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Evaluating the Effectiveness of Winter Chemicals on Reducing Crashes in Idaho

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16. Abstract

Roadway maintenance agencies rely on a number of different materials and chemicals as part of their winter operations. Different chemicals have different performance levels, costs, and best conditions for use. Little research exists regarding the effects of winter maintenance practices on roadway safety, partly because of the cross-cutting nature of the problem and the lack of data. This research was performed for the Idaho Transportation Department (ITD) to investigate the safety issues involved with winter maintenance and to identify the most cost-effective and environmentally sound ways of using winter chemicals. Through lab testing, it was determined that the performance difference between salt brines and solid salts was insignificant, but brines posed less risk to vehicles, infrastructure and the natural environment. The use of sand without salt should be avoided in highway winter operations, especially in light of its low cost-effectiveness and risks to air quality and water quality. Brines, solid salts, and sand-salt mixtures are best suitable for different application scenarios. Different benefit-cost analysis was performed using the estimates of reduced crashes through chemical use. Based on this analysis, it was determined that in most cases, the use of chemicals produced greater benefits than costs. Comparisons of the annual costs per lane mile found that sand and sand-salt mixtures were the lowest cost materials available to ITD. The use of salt as a treatment material was comparable in terms of costs to sand and sand-salt, making that material an attractive option. Similarly, salt brines compared favorably in terms of costs, with only a slightly higher expense than granular salt. Magnesium chloride brines were the most expensive treatment material, which underscores the importance of using such a material in more specific applications and locations.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

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Table of Contents

List of Tables

List of Figures

List of Acronyms

AADT	Annual Average Daily Traffic
BPNN	The Back-Propagation Neural Network
$CaCl_2$	Calcium Chloride
° C	Degrees Celsius
DOT	Department of Transportation
° F	Degrees Fahrenheit
ITD	Idaho Transportation Department
$MgCl_2$	Magnesium Chloride
MDSS	Maintenance Decision Support System
MSE	Mean Square Error
MP	Mile Post
NOAA	National Oceanic and Atmospheric Administration
PR1H	Precipitation in the Past Hour
PDO	Property Damage Only
RS	Rain State
RWIS	Road Weather Information System
SPF	Safety Performance Function
T	Temperature
TRID	Transportation Research International Documentation
WSI	Winter Severity Index

Executive Summary

The purpose of this project was to compare the safety impacts and cost effectiveness of NaCl and MgCl2 and identify best practices for performing winter maintenance based on safety and the cost-effectiveness of these materials. Such chemicals, often referred to as road salts, play a key role in such operations. Chlorides can be found in a wide variety of snow and ice control products used on winter roadways to either prevent the bonding of ice to the roadway (anti-icing) or break the bond between ice and the roadway (deicing). It is known that these materials may cause corrosion to equipment and may impact the surrounding environment and it is necessary to consider these factors and make decisions carefully when selecting chemicals in order to reduce the impact they have on the surrounding environment. However, such tradeoffs were not the focus of the research.

In completing the work, the research team reviewed the positive and negative aspects of winter chemical use, surveyed the current use of different winter chemicals by the Idaho Transportation Department (ITD), summarized the crash data for selected road segments and analyzed the benefits and costs that were associated with using winter chemicals. However, in some respects, the evaluation of the impacts of these materials on preventing crashes on Idaho roads was limited by data availability. While the necessary crash data and historical records were available to the researchers, the files which recorded the types and quantities of materials applied on specific dates were limited. At present, such information is manually recorded on paper files, which were provided to the researchers as scanned PDF documents. These records, while detailed in themselves, left several gaps regarding material usage and application rates on many dates during the study period. Such gaps will be eliminated in the future by new Idaho Transportation Department systems that will record data electronically and have been implemented recently.

In light of the data gaps that were encountered, the researchers analyzed the benefits and costs associated with the use of winter chemicals by developing a model that established the relationship between winter crashes and associated independent variables such as chemical usage, traffic volume, and weather condition. Then, a methodology consisting of Artificial Neural Network (ANN) and sensitivity analysis methods was used to estimate the benefits associated with winter chemicals. The methods were then applied to different routes for which complete data sets were available (including material use) for a specific winter season to investigate the tangible benefits and costs of the materials used. These results for the selected routes are discussed in Table 1, presented below. The following summarizes the findings and conclusions of this research study and provides recommendations for using winter chemicals in winter maintenance.

1. The review of winter chemical maintenance shows that sodium chloride (NaCl) is the most widely used chemical due to its abundance and low cost. But it is rarely used and minimally effective on pavement temperatures below 10° F (-12.2° C). Calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) exhibit better ice-melting performance than salt brine at cold temperatures. However, $CaCl_2$ and $MgCl_2$ are more costly and can be difficult to handle. Furthermore, at low relative humidity, their residue on roads continues to attract more moisture than salt, resulting in a refreeze that can create dangerously slick conditions. In addition to chlorides, acetates are used for anti-icing but they

are generally much more expensive. However, they can be more effective, less corrosive and not as environmentally harmful as chlorides.

2. The survey of salt brine operations in Idaho shows that non-inhibited salt brine was listed as the most commonly used product by ITD district respondents having been used for the last 3 to 5 years. Salt brine was listed as being used equally for anti-icing, deicing and pre-wetting. In addition, changes in air temperature and pavement temperature, followed by humidity, all caused deviations in typical application rates of salt brine.
3. When application rates for salt brine were changed, the majority of respondents said experience was the basis for changes. Note that districts are provided with discretion in determining appropriate methods and application rates, which can vary based on differences including terrain, traffic and so forth. Moreover, the majority of respondents stated that application rates have increased over time, although general experience for the state has been declining application rates.
4. In most cases, parameters like friction, bare pavement, and melting ability were selected by respondents to define the performance of salt brine. In addition, most respondents had no concerns with the use of salt brine, with impacts to concrete and corrosion to metal being of concern to a small group of respondents.
5. The survey of $MgCl_2$ operations shows that corrosion-inhibited liquid $MgCl_2$ was listed as the most commonly used product. Other products, including non-inhibited liquid $MgCl_2$, and corrosion-inhibited solid $MgCl_2$ were also cited as being used, although ITD has never purchased these products. This discrepancy is likely an awareness issue on the part of survey respondents who were not familiar with the products they were using. All but one respondent has used $MgCl_2$ for more than 5 years.
6. Precipitation type and amount caused deviations in typical application rates of $MgCl_2$ most frequently, followed by changes in pavement temperature and air temperature. When application rates for $MgCl_2$ are changed, respondents said that the new rates were determined based on experience.
7. Friction, bare pavement and melting ability were used to define the performance of $MgCl_2$. In addition, all respondents recommended that $MgCl_2$ continue to be used in winter highway maintenance. However, the potential corrosion to metal caused by $MgCl_2$ should be a consideration in use.
8. Under the investigated conditions and assumptions, the difference between brine and solid salts was insignificant.
9. The use of sand without salt should be avoided in most highway winter operations, especially in light its low cost-effectiveness and risks to air quality and water quality.
10. Brines, solid salts, and sand-salt mixtures are integral components of the highway winter maintenance toolbox and are best suitable for different application scenarios. For instance, for anti-icing on relatively warm pavement (18^oF or above), NaCl brine is likely the best product to use; yet $MgCl_2$ brine may be a better choice to use for cold pavements (10^oF to 15^oF). For deicing, the choice between brines, solid salts, and sand-salt mixtures will hinge on how quickly one has to achieve a relatively bare pavement and whether or not a temporary traction layer is needed on the pavement.
11. Past research has indicated that the use of winter maintenance chemicals produces safety benefits through reduced crashes, although the specific materials being used were typically not diverse (typically NaCl) or unspecified.
12. The effectiveness of winter maintenance chemicals and operations in Idaho were underscored by the results of estimations that determined the number of crashes that would have been expected in the absence of treatments. On I-90, it was estimated that 519 crashes would have occurred if deicer and salt had not been used, compared to 319 crashes which occurred with their use during two

winter seasons. Similarly on US-12, the use of liquid deicer reduced the number of crashes that occurred to 42, compared to an estimated 58 crashes without deicer use during one season.

13. The benefit-cost analysis showed that the use of winter chemicals could bring more benefits than costs. The benefits and costs associated with winter chemicals are summarized in the following table. Obviously, the benefits of using winter chemicals were much larger than winter chemical maintenance costs. Consequently, winter chemical maintenance plays a very important role in road safety.

Table 1. Summary of Benefit-Cost Analysis

<table>
<tr><th colspan="2">Cases</th><th>I-90 (2008-2010)</th><th>US-12 (2009-2010)</th><th>I-90 (Nov./Dec. 2012)</th><th>US-95 (Nov./Dec. 2012)</th></tr>
<tr><td colspan="2">Benefits ($)</td><td>$8,559,200</td><td>$684,726</td><td>$256,776</td><td>$470,756</td></tr>
<tr><td rowspan="3">Costs ($)</td><td>Chemical Cost</td><td>$1,487,572</td><td>$87,433</td><td rowspan="3">$229,863</td><td rowspan="3">$100,795</td></tr>
<tr><td>Equipment Cost</td><td>$24,840</td><td>$538</td></tr>
<tr><td>Labor Cost</td><td>$32,696</td><td>$310</td></tr>
<tr><td colspan="2">Benefit-Cost Ratio</td><td>5.54</td><td>7.76</td><td>1.12</td><td>4.67</td></tr>
</table>

14. The benefit-cost analysis only considered equipment costs, labor costs and chemical costs. The costs winter chemicals have on the surrounding environment and corrosion costs were not factored in to this research. That means the cost of winter chemical maintenance may be higher.
15. Comparisons of the annual costs per lane mile for different materials/chemicals found that sand and sand-salt mixtures were the lowest cost materials available to ITD. The use of salt as a treatment material was comparable in terms of costs to sand and sand-salt, making that material an attractive option.
16. Similarly, salt brines compared favorably in terms of costs, with only a slightly higher expense than granular salt. Magnesium chloride brines were the most expensive treatment material, which underscores the importance of using such a material in more specific applications and locations.

The research team also developed recommendations for the use of chemicals in winter maintenance. The recommendations of this study are as follows:

1. For high traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: anti-ice using a salt brine at 20-30 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or an engineered salt brine at 20 gallons per lane mile. For low traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: use an engineered salt brine to anti-ice at 30-50 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or de-ice at 35-70 gallons per lane mile. The upper limit of the recommended application rates corresponds to the lower limit of the target pavement temperature range. For colder pavements (10°F to 15°F), $MgCl_2$ brine may be a better choice to use for either anti-icing or liquid deicing. For extremely cold pavement (below 10°F), the use of liquid deicer is risky and needs to be validated before

implementation and prewet salt may be used for deicing. To achieve the friction benefits of anti-icing or deicing on pavement, plowing is highly recommended once sufficient time has been allowed for the chemical to interact with snow precipitation and traffic. Avoid anti-icing below 20°F when there are strong winds, heavy snowfall, or freezing rain conditions.

2. In lab testing, salt brines were generally most effective, resulting in a composite index of 64, while sand and sand-salt mixtures were less desirable, with composite indexes of 33 (sand) and 39 to 41 (sand-salt). Fore reference, the composite index is a range from 0 to 100 that incorporates the cost performance and risks of using a particular treatment, where an index rating of 100 would represent a best practice. The need for traction must not be discounted when considering the use of these materials, as a material such as sand can produce a significant benefit for spot traction needs, such as at intersection approaches or curves, despite its risks and limitations.
3. Different types of winter chemicals may have different impacts on road safety, which means the use of improper winter chemicals may cause various problems in terms of road safety (ex. slick surfaces) if they are applied too heavily or reapplied without a precipitation event. Similarly, refreezing of the treatment in high humidity fog conditions where precipitation has does not reoccur can also produce a slick surface. Different winter chemicals should be chosen for winter maintenance and properly applied in various conditions with this potential in mind.
4. The case studies show that crashes decreased with an increase of winter chemical usage. Estimates from evaluation of I-90 found that chemical use produced a reduction of 200 crashes over two seasons, while a reduction of 16 crashes was estimated on US-12 over a one season. Based on this, the use of winter chemicals such as those employed on these routes (granular salt and salt brine) is recommended for further use as appropriate.
5. In all of the case studies performed, liquid deicer (NaCl) and granular salt were the chemicals used to treat the roadways segments. Each was found effective in reducing crashes to varying extents, depending on the specific study roadway. From the results of sensitivity analysis, it would appear that liquid deicer is slightly more effective in reducing crashes, which corresponds to the findings of the lab testing. However, it must be stressed that both materials were effective in reducing crashes overall, which one would expect.
6. Lab test results and the crash evaluations both indicate that the use of salt brine is a preferred approach to employ in many winter maintenance applications. This is dependent on current conditions falling within the proper application temperature range for the product however.
7. In terms of future evaluations, complete material use records, as well as transportation agency costs (materials, equipment, technology, fuel use, labor, training and corrosion), road user costs (delays, road closures, safety, corrosion) and societal and environmental costs (damage, emissions) are needed to provide more comprehensive guidance on when and where specific materials may be used.
8. ITD’s recent use of Automatic Vehicle Location (AVL technology, which has enabled the collection of specific material usage data by location will be a significant benefit to future evaluations. This data will allow a direct comparison to be made between material type, use and timing and storm-related crashes.

