nd anti-icing, slushing
	1	RS	107.3	7.0	2/21, Before 1st anti-icing
	2	RS	80.6	7.0	2/23, After >1 in snow
	3	RS	49.2	11.1	2/23, After >1 in snow
	4	RS	96.1	6.4	2/23, After 1st de-icing, 2nd anti-icing, slushing

Table C-23. Anti-icing Decelerometer Data for Storm 3-5

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
1	2/25, After 1st Anti-icing	SB	8:04 PM	2	Control	102%	Slush
			8:06 PM	4	Control	108%	Slush
			8:06 PM	6	Control	106%	Slush
			8:07 PM	12	M-Apex	88%	Slush
			8:08 PM	14	M-Apex	82%	Slush
			8:08 PM	16	M-Apex	90%	Slush
			8:09 PM	22	Control	97%	Slush
			8:09 PM	24	Control	102%	Slush
			8:10 PM	26	Control	96%	Slush
			8:10 PM	32	Salt Brine	104%	Slush
			8:11 PM	34	Salt Brine	100%	Slush
			8:11 PM	36	Salt Brine	105%	Slush
		NB	8:13 PM	38	Control	104%	Slush
			8:13 PM	36	Control	104%	Slush
			8:14 PM	34	Control	99%	Slush
			8:15 PM	28	M-Apex	90%	Slush
			8:15 PM	26	M-Apex	93%	Slush
			8:16 PM	24	M-Apex	97%	Slush
			8:17 PM	18	Control	92%	Slush
			8:17 PM	16	Control	96%	Slush
			8:18 PM	14	Control	94%	Slush
			8:18 PM	8	Salt Brine	100%	Slush
			8:19 PM	6	Salt Brine	109%	Slush
			8:19 PM	4	Salt Brine	100%	Slush

Table C-23. Anti-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
2	2/27, After 1st Plow	SB	7:32 AM	2	Control	28%	Packed Snow
			7:33 AM	4	Control	40%	Packed Snow
			7:34 AM	6	Control	36%	Packed Snow
			7:34 AM	12	M-Apex	51%	Packed Snow
			7:35 AM	14	M-Apex	37%	Packed Snow
			7:35 AM	16	M-Apex	31%	Packed Snow
			7:36 AM	22	Control	36%	Packed Snow
			7:37 AM	24	Control	34%	Packed Snow
			7:37 AM	26	Control	35%	Packed Snow
			7:38 AM	32	Salt Brine	35%	Packed Snow
			7:39 AM	34	Salt Brine	34%	Packed Snow
			7:39 AM	36	Salt Brine	35%	Packed Snow
		NB	7:41 AM	38	Control	37%	Packed Snow
			7:42 AM	36	Control	32%	Packed Snow
			7:42 AM	34	Control	39%	Packed Snow
			7:43 AM	28	M-Apex	32%	Packed Snow
			7:44 AM	26	M-Apex	35%	Packed Snow
			7:44 AM	24	M-Apex	37%	Packed Snow
			7:45 AM	18	Control	32%	Packed Snow
			7:46 AM	16	Control	39%	Packed Snow
			7:46 AM	14	Control	33%	Packed Snow
			7:47 AM	8	Salt Brine	39%	Packed Snow
			7:47 AM	6	Salt Brine	40%	Packed Snow
			7:48 AM	4	Salt Brine	36%	Packed Snow

Table C-23. Anti-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
3	2/27, After 1st de-icing, 2nd anti-icing, slushing	SB	10:22 AM	2	Control	32%	Packed Snow
			10:22 AM	4	Control	38%	Packed Snow
			10:23 AM	6	Control	30%	Packed Snow
			10:24 AM	12	M-Apex	48%	Packed Snow
			10:24 AM	14	M-Apex	37%	Packed Snow
			10:25 AM	16	M-Apex	39%	Packed Snow
			10:26 AM	22	Control	40%	Packed Snow
			10:26 AM	24	Control	42%	Packed Snow
			10:26 AM	26	Control	34%	Packed Snow
			10:27 AM	32	Salt Brine	43%	Packed Snow
			10:28 AM	34	Salt Brine	45%	Packed Snow
			10:28 AM	36	Salt Brine	43%	Packed Snow
		NB	10:30 AM	38	Control	40%	Packed Snow
			10:30 AM	36	Control	39%	Packed Snow
			10:30 AM	34	Control	50%	Packed Snow
			10:31 AM	28	M-Apex	41%	Packed Snow
			10:32 AM	26	M-Apex	41%	Packed Snow
			10:32 AM	24	M-Apex	43%	Packed Snow
			10:33 AM	18	Control	40%	Packed Snow
			10:33 AM	16	Control	39%	Packed Snow
			10:34 AM	14	Control	44%	Packed Snow
			10:35 AM	8	Salt Brine	45%	Packed Snow
			10:35 AM	6	Salt Brine	44%	Packed Snow
			10:36 AM	4	Salt Brine	41%	Packed Snow