Chapter 1
Introduction

Snow and ice control plays an important role in assuring the safety of winter driving. The United States spends $2.3 billion annually to keep roads clear of snow and ice; in Canada, more than $1 billion (U.S. dollars) is spent annually on winter maintenance.(1) Roadway maintenance agencies relied on abrasives (sanding material) in winter maintenance until the use of chemicals for deicing and, more recently, anti-icing strategies gained widespread acceptance. However, only a few research studies have focused on the impacts of different types and levels of winter maintenance on safety and mobility. This is particularly true with respect to different winter maintenance chemicals. At present, chloride-based chemicals, known as road salts, play a key role in such operations. Chlorides can be found in a wide variety of snow and ice control products used on winter roadways to either prevent the bonding of ice to the roadway (anti-icing) or break the bond between ice and the roadway (deicing).

The Idaho Transportation Department (ITD) has been researching winter chemicals since the mid-1990s, and has supplemented traditional methods (snowplowing and sanding) with deicers and anti-icers based on the results of their work. The winter maintenance chemicals most commonly used by ITD are sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), and sometimes coupled with a corrosion inhibitor additive. Different chemicals have different performance levels, costs, and best conditions for use. Currently, there is little research regarding the effects of winter maintenance practices on roadway safety, partly because of the cross-cutting nature of the problem and the lack of abundant (or quality) data. Hence, it is essential for ITD to investigate the safety issues involved with winter maintenance practices and to identify the most appropriate ways of using winter chemicals. This research was conducted to meet these needs.

Research Approach

A multi-faceted approach was employed to complete the research. A comprehensive literature review was performed to identify relevant research literature focused on the state-of-the-art and practice of winter maintenance chemicals and their impact on traffic operations and safety. Information on the performance and impacts of winter chemicals currently used by ITD was also summarized. To the extent documentation existed, the literature review incorporated new findings of winter maintenance practices and policies that were identified throughout the course of the project. The research also employed online surveys of ITD maintenance staff to understand how $MgCl_2$ and salt brine had been used during past winter seasons. A review of ITD's pilot program in District 4 using the Maintenance Decision Support System (MDSS) was part of the original scope of the project, but that work is not discussed in this report as the pilot program was ended due to problems with forecasting accuracy. MDSS was only used in this District for two years, and crash and material use data was not evaluated from this locale during the course of the research.

A comprehensive and quantitative lab evaluation of snow and ice control materials currently used by various ITD districts for highway maintenance operations was performed to provide guidance on the most appropriate winter maintenance strategies. This portion of the study incorporated the most up-to-date information into a multi-criteria decision making framework for the data-driven evaluation of various snow and ice control materials used by a maintenance agency. Friction coefficient measurements on the pavement before and after the anti-icing and deicing operations were incorporated into the characterization of product performance as well. The corrosive effects of products to rebars and dowel bars were incorporated into the characterization of risks, along with the damaging effects of products to asphalt and concrete pavements. Finally, the environmental risks of various products have been quantified to the best possible extent, taking into account average aquatic toxicity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), emission factor for air quality impairment, and chloride emissions into the natural environment (soil, vegetation, surface water, groundwater, etc.).

Multiple approaches were employed to examine the costs and benefits of different treatment materials. Descriptive statistics were initially employed to characterize the historical safety trends along the various study routes identified in consultation with ITD. Next, a model that established the relationship between winter crashes and associated independent variables such as chemical usage, traffic volume, and weather conditions was developed. Then, a methodology consisting of Artificial Neural Network (ANN) and sensitivity analysis methods was employed to estimate the benefits associated with winter chemicals. The methods were then applied to different routes to investigate the tangible benefits and costs of chemicals. Additionally, the costs of different materials on an annual per lane mile basis were established. Based on all of the evaluation work completed during the course of the project, key findings and conclusions were then drawn, along with recommendations for using winter chemicals in winter maintenance.

Report Overview

This report is divided into eight chapters. Chapter 1 has presented an introduction and overview to the research problem being examined and the approaches employed to address it. Chapter 2 presents the results of a literature review that examined the state of knowledge in winter highway maintenance, the use of road salts such as NaCl and $MgCl_2$, with and without corrosion inhibitors, in those activities, the benefits and negative impacts that result from the use of salts, and a discussion of the benefits to safety and mobility that winter maintenance chemicals produce. Chapter 3 reviews the results of the survey of ITD maintenance staff regarding different aspects of their use of $MgCl_2$ and salt brine. Chapter 4 presents a review of the state's pilot program with the Maintenance Decision Support System. Chapter 5 presents the results of detailed lab evaluations of the performance of snow and ice control materials being used by ITD. An overview of historical crash trends on the routes selected by ITD for further safety and benefit-cost evaluations is presented in Chapter 6, and Chapter 7 presents the results of those evaluations. Finally, Chapter 8 provides conclusions and recommendations based on the findings of the research, as well as potential approaches to raising public awareness of ITD's treatment strategies.

Appendices at the end of the report present the various survey instruments used to obtain information from ITD staff.

Chapter 2
Literature Review

Before evaluating ITD's current chemical usage and developing strategies, an identification and review of relevant research literature focused on the state-of-the-art and practice of winter maintenance chemicals and their impact on traffic operations and safety was completed. Information on the performance and impacts of winter chemicals currently used by ITD is summarized in Chapter 3. The researchers employed a number of different strategies to identify relevant literature, including the use of sources such as, but not limited to, the Transportation Research International Documentation (TRID) database, state DOT websites, Federal Highway Administration (FHWA), winter maintenance programs (e.g., Aurora, MDSS), and other databases (e.g., Google Scholar). The literature review was updated quarterly to ensure new findings of winter maintenance practices and policies were identified and incorporated in the final report. The following literature review sections provide:

- A summary of the state of the knowledge pertinent to highway winter maintenance;
- The use of road salts for snow and ice control and associated benefits and negative impacts;
- Review of research regarding the benefits to safety and operations generated by winter maintenance treatments and practices.

Highway Winter Maintenance: State of Knowledge

In the northern United States, Canada and other cold-climate regions, snow and ice control operations are essential to ensure the safety, mobility and productivity of winter highways, where the driving conditions are often worsened by inclement weather. Chloride-based chemicals, known as road salts, play a key role in such operations. Chlorides can be found in a wide variety of snow and ice control products used on winter roadways to either prevent the bonding of ice to the roadway (anti-icing) or break the bond between ice and the roadway (deicing). The chlorides melt ice and snow by lowering the freezing point of the snow-salt mixture. Prior to application onto roadways, liquid salts can also be added to abrasives or solid salts to make them easier to manage, distribute, and stay on roadways (pre-wetting). For simplicity, this article uses the term deicer to refer to all chemicals used for anti-icing, de-icing and pre-wetting operations.

Over the last two decades, maintenance departments in North America have gradually made two transitions in their snow and ice control strategies. First is the transition from a reliance on abrasives (e.g., sand) to the use of more chemicals.(2) The use of sand was traditionally intended to provide vehicle traction throughout the system. Sand use has seen reduced use in recent years, although it may still be employed at point locations such as intersection approaches or curves to enhance traction. The reduction in use is partially owing to the negative impact of abrasives to water quality and aquatic species, air quality, vegetation, and soil and the hidden cost of sanding (e.g., cleanup cost). Depending on its particle size, sand may contribute greatly to air pollution, can potentially cause serious lung disease, and is listed as a carcinogen. (3) Sand also poses significant risk for water quality and may threaten the survivability of aquatic species especially during spring runoff.(2) Even after cleanup, 50 to 90 percent of the sand may remain somewhere in the environment. (4)

In more recent years, there is the transition from mostly deicing to anti-icing wherever possible.(5, 6) Defined as "the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant" (7), anti-icing has proven to be a successful method of maintaining roadways during the winter season. Relative to deicing and sanding, anti-icing leads to improved level of service (LOS, measures set by agencies to establish guidelines, develop route priorities and coordinate winter maintenance activities), reduced need for chemicals, and associated cost savings and safety/mobility benefits.(8, 9) Anti-icing with liquid chemicals is more sensitive to weather conditions than other winter maintenance practices.(5, 8) Near-real-time weather and road condition information and customized weather service are valuable to the success of such proactive maintenance strategies.(8, 10, 11) In practice, most agencies currently take a toolbox approach customized to their local snow and ice control needs and funding, staffing, and equipment constraints. Depending on the road weather scenarios, resources available and local rules of practice, departments of transportation (DOTs) use a combination of tools for winter road maintenance and engage in activities ranging from anti-icing, deicing, sanding (including pre-wetting), to mechanical removal (e.g., snowplowing), and snow fencing.

Maintenance agencies are continually challenged to provide a high LOS and improve safety and mobility of winter roads in a cost-effective manner while minimizing corrosion and other adverse effects to the environment. To this end, it is desirable to use the most recent advances in the application of anti-icing and deicing materials, winter maintenance equipment and sensor technologies, and road weather information systems as well as other decision support systems.(12, 13, 14, 15) Such best practices are expected to improve the effectiveness and efficiency of winter operations, to optimize material usage, and to reduce associated annual spending and corrosion and environmental impacts.

The United States applies approximately 15 million tons of salts each year and spends $2.3 billion annually to keep roads clear of snow and ice, which translates into average nominal cost of $153 per ton for salting.(16,17) This nominal cost considers the costs of materials, staffing and equipment. While snow and ice control activities are essential to maintaining winter roadway safety, mobility and productivity, the use of chemicals has raised concerns about their effects on motor vehicles, the transportation infrastructure, and the environment. (18, 19, 20, 21, 22) One study published in 1992 estimated that road salt imposed infrastructure corrosion costs of at least $615 per ton, vehicular corrosion costs of at least $113 per ton, aesthetic costs of $75 per ton if applied near environmentally sensitive areas, plus uncertain human health costs.(23)

Successfully implementing a highway winter maintenance program requires appropriate selection of chemicals for snow and ice control, obtaining the right equipment, having well-trained staff, making informed decisions, and proper execution of strategies and tactics. Russ et al. developed a decision tree for liquid pretreatments for the Ohio DOT. (24) The decision tree was designed to help maintenance supervisors consider a number of factors, including: current road and weather conditions, the availability of maintenance personnel and the best treatment strategy. Relying on an established decision-making process can help maintenance professionals make timely and consistent decisions on a day-to-day basis. This is especially important for anti-icing which is sensitive to pavement temperature, dilution, and other factors.(8) Furthermore, Fay and Shi developed a systematic approach to assist maintenance agencies in selecting or formulating their deicers, which integrates the information available pertinent to various aspects of deicers and incorporates agency priorities.(12)

Chemical Use in Snow and Ice Control

Acetates such as potassium acetate (KAc) and calcium magnesium acetate (CMA) can be used for anti-icing. . However, KAc and CMA can be more effective, less corrosive to carbon steel, and not as environmentally harmful as chlorides.(25) However, they are generally much more expensive than chloride products. Also available are a variety of agriculture-based chemicals used either alone or as additives for other winter maintenance chemicals. (26) The agro-based chemicals often come from the fermentation and processing of beet juice, molasses, corn, cheese, and distillery byproducts.(27, 28, 29) They increase cost but may provide enhanced ice-melting capacity, reduce the deicer corrosivity, and/or last longer than standard chemicals when applied on roads. (3, 30)

Chloride-based salts are the most common chemicals used to serve as freezing-point depressants for winter road maintenance applications. NaCl is the most widely used chemical due to its abundance and low cost.(3) It can be used either as rock salt (for de-icing) or as salt brine (for anti-icing). However, it is rarely used and minimally effective below pavement temperatures of 10° F (-12° C.(31) Salt is also added to sand and other abrasives to prevent freezing. $CaCl_2$ and/or $MgCl_2$ are used by many DOTs in a brine solution for anti-icing, which exhibits better ice-melting performance than salt brine at cold temperatures such as 10^oF. (7, 32) The minimum effective application temperature for $CaCl_2$, $MgCl_2$ and NaCl was reported to be -13°F (-25°C), 5°F (-15°C) and 14°F (-10°C), respectively (33). $CaCl_2$ and $MgCl_2$ are more costly than NaCl, and they can be difficult to handle. At low relative humidity, their residue on roads can attract more moisture than salt, resulting in dangerous, slippery conditions under certain circumstances.(34) In some cases, field studies have shown $CaCl_2$ to be more effective than NaCl, owing to its ability to attract moisture and stay on the roads. (35) Granular $CaCl_2$ can be combined with salt to increase the effectiveness of salt in cold conditions, as $CaCl_2$ acts quickly, gives off heat, and forms initial brine with moisture in the air.(36) However, some agencies choose not to use $CaCl_2$ as it does not dry and can cause roads to become slippery.(37) Chlorides are generally considered the most corrosive winter maintenance chemicals.(25) Often, commercially available, corrosion-inhibited versions of these chemicals are used to reduce their deleterious impacts on vehicles and infrastructure.

Extensive research has been conducted to evaluate the performance of various chemical deicers. While they generally agree on the eutectic temperature of a given chemical, they often disagree on its effective temperature. Eutectic temperature is the minimum temperature a deicer solution remains in liquid form, which depends on the concentration of the deicer, usually expressed as percent weight of the solution. During the process of melting snow or ice, additional water is produced and the deicer is diluted, which may cause the solution to re-freeze. The effective temperature is often based on field observations and affected by the specific road weather scenario. Table 2 shows that the eutectic temperature can be significantly different from the effective temperature for a deicer.

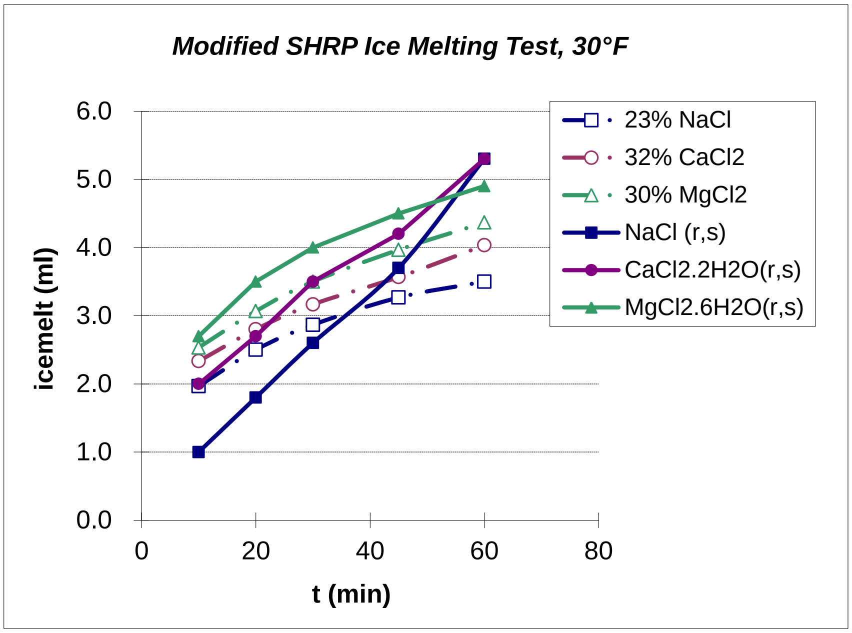
Table 2. Comparison of Eutectic and Effective Temperature for Several Deicers (38, 39).

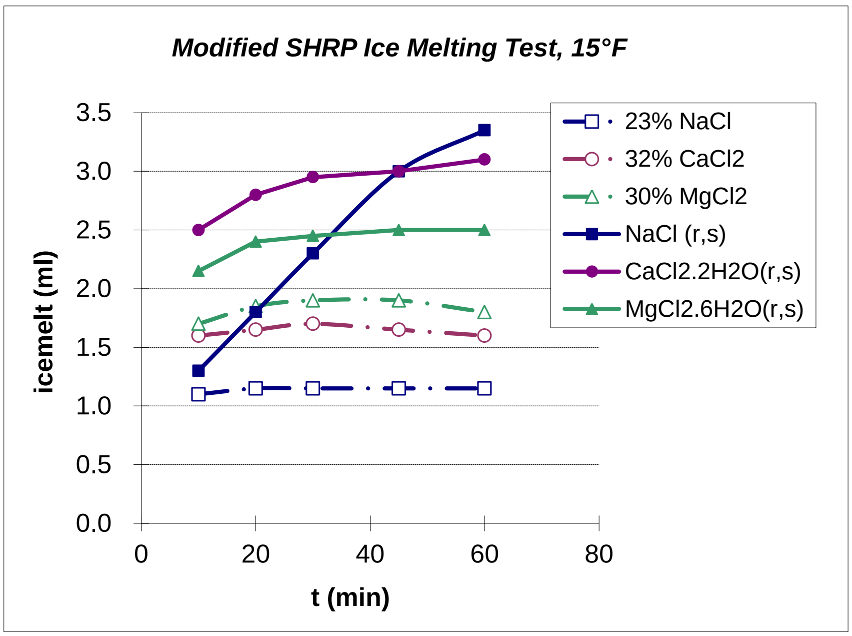
Deicer	Eutetic Concentration	Eutetic Temperature		Minimum Effective		Reference
	%	°C	°F	°C	°F	
$CaCl_2$	29.8	-51.6	-60.9	-35.0	-31.0	36
$CaCl_2$	*Not provided*	-51.1	-60.0	-28.9	-20.0	37
$MgCl_2$	21.6	-33.3	-27.9	-20.0	-4.0	36
$MgCl_2$	*Not provided*	-33.3	-28.0	-15.0	5.0	37
Urea	32.6	-11.7	10.9	-9.0	15.8	36
Urea	*Not provided*	-12.2	10.0	-3.9	25.0	37
Formamide	60.0	-45.0	-49.0	-18.0	-0.4	36
NaCl	*Not provided*	-21.1	-6.0	-9.4	15.0	37
Potassium Acetate	*Not provided*	-60.0	-76.0	-26.1	-15.0	37
CMA	*Not provided*	-27.2	-17.0	-6.1	21.0	37
CMA	*Not provided*	-10.0	14.0	-10.0	14.0	36
$C_2H_6O_2$ (Ethylene Glycol)	60.0	-51.0	-59.8	-23.3	-9.9	36

Figure 1 presents the average volume of brine collected at -1°C (30°F), -9°C (15°F), and -18°C (0°F) respectively, for each 1 g of solid chemical or each 0.9 ml of liquid deicer.(40) The data indicate that ice melting by deicers is a dynamic, time-sensitive process and the relative performance of different deicers depends on the form of the deicer, the time of ice melting, and the test temperature. With few exceptions, the solid form of the deicers produced more icemelt than their corresponding liquid form (in term of integrated area under the ice melting curve).

If one is interested in achieving the most icemelt at 60 minutes of application, then at -1°C (30°F) and -9°C (15°F) solid NaCl and $CaCl_2$ are the best performers respectively. When solid NaCl is applied on ice, sufficient time (e.g., 60 minutes) should be allowed in order to achieve its full potential. This helps to explain the findings of a laboratory study by Blackburn et al. (1991), which demonstrated that at 15°F and 5°F $CaCl_2$ produced more undercutting of ice than NaCl on pavement materials.(41) At -18°C (0°F), however, all the other deicers achieved their potential in less than 30 minutes and further extending the time showed little benefits and in some cases even led to re-freezing. At -18°C (0°F), solid $MgCl_2$ greatly outperformed solid NaCl and liquid $MgCl_2$ greatly outperformed liquid NaCl, whereas Nixon et al. (2007) reported much less differences between $MgCl_2$ and NaCl. Be it in solid or liquid form, $CaCl_2$ exhibited much better performance than NaCl.(42) This confirms the findings by a previous laboratory study, in which Brandt (1973) found that relative to NaCl, the use of $CaCl_2$ for comparable deicing performance between 0 and 10°F within 1 hour would introduce five times fewer chloride anions and ten times fewer cations.(43) As the temperature gets colder, the difference between different deicers becomes more apparent and the need for selecting the right type of deicer becomes more crucial. This is consistent with findings from a previous study.(12)

Note that there are many parameters in the field environment that play a role in the effectiveness of deicer products used for winter road maintenance. These include traffic, pavement type and condition, and meteorological conditions. The amount and type of traffic influence the road surface conditions, as do pavement temperature, type, texture, etc. Meteorological conditions that are important include air temperature, wind speed and direction, solar radiation, humidity, rate and type of precipitation, water content of snow, etc. Also important are the physical and chemical properties of deicers such as gradation (for solids), color, viscosity, etc.





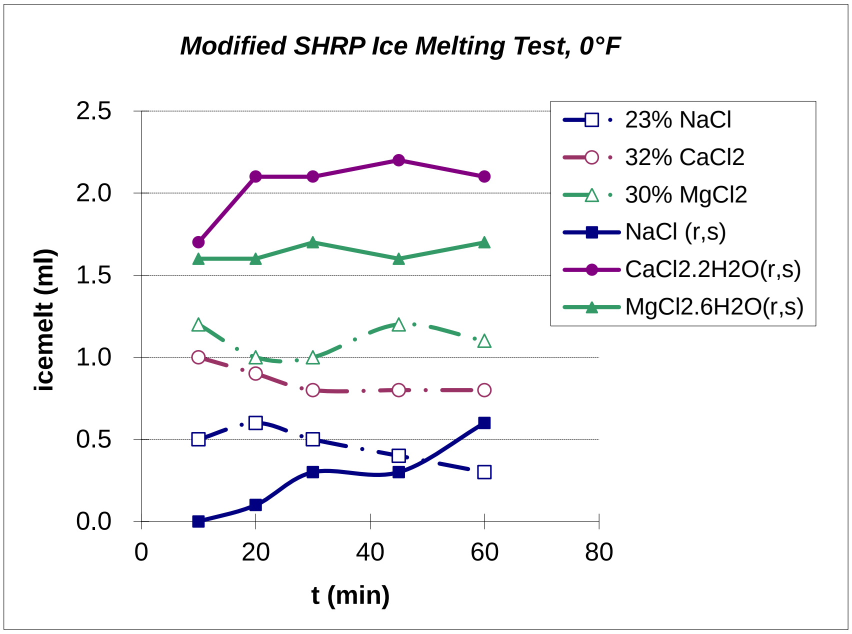


Figure 1. Temporal Evolution of Performance of Various Solid Chemicals and Liquid Deicers at 30°F, 15°F, and 0°F.

Table 3 presents the thermal properties (measured by differential scanning calorimetry or DSC) and ice melting performance (measured by the modified SHRP test) of these solid chemicals and liquid deicers as well as the blends of common liquid deicers with or without the sugar beet byproduct AGBP. The DSC thermogram of each deicer solution provides a characteristic peak that corresponds to the initiation and growth of ice crystals in the test solution, instead of the complete freezing of the test solution (eutectic formation). The characteristic temperature T_c coincides with the "effective temperature" of the test solution as a deicer, at which temperature ice crystals start to form and the pavement becomes icy. The data reveal that up to 20% replacement of the 23% NaCl deicer by the 32% $CaCl_2$ deicer had no significant effect on the T_c, slightly reduced the characteristic enthalpy of fusion *H*, and slightly increased the icemelt at 15°F, 20 min and at 30°F, 60 min. Up to 15% replacement of the 23% NaCl deicer by AGBP slightly increased the T_c, slightly reduced the characteristic enthalpy of fusion, and slightly decreased the icemelt at 15°F, 20 min and at 30°F, 60 min. Note that only the results for the solid deicers are reported, since AGBP and the liquid deicers did not perform well at 0°F.

Table 3. Thermal Properties and Ice Melting Performance of Various Solid Chemicals and Liquid Deicers.

	DSC Data		***Modified SHRP Ice Melting Capacity (ml/ml)***					
			30°F		**15°F**		**0°F**	
Product	T_c (°F)	*H* (J/g)	20 min	60 min	20 min	60 min	20 min	60 min
N: 23% NaCl deicer	21.8±0.1	165±2	2.7±0.1	3.5±0.0	1.1±0.0	1.1±0.0	Not Available	
C: 32% $CaCl_2$ deicer	16.2±0.4	121±11	2.8±0.2	4.0±0.2	1.8±0.1	1.6±0.1		
M: 30% $MgCl_2$ deicer	8.5±0.4	74±3	3.0±0.1	4.3±0.1	1.8±0.2	1.6±0.2		
AGBP	26.2±0.2	184±17	2.0±0.0	2.2±0.1	0.7±0.2	0.6±0.1		
95% N + 5% C	21.9±0.4	158±7	2.6±0.2	3.8±0.1	1.2±0.0	1.0±0.1		
90% N + 10% C	22.2±0.1	148±2	2.5±0.1	3.7±0.1	1.2±0.0	1.2±0.2		
85% N + 15% C	22.3±0.4	145±4	2.6±0.1	3.8±0.3	1.2±0.2	1.1±0.1		
80% N + 20% C	21.7±0.3	147±2	2.7±0.1	4.0±0.2	1.3±0.1	1.1±0.1		
90% N + 5% C + 5% AGBP	23.0±0.2	141±6	2.5±0.1	3.8±0.0	0.7±0.3	0.8±0.3		
85% N + 5% C + 10% AGBP	22.8±0.2	148±11	2.5±0.0	3.7±0.1	1.1±0.1	1.0±0.0		
80% N + 5% C + 15% AGBP	22.3±0.4	147±12	2.4±0.2	3.3±0.1	1.0±0.0	0.9±0.1		
NaCl (r,s)	Not Available		1.8±0.2	5.3±0.8	1.9±0.2	3.5±0.3	0.1±0.1	0.6±0.3
$CaCl_2$ (r,s)			2.7±0.1	5.3±0.4	3.1±0.2	3.2±0.2	2.1±0.1	2.1±0.2
$MgCl_2$ (r,s)			3.5±0.1	4.9±0.2	2.4±0.0	2.5±0.2	1.6±0.2	1.7±0.1

Application Rates and Best Practices

The application rates of deicers depend on a variety of factors including the strategies used, deicer used, air and pavement temperature, amount of snow on the ground, and steepness of the roadway. For anti-icing, low temperatures below 20°F, strong winds, and heavy snowfall or freezing rain conditions all make anti-icing problematic or ineffective.(7) Liquid deicers tend to freeze in temperatures below 20°F, and can work effectively when temperature is over 28°F. Previous research has suggested its best to apply anti-icing before snow events at temperatures higher than 20°F. (8, 44) The application rates of liquid deicers were documented in several references.(3, 25, 45) For magnesium chloride, the application rate for anti- icing ranges from 35-45 gallons per lane mile, while the application rate for deicing varies from 40-80 gallon/lane-mile. In Colorado $MgCl_2$ application rates ranged from 20 to 100 gallons per lane mile.(25) For heavy snowpack, the application rate goes up to 60 gallon/lane-mile or higher. According to the Colorado DOT, the application rate adopted in Glenwood Canyon, where sand is prohibited, may go up to 80 gallons per lane mile.