Table C-23. Anti-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
4	2/27, After 2nd Plow	SB	11:53 AM	2	Control	38%	Patchy Packed Snow
			11:54 AM	4	Control	36%	Patchy Packed Snow
			11:54 AM	6	Control	45%	Patchy Packed Snow
			11:55 AM	12	M-Apex	48%	Patchy Packed Snow
			11:56 AM	14	M-Apex	49%	Patchy Packed Snow
			11:56 AM	16	M-Apex	41%	Patchy Packed Snow
			11:57 AM	22	Control	39%	Patchy Packed Snow
			11:58 AM	24	Control	50%	Patchy Packed Snow
			11:58 AM	26	Control	42%	Patchy Packed Snow
			11:59 AM	32	Salt Brine	50%	Patchy Packed Snow
			12:00 PM	34	Salt Brine	50%	Patchy Packed Snow
			12:00 PM	36	Salt Brine	39%	Patchy Packed Snow
		NB	12:02 PM	38	Control	35%	Patchy Packed Snow
			12:02 PM	36	Control	57%	Patchy Packed Snow
			12:03 PM	34	Control	44%	Patchy Packed Snow
			12:04 PM	28	M-Apex	46%	Patchy Packed Snow
			12:04 PM	26	M-Apex	42%	Patchy Packed Snow
			12:05 PM	24	M-Apex	43%	Patchy Packed Snow
			12:05 PM	18	Control	47%	Patchy Packed Snow
			12:06 PM	16	Control	43%	Patchy Packed Snow
			12:06 PM	14	Control	53%	Patchy Packed Snow
			12:07 PM	8	Salt Brine	49%	Patchy Packed Snow
			12:07 PM	6	Salt Brine	55%	Patchy Packed Snow
			12:08 PM	4	Salt Brine	48%	Patchy Packed Snow

Table C-23. Anti-icing Decelerometer Data for Storm 3-5 Continued

Test Set	Date, Conditions	Lane	Time	Section #	Section Type	Percent G	Comments
5	2/27, After 2nd de-icing, slushing, 3rd plow	SB	2:19 PM	2	Control	92%	Wet
			2:20 PM	4	Control	92%	Wet
			2:20 PM	6	Control	54%	Wet
			2:21 PM	12	M-Apex	91%	Wet
			2:21 PM	14	M-Apex	87%	Wet
			2:22 PM	16	M-Apex	81%	Wet
			2:22 PM	22	Control	77%	Wet
			2:23 PM	24	Control	90%	Wet
			2:23 PM	26	Control	78%	Wet
			2:24 PM	32	Salt Brine	93%	Wet
			2:24 PM	34	Salt Brine	99%	Wet
			2:25 PM	36	Salt Brine	93%	Wet
		NB	2:26 PM	38	Control	67%	Wet
			2:27 PM	36	Control	88%	Wet
			2:27 PM	34	Control	69%	Wet
			2:28 PM	28	M-Apex	65%	Patchy Packed Snow
			2:28 PM	26	M-Apex	65%	Patchy Packed Snow
			2:29 PM	24	M-Apex	64%	Patchy Packed Snow
			2:29 PM	18	Control	69%	Patchy Packed Snow
			2:30 PM	16	Control	78%	Patchy Packed Snow
			2:30 PM	14	Control	71%	Patchy Packed Snow
			2:31 PM	8	Salt Brine	98%	Wet
			2:31 PM	6	Salt Brine	77%	Wet
			2:32 PM	4	Salt Brine	87%	Wet