The Salt Institute (2007) provided guidelines for salt application in *The Snowfighters Handbook: A Practical Guide for Snow and Ice Control*.(46) Depending on weather, road surface and temperature conditions, recommended application rates ranged between 100 and 400 pounds per lane mile. When salt treated abrasives were employed, a range of 750 to 1000 pounds per lane mile was recommended. Field tests conducted in Michigan revealed that doubling the application rate of a commercially available liquid calcium chloride ($CaCl_2$) product from 30 gal/lane-mi (70 L/lane-km) to 60 gal/lane-mi led to a drop of average friction coefficient from 0.52 to 0.43. Note that the friction coefficient for dry and wet pavements averaged at 0.72 and 0.62 respectively.(34) The NCHRP Report 577 provided guidelines for the selection of snow and ice control materials.(21) Depending on the pavement temperature, an anti-icing application rate of 65 to 400 pounds per lane mile was recommended. For deicing, an application rate of 200 to 700 pounds per lane mile was recommended. For abrasives (pre-wet, dry, or mixed with road salt), an application rate of 500 to 600 pounds per lane mile was recommended. The FHWA provides guidance on the application rate of anti-icing materials, including liquid chemicals, solids and pre-wetted solids in its "Manual of Practice for an Effective Anti-icing Program".(7)

Prewet can increase material retention on the roadway by 26 percent . (5) For prewetting by the Wisconsin DOT, "salt is usually prewetted with 8-12 gallons of liquid per ton of salt". Prewetting can be done in the stockpile; as spreader trucks are loaded; or by spraying the salt as it is spread on the road (prewetting at the auger or spinner). Prewetting at rates of 10-30 gallons of liquid chemical per ton of sand or other abrasives has proven effective.(47) To minimize bounce and scatter, the suggested application rate for prewetting is 10-12 gallon per ton in Blackburn's study.(8) When there is rain before the snow events or there is snow at 32°F, prewet is not needed.(48) Gerbino-Bevins has summarized the observations and suggestions for best anti-icing and prewetting practices in his study conducted in 2011.(49)

Shi et al. (2013) recently conducted extensive laboratory tests to examine the friction behavior of asphalt pavement treated by various liquid deicers, either for anti-icing, liquid deicing, or prewet salt deicing. (50) Some of the key findings are provided as follows. For high traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: anti-ice using a salt brine at 20-30 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or an engineered salt brine at 20 gallons per lane mile. For low traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: use an engineered salt brine to anti-ice at 30-50 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or de-ice at 35-70 gallons per lane mile. The upper limit of the recommended application rates corresponds to the lower limit of the target pavement temperature range. For colder pavements (10ºF to 15ºF), $MgCl_2$ brine may be a better choice to use for either anti-icing or liquid deicing. For extremely cold pavement (below 10ºF), the use of liquid deicer is risky and needs to be validated before implementation and prewet salt may be used for deicing. To achieve the friction benefits of anti-icing or deicing on pavement, plowing is highly recommended once sufficient time has been allowed for the chemical to interact with snow precipitation and traffic.

Impacts of Using Road Salts

Highway winter maintenance activities offer such direct benefits to the public as fewer accidents, improved mobility, and reduced travel costs. For a 30-mile roadway segment in Iowa, accidents increased by 1,300 percent and traffic volume decreased by 29 percent during severe winter weather events.(51) Another case study in 1992 found that costs related to accidents decreased by 88 percent after application of deicing salts.(19) Studies in both Canada and United States show that on average, winter driving requires 33 percent more fuel.(52) Indirect benefits of snow and ice control operations include: sustained economic productivity, reduction in accident claims, continued emergency services, etc. Winter maintenance also allows economies to continue to operate. The impacts of the absence of winter maintenance were demonstrated in 1996, when a 4-day blizzard shutdown much of the northeastern United States and led to loss in production estimated at $10 billion, and this estimate does not include the costs of accidents, injuries or other associated costs.(16)

Research has indicated that the detrimental environmental impacts of abrasives (such as sand) generally outweigh those of chlorides.(2) In addition, the use of abrasives requires at least seven times more material to treat a given distance of roadway, compared with salt.(16) Therefore, a combination of salting and snowplowing is considered the best practice for snow and ice control.

Road Salt Corrosion of Vehicles

With the increased use of road salts, the general public and the trucking industry are increasingly concerned about the corrosion damage that snow and ice control operations may cause to motor vehicles. Today's motor vehicles have a wide array of metals in them, e.g., steel, cast irons, aluminum alloys, magnesium alloys, and copper and copper alloys, all of which are subject to the corrosive effects of deicers. In addition to detrimental cosmetic effects of corrosion, road salts may also lead to corrosion of critical vehicular parts such as brake linings, frames, and bumpers. A 1985-1990 field study in Sweden revealed that compared with those exposed to NaCl salted roads, the cars driven on unsalted roads had 50 percent less incidence of cosmetic corrosion and the carbon steel test panels had more than 90 percent reduction in corrosion rate.(53) While manufacturers have increased the corrosion resistance of motor vehicles in the last two decades, the annual cost of corrosion in the vehicle sector is still substantial. As of 1999, there were more than 200 million registered motor vehicles on the United States' roadways, with a combined value of more than $1 trillion and annual corrosion cost of $23.4 billion.(54) A study published in 1991 examined the average depreciation of motor vehicles in different regions of the United States Automobiles in the North Atlantic region were compared with those in the Southern Atlantic and Gulf Coast regions in order to control for corrosion due to marine environments and only investigate corrosion due to road salts.(55) The study came to an estimate of $17 of additional corrosion damage per year for each vehicle in the Snowbelt region, where approximately 60 percent of the vehicles in the United States operate. Hence, the cost of vehicular corrosion damage due to road salts was estimated at $2.04 billion per year (60 percent × 200 million × $17), which translates into *$136 per ton of road salts*. Note that this estimate is relatively conservative, since this does not account for the cost of repairs and maintenance necessitated by corrosion, which could increase the cost of the corrosion of motor vehicles due to road salts to between $2.8 billion to $5.6 billion per year.(55)

One laboratory study evaluated the corrosivity of various three percent deicer solutions by intermittently spraying them on carbon steel coupons at room temperature and found that the relative order of deicer corrosivity was as follows from the highest to the lowest: $CaCl_2$, $MgCl_2$, NaCl, NaCl + corrosion inhibitor, $MgCl_2$ + corrosion inhibitor, CMA, and water (H_2O) (56). Nixon and Xiong found considerable uncertainty" in evaluating how effective corrosion inhibitors added in deicers are in terms of reducing corrosion in winter maintenance equipment.(57) A study using simulated concrete pore solutions indicated that the corrosion behavior of galvanized steel in the presence of chlorides was controlled by the pH value of the electrolyte, which varies with the cation associated with the chloride anion (58).

The relative corrosivity of deicers is dependent on many details related to the metal/deicer system. Therefore, when evaluating the corrosive effect of deicers to metals or assessing the effectiveness of countermeasures, it is important to note the test protocol employed, the metal coupons tested, the deicer concentrations, the test environment, etc. For instance, in a study in our laboratory, the Pacific Northwest Snowfighters/National Association of Corrosion Engineers (PNS/NACE) corrosion test using carbon steel coupons suggested that plain $MgCl_2$ was the least corrosive among 5 common deicers with the same Cl^- concentration of 0.5M, i.e., NaCl, $MgCl_2$, $CaCl_2$, NaCl+10wt.% $MgCl_2$, and NaCl+20wt.% $MgCl_2$ (59). Xi and Xie performed metal coupon testing following the ASTM B 117 and the PNS/NACE test methods and also found $MgCl_2$ to be less corrosive than NaCl to the bare metals tested (stainless steel 410 and 304L, aluminum 2024 and 5086, copper wires, and mild steels).(60, (61),(62) Nonetheless, the test results led to the opposite conclusion. The inconsistencies in the test results were attributed to the different moisture conditions and to the different properties of the two salts under high humidity environment. $MgCl_2$ was found to be more corrosive than NaCl in humid environments (due to its hygroscopic nature and higher viscosity of its solution), and NaCl was found to be more corrosive under immersion and in arid environments.

Road Salt Corrosion of Infrastructure

The corrosion damage of road salts to the transportation infrastructure (steel bridges, large span supported structures, parking garages, pavements, etc.) has enormous safety and economic implications.(63) Over $5 billion are spent each year by state and local agencies to repair infrastructure damage caused by snow and ice control operations, which translates into *$333 per ton of road salts*.(16) According to the NACE International, "there are 607,380 bridges in the United States (2013)… and approximately 30 percent of the bridges are structurally deficient or functionally obsolete. The annual direct cost of corrosion for highway bridges is estimated to be $13.6 billion".(64) It was estimated that installing corrosion protection measures in new bridges and repairing old bridges could cost snowbelt states between $250 million and $650 million per year (31). Parking garages, pavements, roadside hardware, and non-highway objects near salt-treated roads are also exposed to the corrosive effects of road salts. Indirect costs to the user in traffic delays and lost productivity are estimated at more than 10 times the direct cost of corrosion maintenance, repair, and rehabilitation.(65) First of all, chloride ions from road salts can diffuse into concrete structures such as bridge decks and result in corrosion of the reinforcing steel.(66) The major cause of concrete deterioration (cracking, delamination, and spalling) is the corrosion of steel often initiated and promoted by chloride ions. In addition to marine environments and contaminated mix constituents, the road salts are a major source of these aggressive agents. The chloride diffusion coefficients for $MgCl_2$ are about 2 to 3 times greater than those of NaCl, which may reduce the time to corrosion initiation for the concrete embedded reinforcing steel by 10 to 15 years. (67,68,69,70) In the snowbelt region, the synergism of freeze-thaw cycles and corrosion of rebar or dowel bar can lead to serious problems against reinforced concrete structures or pavements. The use of properly cured, air-entrained concrete can minimize the damage by freeze-thaw cycling, but chlorides can still penetrate and migrate through the concrete and cause the depassivation (material becoming more affected by environmental factors such as air or water) and corrosion of steel. The corrosion products lead to expansion in volume and build up tensile stresses in concrete, which can cause cracks and compromise the design strength of the structure. Second, road salts may pose a risk for the durability of concrete structures and pavements through three main pathways:

- Physical deterioration of the concrete through such effects as salt scaling (71, 72);
- Chemical reactions between deicers and concrete (especially in the presence of Mg^{2+} and Ca^{2+}) (73, 74, 75);
- Deicer aggravating aggregate–cement reactions.(76, 77)

For instance, laboratory studies have also demonstrated that concentrated $MgCl_2$ deicers cause deterioration of mortar and concrete specimens.(67, 78, 79, 80) Finally, the deicer impacts on asphalt concrete pavements had been relatively mild until acetate- and formate-based deicers were introduced in recent years. The damaging mechanism seems to be a combination of chemical reactions, emulsifications and distillations, as well as the generation of additional stress in the asphalt concrete.(77) A study in 2002 examined the effect of different deicers (NaCl, KAc, sodium formate, and urea) on airfield asphalt concrete materials and mixes, and the presence of deicers was found to have a damaging effect on both the aggregates and the asphalt mixes.(71)

Previous studies on deicer/concrete interactions used mostly concentrated deicer solutions. A transportation pooled-fund study led by the South Dakota DOT (*Deleterious Chemical Effects of Concentrated Deicing Solutions on Portland Cement Concrete*) investigated the effects of concentrated brines of NaCl, $MgCl_2$, $CaCl_2$, and CMA on Portland cement concrete (PCC) and concluded that both physical and chemical interactions occur within concrete when it is exposed to freeze–thaw conditions and deicers. (74) Based on the ASTM C 666 freeze–thaw test results, concrete prisms of 10 cm diameter by 5 cm height were subjected to 300 freeze–thaw cycles in 14 percent $MgCl_2$ and 15 percent $CaCl_2$ with the following results:

- Considerable expansion (0.17 percent [$MgCl_2$] and 0.18 percent [$CaCl_2$] length change);
- Mass change (3.5 percent [$MgCl_2$] and -3.5 percent [$CaCl_2$]);
- Loss in the dynamic modulus of elasticity (50 percent [$MgCl_2$] and 40 percent [$CaCl_2$]).(81)

In contrast, samples exposed to 18 percent NaCl did not expand more than 0.04 percent and reported 0.5 percent mass gain and approximately 5 percent loss in the dynamic modulus of elasticity. Significant evidence existed that $MgCl_2$ and $CaCl_2$ chemically reacted with hardened cement paste, as indicated by the dissolution of the cement paste and formation of expansive oxychloride phases. These mechanisms were assumed responsible for the observed expansive cracking, increased permeability, and significant loss in compressive strength of the concrete. Exposure to NaCl, however, did not result in noticeable chemical interaction or related distress in concrete mortar or concrete. Other laboratory studies have also demonstrated that concentrated $MgCl_2$ deicers cause deterioration of mortar and concrete specimens.(67, 78, 79, 80)

A recent study in our laboratory investigated the effects of diluted deicers on PCC, assuming a 100-to-3 dilution ratio for all liquid and solid deicers. (72) Based on the gravimetric and macroscopic observations of freeze–thaw specimens following the SHRP H205.8 laboratory test, de-ionized water, the CMA solid deicer, and the $MgCl_2$ liquid deicer were benign to PCC durability, whereas potassium formate (KFm) and sodium acetate (NaOAc)/sodium formate (NaFm) blend deicers showed a moderate amount of weight loss and noticeable deterioration of the concrete. NaCl, the NaCl-based deicer, and the KAc-based deicer were the most deleterious to the concrete. In addition to exacerbating physical distresses, each investigated chemical or diluted deicer chemically reacted with some of the cement hydrates and formed new products in the pores and cracks. Such physiochemical changes of the cement paste induced by the deicers pose various levels of risks for concrete durability. Another study in our laboratory investigated how continuous deicer exposure affects the strength and chemistry of PCC by ponding 2 types of concrete samples under 4 diluted chloride-based deicers at room temperature for an average of 338 days. (75) The 2 mix designs investigated represent the roadway pavements and bridge decks built by the Washington State Department of Transportation (WSDOT) prior to 1980. For the pavement mix, the continuous exposure to three deicers (non-inhibited NaCl, inhibited NaCl and inhibited $CaCl_2$) led to limited levels of strength gain of the concrete, whereas exposure to inhibited $MgCl_2$ led to significant strength loss. For the bridge mix, continuous exposure to the four deicers led to significant strength loss of the concrete, with the inhibited $CaCl_2$ deicer having the least impact. These results suggest the deleterious role of Mg^{2+} cations and the beneficial role of Ca^{2+} cations in altering concrete strength, although more concrete samples need to be tested in order to validate the findings. Microscopic analysis revealed that each investigated deicer chemically reacted with some of the cement hydrates and formed new products, with potential implications for concrete durability. Corrosion inhibitors and other additives in deicers did not show significant benefit in inhibiting the strength or chemical changes of concrete induced by cations and/or anions in deicers.

Yet another laboratory study investigated the effects of both diluted and concentrated deicers on PCC. Concrete specimens were exposed to weekly cycles of wetting and drying in distilled water and in solutions of NaCl, $CaCl_2$, $MgCl_2$, and CMA with either a 6.04M ion concentration (equivalent to a 15 percent solution of NaCl), or a 1.06M ion concentration (equivalent to a 3 percent solution of NaCl), for periods of up to 95 weeks. At lower concentrations, NaCl and $CaCl_2$ showed a relatively small negative impact on the properties of concrete, whereas $MgCl_2$ and CMA caused measurable damage to concrete. At high concentrations, NaCl showed a greater but still relatively small negative effect, whereas $CaCl_2$, $MgCl_2$ and CMA caused significant loss of material and a reduction in stiffness and strength of the concrete.(73)

Of the two major types of pavements-PCC pavement and asphalt pavement-the latter is generally believed to be less effected by deicers. This is attributable to the relatively high chemical resistance that asphalt binder demonstrates in the presence of chloride-based deicers. Thus far, there are no specific guidelines established in the United States for application of deicers on asphalt pavements and little fundamental research carried out in investigating the asphalt/bitumen deicer reaction, although more severe loss of skid resistance on asphalt surface has been observed by state and federal highway agencies with the application of various road salts.(7). Current research studying deicers effects on asphalt pavement is focused on improving surface skid resistance of the pavements of different mix types.

Frost action within the pavement granular layers can be aggravated by an ice enrichment process and differential freezing conditions associated with the contamination of the base material by deicing salt.(82) A comprehensive laboratory study evaluated the relative destructive effects of various deicers on asphalt pavement, considering the effect of freeze/thaw cycles (71, 83) This study involved actual aggregates and asphalt specimens cored from the field, as well as four types of deicers used on both highway and airport pavements, namely, urea, NaCl, NaFm, and KAc. Various degrees of material disintegration as a combined result of frost action and deicers were observed, revealing that the effect from freeze/thaw cycling was significant whereas the effects of different deicers on both the aggregates and the asphalt concrete mixes varied. The extent of damage due to freeze/thaw cycling in distilled water was less than that caused by any deicer used. A critical range of deicer concentration was found to exist between 1% and 2% by weight of solid deicer to deicer solution, in which the maximum damaging effect of deicers to the aggregate was observed. The limestone aggregates showed a higher resistance to disintegration than the quartzite aggregates when subjected to freeze/thaw cycles in the presence of the deicers. The urea was found to have the highest damaging effect among all the deicers on both the aggregates and asphalt concrete samples, while the least damaging deicer for limestone was NaCl and for quartzite was KAc.

Winter chemicals used on cracked asphalt pavements allows the chemicals to infiltrate the gravel base which can shorten the winter frozen time and prolong the spring breakup time. In the colder areas of Idaho, there is risk involved with using these chemicals on older cracked asphalt pavements. Asphalt pavements that are chip sealed and crack sealed do not seem to be susceptible to accelerated deterioration[1].

Environmental Impacts of Road Salts

The environmental impacts of road salts have been a subject of research since their usage became widespread during 1960s for highway maintenance.(84, 85, 86, 87) For instance, increased salinity in adjacent waterways and soils, degradation of the environment along the roadside, and infiltration of cations (Na^+, Ca^{2+}, Mg^{2+}, etc.) and the chloride anion (Cl^-) into soils and drinking water are concerns associated with the use of chloride salts.(31) Abundant evidence demonstrates that chloride salts can accumulate in aquatic systems, cause damage to terrestrial vegetation, and alter the composition of plant communities.(88, 89, 90,91, 92) The use of chloride salts may liberate mercury and other heavy metals from lake sediments or soil through ion exchange processes.(93) NaCl, $MgCl_2$, and $CaCl_2$ all contribute chloride to surrounding environments, which may have detrimental effects once reaching certain levels. The specific threshold levels to cause environmental damage depend on site-specific conditions and concentrations of pollutants in the receiving environments. The U.S. Environmental Protection Agency (EPA) has set the maximum chronic exposure levels for chloride content in water at 250mg/L.(94) Environment Canada reported that many woody plant species sensitive to salt had vanished from Canadian roadsides (95). The environmental impacts of road salts are difficult to quantify in monetary terms, as they are site-specific and depend on a wide range of factors unique to each formulation and spatial and temporal factors of the location. Since most chlorides are readily soluble in water and difficult to remove, there have been concerns over their effects on water quality. However, several studies have found that chloride concentrations in highway runoff are typically low enough that chloride is quickly diluted in receiving waters. Therefore, the impacts of chemical deicers on receiving waters may be negligible in many cases, depending on the type and designated use of the receiving water, and on the drainage system used to discharge the runoff.(96) Chloride also causes great concern if it reaches groundwater used as a source of drinking water. In a WSDOT field evaluation, however, chloride levels in roadside soils, surface water and underlying groundwater were found to be generally low and well below any applicable regulatory standards or guidelines.(32) Deicers are relatively non-toxic to aquatic organisms with some concerns about NaCl and $CaCl_2$.(27) A Colorado DOT study examined the impacts of $MgCl_2$ on several aquatic organisms and concluded that during the study period in 1997-98 $MgCl_2$ had a very limited potential to cause environmental damage more than 20 yards from the roadway.(97) A Michigan DOT study concluded that deicers could be toxic to aquatic organisms, but only in streams with very low flows and in wetlands and ponds with long turnover times. The negative impacts of chloride compounds are most likely to occur in areas of high deicer use, where roadway runoff is channeled directly to small water bodies.(90)

The Salt Institute suggested application rates of NaCl are 100 to 300 pounds per lane mile (30 to 90 kg per lane km) of solid material, and 45 to 165 gplm (105 to 388 liters per lane km) of 23 percent liquid salt brine. An application rate of 300 pounds per lane mile of NaCl applied to a 0.2-in (0.5-cm) thick ice layer in Milwaukee resulted in an initial salt solution of 69,000 to 200,000 mg/L during heavy snowmelt.

[1] Personal communication, Jason Giard, Idaho Transportation Department, 2013

Runoff to surrounding soil and water bodies from this type of application may be in the thousands of mg/L.(98)

Similar to NaCl, $MgCl_2$ and $CaCl_2$ can cause damage to vegetation such as growth inhibition, scorched leaves, or even plant death.(31, 90, 99)Laboratory data demonstrate that, compared to NaCl, the use of $CaCl_2$ for comparable deicing performance at 0 - 10°F within 1 hour, would introduce 5 times fewer chloride anions and 10 times fewer cations.(43) Cunningham et al. found that in an urban environment the magnesium cation from a $MgCl_2$ deicer application was the most abundant cation in soils adjacent to roadways even though NaCl was the most frequently used deicer.(100) The sodium cation was found to rapidly leach from the soil, decreasing toxicity to plants but increasing input to adjacent waterways. These contain a higher concentration of chloride than NaCl by unit weight, and therefore may be more harmful when applied at the same rates.(90) Field and greenhouse studies have found direct application of $MgCl_2$ to be more damaging to plant foliage than NaCl, causing decreased photosynthesis rates on exposed foliage adjacent to roadways.(99) Despite the potential damaging effects of these materials, their use can reduce the need for applying abrasives, and pose less threat to the surrounding vegetation, water bodies, aquatic biota, air quality, and wildlife.(101)

In summary, we should account for the use of road salts, while improving roadway safety and mobility, does present corrosion and environmental costs.(102) These costs were estimated to be an average of $469 per ton of material used (in 2005 dollars).

Winter Maintenance Chemicals and Safety

Qiu and Nixon developed a method to measure the performance of a winter maintenance program with respect to the provision of safety and mobility to motorists.(103, 104) The researchers noted that many past studies did not evaluate winter maintenance outcomes while accounting for factors including storm severity, road characteristics and maintenance efforts. To address this, a storm severity index was developed, with the effects of weather and winter maintenance on road surfaces estimated by Multinomial Logistic Regression (MLR). Multiple Classification Analysis (MCA) was applied to estimate the contributions of winter maintenance to safety, including the use of chemicals. Chemicals included NaCl solution (brine), $CaCl_2$ solution, or granular NaCL (application rates were only available for brine and $CaCl_2$). Results of the MCA indicated that the chemical variable was a strong indicator of property damage only (PDO) crash probabilities; the impacts of specific chemical types were not broken out (104). However, winter highway maintenance operations collectively (plowing and chemical use) were found to be a weak predictor of crash severity. Modeling results did not show a direct impact on reducing crashes from maintenance operations, but these operations were still found to indirectly impact safety through reducing snow/ice surface conditions.(103)

Usman *et al.* quantified the safety benefits of winter maintenance through an investigation of the association between accident frequency during snow events and road surface conditions, visibility and other influencing factors (controlling for traffic exposure).(105) The research did not consider specific maintenance operations directly in the models that were developed, as it was assumed that these operations were reflected in the measurements of road surface conditions (measured by the road surface condition index(RSI)). Exploratory analysis indicated that maintenance activities were correlated to RSI and were not statistically significant once road surface conditions were accounted for.(105) Three event-based models were developed by this work, including a negative binomial, a generalized negative binomial, and a zero-inflated negative binomial, with the intention of determining which was most suitable to fit the available data. It was determined that the generalized negative binomial best fit the data, with the coefficient associated with the RSI indicating that a 1 percent improvement in this metric would produce a 2.28 percent reduction in expected crashes. The key limitation of this work is that it did not explicitly incorporate specific maintenance activities into the developed models, instead relying on the assumption that RSI accounted for them based on observations made during exploratory data analysis. Consequently, a determination of the specific contributions of specific maintenance practices and materials (ex. salt, sand, brine, etc.) was not determined.

Usman *et al.* developed disaggregate models for quantifying the safety effects of winter maintenance activities at an operational level.(106) Two types of models were developed: a single-level generalized negative binomial model and a multilevel Poisson lognormal model. The generalized negative binomial model did not account for weather variations within the storm event itself, while the Poisson lognormal model could account for hierarchical data (ex. individual snow events and the individual hours within each storm). The models examined the link between winter road crashes and weather, road surface conditions, traffic exposure, temporal trends and site-specific effects. Hourly data from 31 highway routes in Ontario, Canada, were used in the analysis.

Model results indicated that factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, month of winter season and time of day the storm occurred all had significant effects on safety. The work also allowed for a quantification of the benefits of maintenance operations and service standards in terms of expected crashes. This included identifying the safety benefits of combined plowing and salting versus a no maintenance condition and the timing of those operations (ex. 2 hours into event, 4 hours, etc.) and the time to bare pavement. For plowing and salting operations, the mean number of accidents expected following that operation are quite low, steadily rising back to the expected mean had no maintenance been performed over a period of hours following the maintenance. This is illustrated in Figure 2. An examination of the expected reduction in accidents from the models versus time to bare pavement indicated that, as one would expect, the sooner maintenance activities produce bare pavement, the greater the reduction in the percent of crashes. This is illustrated in Figure 3.

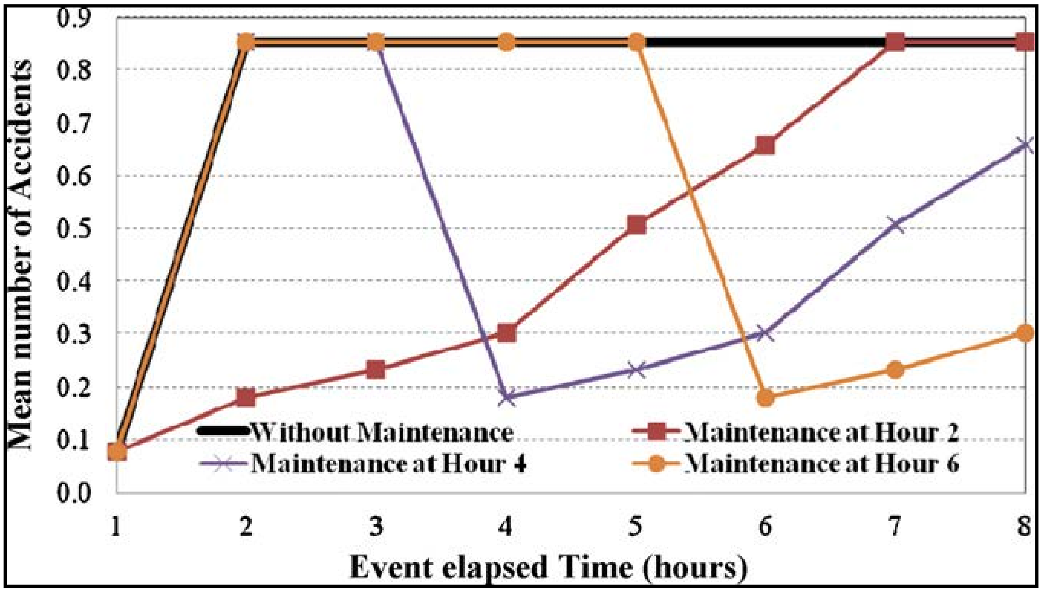


Figure 2. Safety Benefits of Plowing and Salting Operations Versus No Maintenance (106).

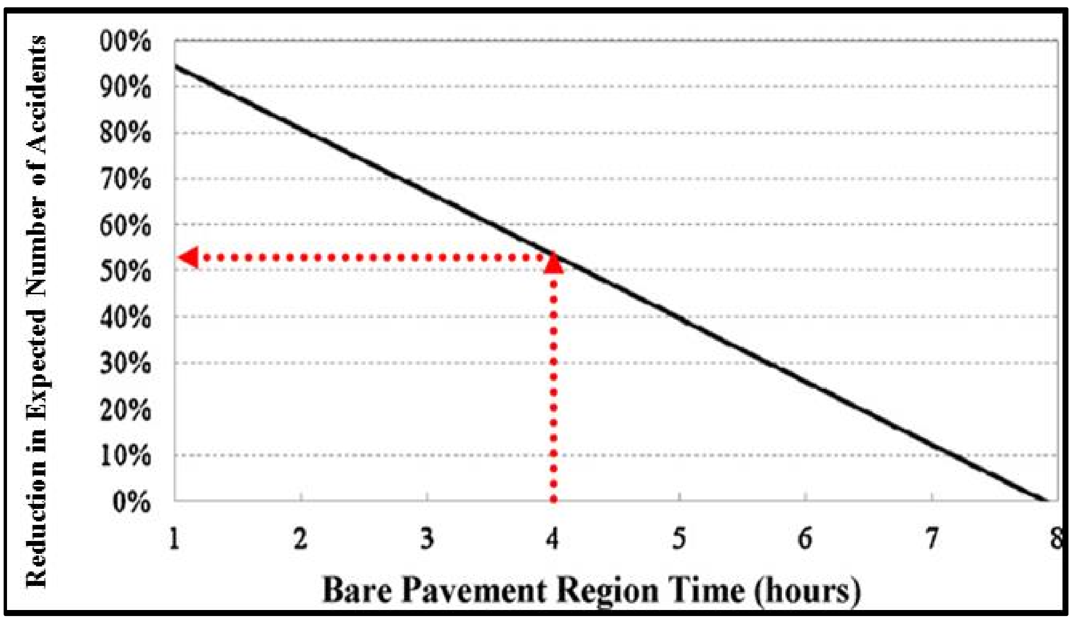


Figure 3. Effect of Time to Bare Pavement on Safety (106).

Kuemmel and Hanbali performed a simple before-and-after analysis on the effectiveness of salting on safety in New York, Minnesota and Wisconsin.(19, 107) The researchers found a significant reduction in crashes following salting operations, with an 87 percent reduction observed on two-lane undivided highways and a 78 percent reduction on freeways. As noted, a simple before-and-after approach was employed by this work which estimated traffic volumes based on historical data rather than observed counts. Weather-related factors, as well as the use of other winter maintenance operations (ex.

plowing), were not considered by this work either, which calls into question the true contribution of salting to the observed crash reductions.

Norrman *et al.* quantified the relationship between safety and road surface conditions based on types of slipperiness.(108) Accident risk was compared to the percentage of maintenance activities performed. It was found that generally, increased maintenance was associated with a decreased number of accidents. However, the work was limited in that it considered all roadway classes and locations together, failing to account for factors such as functional classification, geometry, traffic volume and weather, which all affect safety. In addition, the approach that was developed did not facilitate comparisons between the effects of different maintenance practices and materials.

Fu *et al.* examined the effects of winter weather and maintenance treatments on safety.(109) Daily accident data, weather conditions and maintenance operations data were examined for two provincial highways in Ontario, Canada. The researchers employed a Generalized Linear Model (GLM) to identify weather and maintenance factors that had a significant impact on crash frequency. It was found that anti-icing and prewetting operations improved safety on one study route (anti-icing was used on only one study route), while sanding operations had a positive effect on safety on both routes. The researchers noted that the safety effect of plowing and salting operations could not be statistically confirmed by their work. It was possible that there could have been an inter-dependency between maintenance operations and snow conditions, since more maintenance operations were dispatched during more severe weather conditions. Consequently, the variation in these operations under a given weather condition may have been small.(109)

Fu *et al.* performed a statistical analysis on observational data to identify the quantitative effects of weather and maintenance operations on snow melting trend.(110) Chemicals included rock salt with and without pre-wetting liquid, near-saturation solutions of NaCl brine, $CaCl_2$ brine with corrosion inhibiting additives), and $MgCl_2$ brine with corrosion inhibiting additives. The test site was a 50 kilometer route on Highway 21 in southwest Ontario, Canada. The researchers noted that historically, quantifying the effectiveness of alternative winter maintenance treatments was a challenge due to the large variations in observational environments including weather, traffic and location. To address this, multinomial logit models were employed to capture snow melting outcomes under these conditions. The primary findings of this work were that pre-wetted salt outperformed dry salt by a reduction in snow cover from 17.9 percent to 40.0 percent, $CaCl_2$ was found to be much more effective as a pre-wetting agent and outperformed $MgCl_2$ by 9.5 percent to 71.4 percent , and was also more effective than salt brine (NaCl). While these findings were not directly tied to safety (or operational) performance, they do present insight into the effectiveness of different chemicals in achieving snow melt, which has potential safety and operational benefits.

Usman *et al.* investigated the potential effects of data aggregation and correlation on accident prediction models of winter road safety.(111) A multilevel regression approach which developed generalized negative binomial and Poisson lognormal models was used to capture the clustered nature of accident data, focusing on what the impact of using a disaggregate modeling approach was and whether multilevel models gave substantively different results over a single-level model. Data from four patrol routes in Ontario, Canada, including hourly traffic, accident data, road condition and weather data were employed in the analysis. In general, it was found that the effect of data aggregation had a significant effect on model results while the difference between the conventional regression and multilevel regression was inconsequential. Of greater interest to this work were the general observations made of some of the model outputs. It was found that the RSI was a statistically significant factor influencing road safety across all sites, with higher accident frequencies associated with poor road surface conditions. Additionally, hourly traffic was also found to be significant in the aggregate data analysis, which suggested that traffic variation within events was an important factor affecting accidents.

Johnson *et al.* examined the inter-dependence of road classification, road surface condition, and driver age on winter road surface condition crashes in Maine for a five-year period (112). Two way chi-squared analyses were used to investigate these interdependencies, with a focus on anti-icing practices. Results indicated that all age groups experienced more crashes on rural roads with higher speed limits, regardless of whether de-icing or anti-icing was used. On urban state highways where anti-icing was used, all age groups experienced fewer winter crashes. The researchers noted that the limitation of their work was that it did not incorporate exposure data for each of the age groups examined; it was believed that the use of such data in future work might improve the certainty of the interactions observed between age groups, road types and road surface conditions.

In related work, Rubin *et al.* observed a significant reduction in fatalities from accidents in Maine between 1989 and 2008, which coincided with the adoption of anti-icing practices.(113) Specifically, winter crashes on state highways after 2000 (when anti-icing was adopted) fell by 19.7 percent compared to the years 1989 through 1999. During the same period, fatal crashes fell by 30.5 percent on these same roads.

Kahl completed work for the Michigan Department of Transportation investigating the use of agricultural by-products (Ice Beeter, Caliber M-1000, Ice Ban and First Down) for anti-icing and deicing in southwest Michigan.(114) As part of this work, the impact of anti-icing was determined on 1 route (I-94, 123 miles). It was estimated that anti-icing activities along the study route reduced the number of expected crashes from an estimated 831 to an observed 430, a difference of 401, during the winter of 2000-2001. However, caution is strongly recommended in interpreting this result, as linear regression was employed to estimate the expected number of crashes; this approach has historically been shown to be inappropriate for modeling crashes. Based on the overall findings of the project, it was recommended that agricultural by-products should be used for anti-icing and the prewetting of rock salt, but not for deicing.

In a review of past work, Wallman *et al.* summarized the effects of winter road maintenance on safety, operations and corrosion.(115) In their review, the researchers observed that accident rates in Europe ranged from 5 to 14 times higher before maintenance activities were carried out compared to after. Similarly, accident rates in the U.S. on two-lane roads were 8 times higher before maintenance compared to after.

O'Keefe and Shi presented a synthesis of research on anti-icing and pre-wetting in North America.(5) Included in their discussion was the observation that anti-icing and pre-wetting had generally lowered accident rates in many locations. Specific information provided included an 83 percent reduction in accidents in Idaho following the use of anti-icing, as well as a 14 percent reduction in accidents in Colorado after improved maintenance strategies were implemented however specific strategies were not cited.(116)

Norem discussed the selection of winter maintenance strategies based on climatic parameters in Sweden.(117) Of interest to this work was the discussion of the safety performance of salting activities on safety. In the southern region of the country, it was determined that salted roads had a 28 percent reduction in accidents over unsalted roads. Data from the northern region indicated that there were no more accidents on unsalted roads than on salted ones. The overall work concluded that salt should not be used when temperatures fall below 17° F (-8° C).

Environment Canada summarized the different costs and benefits associated with road salt use in Canada.(118) Among the benefits cited was a reduction in accidents of up to 88 percent, a figure obtained from the Salt Institute.(119) The estimated financial savings (all Canadian dollars)per crash from the use of salt per accident type were $1,594,412 per fatality, $26,628 per injury and $5,724 for property damage. Additionally, decreased liability claims against highway agencies were also cited as an indirect benefit of salt use.

Johansson found that in central Sweden on days where temperatures were below 32° F (0° C), and more than 2 millimeters of precipitation was present, 400 kilograms of salt per kilometer was required.(120) Meanwhile, the number of serious accidents (fatal/injury) on such days was 2.7 times higher as a winter day without a storm event. The conclusion drawn by the researchers was that the observed speeds of vehicles when snow was on the road remained higher than they should, contributing to the increase in accidents during the weather parameters examined. This finding is of interest in that winter maintenance (salt use) was undertaken, but safety was observed to deteriorate.

Berrocal et al. developed probabilistic models to forecast ice formation on roadways. The intent of this work was to improve decision-making with respect to the use of anti-icing.(121) Based on a probabilistic model, it was determined that the potential existed for considerable cost-savings to be generated through improved decision-making regarding when anti-icing should be used. While not cited by the researchers, improving the use and timing of anti-icing also held potential for improving roadway safety and operations.

Kroeger and Sinhaa, in developing a highway maintenance concept vehicle, indicated that the use of advanced technology in anti-icing operations could potentially reduce accident rates by 73 to 80 percent.(122) While this range was developed through a review of existing literature, it does indicate the potential that anti-icing coupled with technological advances (ex. controllers, etc.) holds in improving safety.

Hans *et al.* examined the safety impacts of winter weather, specifically opportunities to improve safety on state-maintained roads in Iowa.(123) The effort entailed the development of approaches to identify locations systematically that exhibited poor winter weather safety performance based on crash history. While the work did not focus specifically on the cost or benefit impacts of maintenance practices on safety or operations, it did establish mechanisms for maintenance forces to use in examining historical crash data while planning future maintenance strategies and operations.

Winter Maintenance Chemicals and Mobility (Operations)

Qiu and Nixon examined performance measurements for winter maintenance operations.(103, 104, 124) As part of this work, the effects of maintenance operations on vehicle speeds and volumes were investigated, among other topics such as safety (discussed elsewhere in this text). The work examined the effects of weather and maintenance on Interstates and primary highways with different average annual daily traffic (AADT) levels and speed limits by using Structural Equation Modeling. In general, the winter maintenance operations (plowing, chemical treatment) examined had positive effects on the speeds observed (i.e. speeds were higher where maintenance was employed at a higher priority level compared to a lower level). While plowing had a measureable impact, producing 2 to 3 mph higher speeds during the hour following plowing, chemical treatments did not produce higher speeds (far below 1 mph higher speeds the following hour). Additionally, maintenance operations also had positive effects on traffic volume, with only a slight reduction in traffic volume observed during average winter storms for service routes that received a high level of maintenance.

Shahdah and Fu conducted a simulation-based analysis to quantify the mobility benefits of winter maintenance using a freeway segment near Toronto, Ontario, Canada.(125) The simulation model was used to model traffic operations under a set of assumed snow storm events (low, medium, and heavy snowfall intensities) and maintenance scenarios (generalized extremes, either no maintenance performed or road maintenance producing a bare, wet surface). The research results found that road maintenance producing bare, wet pavement during low snowfall events could save a total travel time (compared with snow-covered scenario) of about:

- 6 to 7 percent for volume/capacity (V/C) ratios from 0.35 to 0.60,
- 26 to 27 percent for V/C ratios of 0.70 to 0.75,
- 10 to 11 percent for V/C ratios between 0.90 and 1.00.

This travel time savings increased with snowfall intensity, with savings during heavy snowfall estimated to be between:

- 7 to 11 percent for V/C ratios of 0.35 to 0.60,
- 29 to 36 percent for V/C ratios of 0.70 to 0.75
- 5 to 12 percent for V/C ratios of 0.90 and 1.00.

Of course, the limitation to this work is that it did not examine the impacts of specific winter maintenance practices in a real world setting. Still, the results indicate that aggressive winter maintenance strategies result in improved operations.

Pesti and Liu evaluated the use of salt brine and liquid corn salt on Nebraska highways.(126) Field studies on two highway segments were conducted to evaluate the performance of each treatment, with cost-benefit analysis performed to determine the cost effectiveness of each treatment. Among the benefits measured was the road user savings achieved through faster bare pavement conditions resulting in reductions in travel times and delays for motorists. Liquid corn salt was determined to be a more cost effective treatment based on bare pavement being achieved more quickly (with resulting higher vehicle speeds, lower travel times and decreased delay) compared to salt brine. The limitation of this work is that while the pavement conditions were measured in the field, traffic conditions/performance were only estimated/assumed. Consequently, the results of this work, while reasonable, were not observed in the field.

As part of examining the use of agricultural by-products for anti-icing and deicing in Michigan, Kahl discussed user delay costs from storms.(114) The work determined that as speeds decreased due to weather, user delay costs rose, approaching $200 per vehicle on higher speed roads. Given a cost for anti-icing of $22 per lane mile, it was noted that the improved mobility benefits that would result from its use were justified. However, aside from this simplistic overview, no detailed field examination of the effects of anti-icer and deicer use on operations was conducted.

Hanbali and Kuemmel performed a simple before-and-after analysis on the effectiveness of salting on vehicle operating savings.(127) In computing user mobility benefits/savings, it was assumed that speed reductions of 10 mph on both two-lane highways and freeways resulted from weather. The researchers found that total direct operating costs for motorists fell from:

- 7.3 cents to 6.1 cents per vehicle mile traveled on two-lane highways
- 53.5 cents to 23.8 cents per vehicle mile traveled on freeways following maintenance activities.

During the first two hours following maintenance, the direct road user benefits amounted to $6.50 for every $1.00 spent on two-lane highways and $3.50 for every $1.00 spent on freeways for maintenance. The direct costs of maintenance were offset once 71 vehicles and 280 vehicles had driven over a two-lane highway and freeway, respectively, with maintenance costs being paid for after approximately 35 minutes.

A literature review for the Wisconsin DOT highlighted the limitations of the use of abrasives in winter maintenance.(128) The report noted that abrasives, especially those not prewetted, had limited effectiveness on roads with higher vehicle speeds. This indicates that the use of abrasives will not necessarily improve operations or mobility on many roads. Additionally, the report noted that abrasives do not necessarily contribute to a reduction in accidents. This was based on work reported by Kuemmel and Bari.(129)

While not examining the use of treatments/materials, Maze, *et al*. made several observations as part of work examining the costs and benefits of winter storm road closures.(130) The researchers noted that road closures allowed users to avoid being involved in accidents and eliminated stranded motorist rescue costs. However, the delays incurred by users were a significant cost from the perspective of operations. Consequently, the researchers recommended that travel time reliability needed to be better understood and quantified in order to determine the value of maintaining roadways versus closure during storms.

Cuelho, *et al.* developed recommended practices for anti-icing on California roads.(45) As part of this work, laboratory and field measurements were made of road surface friction where anti-icing had been used after plowing operations. It was found that anti-icing chemicals maintained roadway friction after plowing, providing the potential for improved operations and safety.

Chapter Summary

Maintenance agencies are continually challenged to provide a high level of service and improve safety and mobility of winter roads in a cost-effective manner while minimizing corrosion and other adverse effects to the environment. Some products for snow and ice control may cost less in regard to materials, labor and equipment, but cost more in the long run as a result of their corrosion and environmental impacts. A balanced perspective should be utilized to ensure that any benefits of winter maintenance practices would not be achieved at the price of deteriorated infrastructure, impaired environment, or jeopardized traveler safety. The use of road salts for sustainable highway winter maintenance necessitates the application of collaborative decision-making among all relevant stakeholders.

Only limited research has been completed specific to the impacts of winter maintenance treatments and materials on roadway safety and operations. As one would expect, winter maintenance treatments had a positive impact on highway safety to varying degrees, with some instances of decreased safety observed. Similarly, winter maintenance treatments also produced operational benefits, although only a limited number of studies quantified these through field data. Overall, the primary conclusion that can be drawn from the work reviewed here is that, while some progress has been made over the years in identifying and quantifying the benefits of winter maintenance treatments on safety and operations, this work has often relied on simplifications or assumptions rather than observed field data. Consequently, the results generated, while providing a general idea of the benefits of winter maintenance treatments, cannot be considered completely representative of their true values.

Chapter 3
Review of Magnesium Chloride and Salt Brine Operations

Magnesium chloride and salt brine are two materials used in different areas of Idaho for winter maintenance operations. Their use in different districts can vary, and in order to understand the materials/chemicals used during past winter seasons, application rates (e.g., by lane-mile, by hour, by day) under different road weather scenarios, costs, etc., the researchers undertook surveys of ITD district staff. Historical data on winter maintenance activities related to the use of $MgCl_2$ in Districts 2 and 3 was acquired by the researchers and surveys of operators in these 2 districts were conducted to investigate the performance of the material in these districts. Similarly, historical data on winter maintenance activities related to the use of salt brine in Districts 1 and 5 was acquired by the researchers and surveys of operators in these 2 districts were conducted to investigate the performance of these respective materials. The following sections discuss the results of those surveys and data analysis. When reviewing and interpreting these results, the reader is urged to use caution. Small sample sizes, combined with apparent issues with staff understanding of terms used in the survey may have led to some questionable results.

Magnesium Chloride Results

Methodology

In order to obtain specific information pertaining to the use and performance of $MgCl_2$ in ITD Districts 2 and 3, an online survey was conducted. This survey is presented in Appendix A. A total of 11 responses were received from respondents in District 2. The following sections summarize the results obtained from the survey regarding $MgCl_2$ use.

Products, Form and Application Methods Used

Corrosion-inhibited liquid $MgCl_2$ was listed as the most commonly used product, with the percent of time used ranging from 15 percent to 100 percent. One response indicated that non-inhibited liquid $MgCl_2$ was used 100 percent of the time. Another response indicated that corrosion-inhibited solid $MgCl_2$ was used 30 percent of the time, with wet salt being used the remaining 70 percent of the time. The respondent that stated they used corrosion-inhibited liquid $MgCl_2$ 100 percent of the time also listed dry salt as being used. Additionally, one respondent that listed corrosion-inhibited liquid $MgCl_2$ as being used 50 percent of the time also listed using granular road salt.

In general, corrosion-inhibited liquid $MgCl_2$ was used by 7 respondents. The percentage of use of this product ranged from 15 to 100 percent. Other products listed as being used included non-inhibited liquid $MgCl_2$ (n=1), corrosion-inhibited solid $MgCl_2$ (n=1), granular salt (n=1), dry salt (n=1), and wet salt (n=1). All but 1 respondent indicated that they have been using $MgCl_2$ for more than 5 years.

The following vendors were listed as providing $MgCl_2$:

- Great Salt Lake Minerals Corp.
- Road Wise delivered from Spokane, WA (n =3)
- Road Wise delivered from Lewiston
- Road Wise, delivered from Hayden using Idaho Rail siding
- North American Salt from Salt Lake City, UT (n= 2)
- North American Salt from Ogden, UT (n=2)

$MgCl_2$ was listed by respondents as being using most commonly for anti-icing, but also for pre-wetting, deicing, deicing with liquid (n=2) and to “burn off frost and skim ice” (Figure 4).

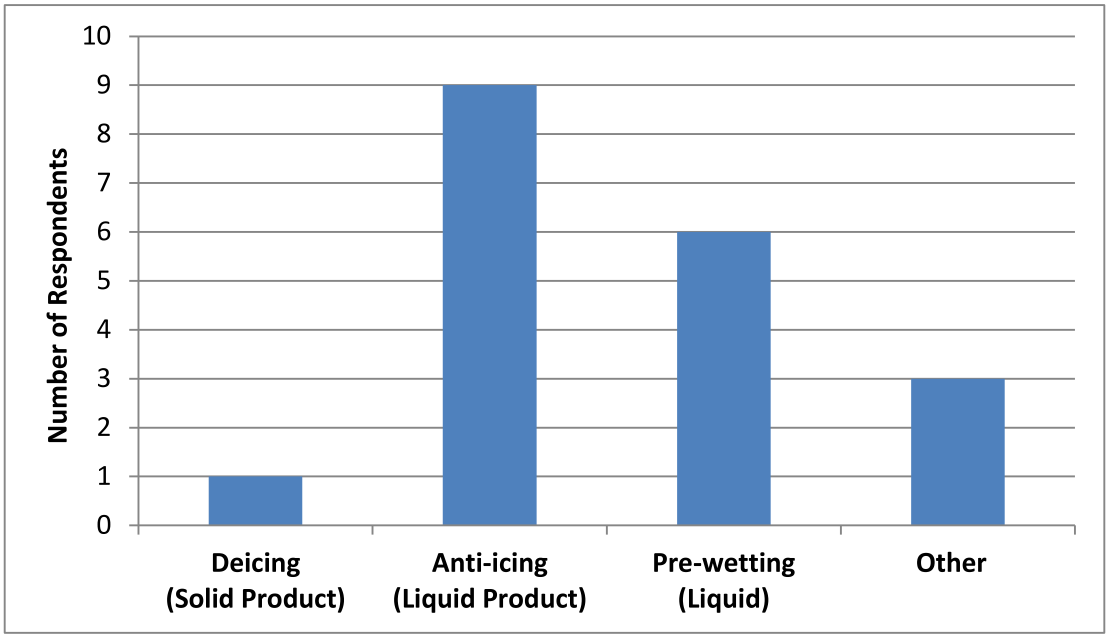


Figure 4. How Magnesium Chloride is Used by Survey Respondents.

Three respondents indicated they do not use $MgCl_2$ for pre-wetting. Respondents that indicated they use $MgCl_2$ for pre-wetting provided the following definitions for pre-wetting:

- “Apply ahead of snow storm to help keep snow from adhering to the surface, apply to prevent frost.”
- “We used pre-wetting at one time, application of Mag to sanding material. Our pumps in the saddle tanks have gone bad are not being replaced.”
- “Wet problem areas before a predicted storm event.”
- “Pre-wetting includes; applying liquid to road surface at start of storm and applying liquid to granular material during application.”
- “Applying $MgCl_2$ to the salt prior to application of salt to road.”
- “Shooting the sand with chemical deicer as it comes out of the sander chute.”

- "Pre wet the salt."

Based on the definitions of pre-wetting provided by the respondents, which are highly variable, some clarification may be needed on the definition of pre-wetting versus anti-icing among operators.

$MgCl_2$ Application Rates

The next portion of the survey sought information on the application rates used with magnesium chloride. The typical application rates cited by respondents are presented in Table 4.

Table 4. Typical $MgCl_2$ Application Rates Provided by Respondents.

Deicing (gplm)[1]	Anti-icing (gplm)	Pre-wetting	Other
35-45	25-35	25-35 gplm	40-50[2]
20-40	25-35	7-10[3]	-
30	-	-	-
30+	30	15-25 gplm	-
-	10-25	-	-
30-50	20-30	5-10 gpt[4]	-
30-60	15-30	5-7 gpt	-
-	25-35	6-10 gpt	-
40	30	10 pgt	-

1: Gallons per lane mile..
2: In extreme conditions.
3. no units provided.
4. Gallons per ton.

When asked if typical application rates used for $MgCl_2$ deviate from FHWA or ITD guidelines, the majority of responses was no, they do not, with one respondent not knowing. When asked if changes in specific parameters cause deviations in the typical application rates of $MgCl_2$, two respondents indicated they never deviate from their typical application rates. Figure 5 shows the frequency which different parameters cause deviations in typical application rates of $MgCl_2$. Precipitation type and amount was listed as causing deviations in typical application rates of $MgCl_2$ most frequently, followed by changes in pavement temperature and air temperature.

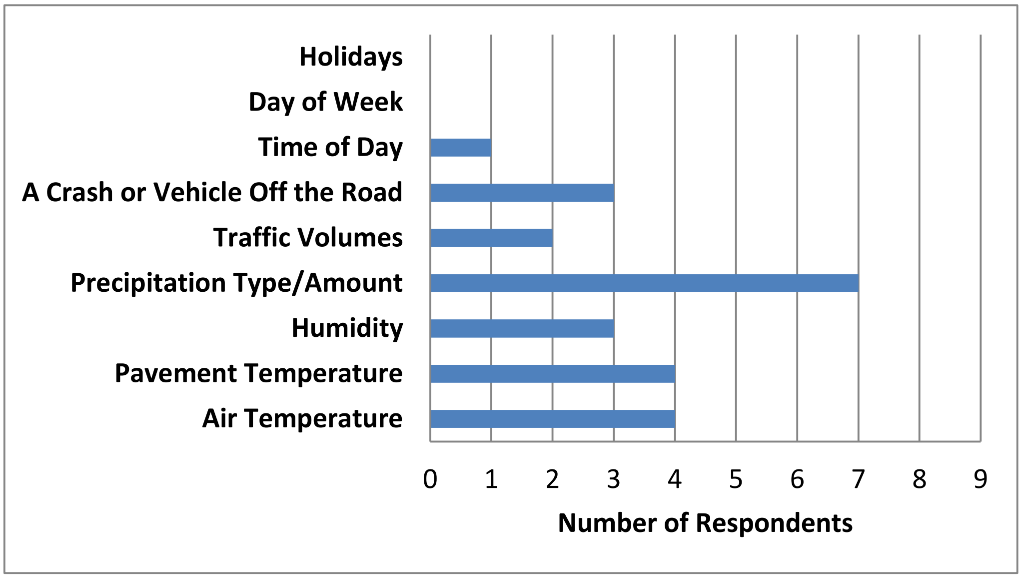


Figure 5. Parameters That Cause a Deviation in Typical Application Rates of $MgCl_2$.

Next, respondents were asked what may have led to changes in past application rates for $MgCl_2$. The majority of respondents said that this was determined based on experience (n=8), followed by ITD guidelines (n=3), and dilution rate (n=1). One respondent stated that they never change application rates.

Survey respondents were asked who determines what application rates for $MgCl_2$ are used, with responses shown in Figure 6. It is important to note that 7 of the 9 respondents listed multiple options for who makes the decision on $MgCl_2$ application rate.

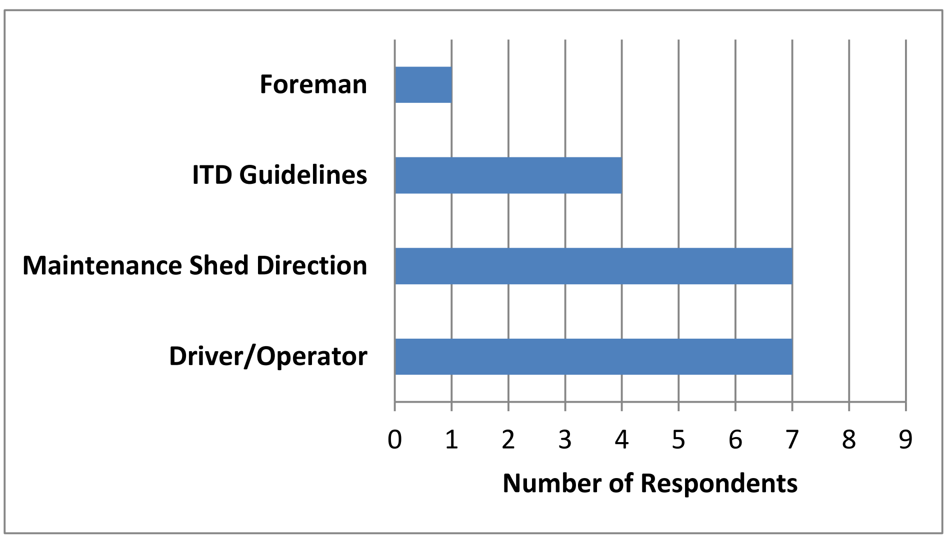


Figure 6. Who Determines the Application Rates of $MgCl_2$ Used.

Respondents were asked to comment on how application rates for $MgCl_2$ have changed over time. For deicing with $MgCl_2$, the majority of respondents (66.7 percent) stated that application rates have increased over time, with a smaller group (33.3 percent) stating that there has been no change in application rates over time. For anti-icing, 44.4 percent of respondents stated that there has been no change in application rates over time, while 33.3 percent said that anti-icing application rates have decreased and 22.2 percent said that rates have increased. For pre-wetting, the majority of respondents (57.7 percent) said that application rates for $MgCl_2$ have increased over time, with responses that pre-wetting rates have had no change (28.6 percent) or decreased (14.3 percent).

$MgCl_2$ Temperature Ranges for Application Type

Table 5 presents the results of responses for the temperature ranges that magnesium chloride is used at. As the table indicates, most operators applied $MgCl_2$ at temperatures between 20° and 32° F (7° C and 0°C) for deicing and anti-icing and between 15° and 32° F (9° C to 0° C) for prewetting.

Table 5. Typical Temperature Ranges That $MgCl_2$ is Applied.

Deicing (°F)	Anti-icing (°F)	Pre-wetting (°F)
0 to 32[1]	-10 to 32[1]	-10[1]
20 to 35 (l)	20 to 35 (l)	-
-	≤34 (l)	-
-	0 to 32 (l)	-
20 to 32 (l)	20 to 32 (l)	15 to 32 (l)[2]
>20 (l)	>20 (l)	>25 (l)
28 to 32 (l)	20 to 32 (l)	15 to 32 (l)
20 to 32[1]	20 to 32[1]	20 to 32[1]

1. Respondents did not state whether they apply as liquid or solid products.
2. Liquid applied to granular material.

District Lane-miles Maintained

Table 6 presents the results of responses for the number of lane miles being maintained through the use of $MgCl_2$. As the table indicates, responses to this question varied significantly, with the reported mileage ranging between approximately 200 and 2,600 (the 2,600 figure is assumed to be an error by the respondent and they meant to say 260). When identified, the portion of these lane miles that $MgCl_2$ was applied to over 50 percent.

Table 6. Lane-Miles Per District Maintained and Estimated Percent of Treatment Type.

Lane-miles maintained per district for WMO[1]	Deicing (%)	Anti-icing (%)	Pre-wetting (%)
268	Unknown	Unknown	Unknown
210	100	100	-
2600	-	-	-
618	51	51	70
242	100	100	100
540	80	80	80

[1] Winter Maintenance Operation

Cost of $MgCl_2$

Respondents were then asked if they could provide cost information for the $MgCl_2$ they used. Two respondents were able to provide cost data:

- $158.58 per ton (vendor Great Salt Lake Minerals Corp.)
- $114 delivered to Caldwell, ID (vendor North American Salt, Salt Lake City, UT)

When respondents were asked if they experienced any issues with storage and handling or costs to equipment (e.g., corrosion), one respondent replied yes, stating they have had "some corrosion with valves and snivies[2] wiring."

Amount of $MgCl_2$ Used in a Typical Winter Season

Respondents were asked for information regarding the amount of $MgCl_2$ they used during a typical winter season. Responses included:

- 800 to 900 tons (Note: As the solid magnesium chloride typically comes in the form of $MgCl_2.6H_2O$, a ton of the solid would make approximately 293 gallons of the 30% $MgCl_2$ brine. A ton of the liquid would be equivalent of approximately 188 gallons.)
- 385 tons, 72,000 gallons
- 18,000 to 24,000 gallons
- 450 tons
- 167.23 tons (liquid, 2010-2011)
- ~65,000 gallons
- 400,000 gallons

Respondents were then asked to comment on the typical road weather scenarios for winter maintenance in their district and the main challenges they face with the use of chemicals for snow and ice control. Responses included:

[2] Note: this response is verbatim from the survey participant and it is assumed that "snives" is a misspelling referring to a wiring harness manufactured by Viking-Cives.

- Cold spells for frost, rain and freeze, and heavy snowfall.
- Blowing drifting snow, snow pack. Difficult when we are not able to use the product when windy.
- We have a diverse geographical area from high desert conditions to high mountain passes creating a variety of scenarios including light snow and icing, heavy snow and cold, snow and high winds. Each area is treated differently.
- Typical is 2 to 3 day storm with up to 3 in. of snow a couple of times a season. Wind and drifting are main issues.
- When it is cold and then warms a little and snows. Main challenges are inaccurate forecasts.
- For snow and ice we strive to achieve bare pavement.

Respondents were asked if "trouble" spots, such as areas of frequent crashes or vehicles off the road, are identified at the District level and if so, are they treated differently. Two respondents replied no, while three replied yes and provided the following feedback:

- Depends on the area and level of the road.
- Trouble areas are generally the first ones treated.
- Bridge decks get pre-treated when possible.

Respondents were asked, once a crash has occurred or a vehicle has run-off-the-road, are additional resources sent to the site to apply more $MgCl_2$? If so, what are the typical application rates used? Four respondents replied no, additional resources are not sent to the site, and two provided the following feedback:

- It depends on the weather conditions; we don't just apply more Mag because of a crash.
- During storm events we have all resources on the road so no additional ones are available.

Additional comments on this topic included:

- Application of sanding material.
- Occasionally, if a truck is not already busy elsewhere we will apply 30 gallons per mile.

Performance of $MgCl_2$

Respondents were asked how they define the performance of $MgCl_2$. Three replied friction measurements, seven replied they use bare pavement, and seven replied they use melting ability. It is important to note that in call cases where friction measurements were listed as being used, bare pavement and melting ability were also cited.

Respondents were asked to compare $MgCl_2$ to other deicing, anti-icing and pre-wetting materials they have used during Winter Maintenance Operations. One respondent commented that it depends on the reason for application of $MgCl_2$, stating that $MgCl_2$ does not work well in snow floor situations, but it can work extremely well for black ice. User percentages of respondents' ratings for various aspects of $MgCl_2$ are presented in the table below (Table 7).

Table 7. Respondents Rating of $MgCl_2$ Based on Various Performance Aspects.

	1 (best) (%)	2 (%)	3 (%)	4 (%)	5 (worst) (%)
Performance	37.5	37.5	25	0	0
Ease of Use	25	50	25	0	0
Safety	37.5	25	25	12.5	0
Operator Satisfaction	25	75	0	0	0
Road User Satisfaction	42.9	28.6	0	28.6	0

Respondents were asked if they have any concerns about the use of $MgCl_2$ in winter maintenance operations. The issue of greatest concern to respondents was the potential corrosion to metal caused by $MgCl_2$ (Figure 7).

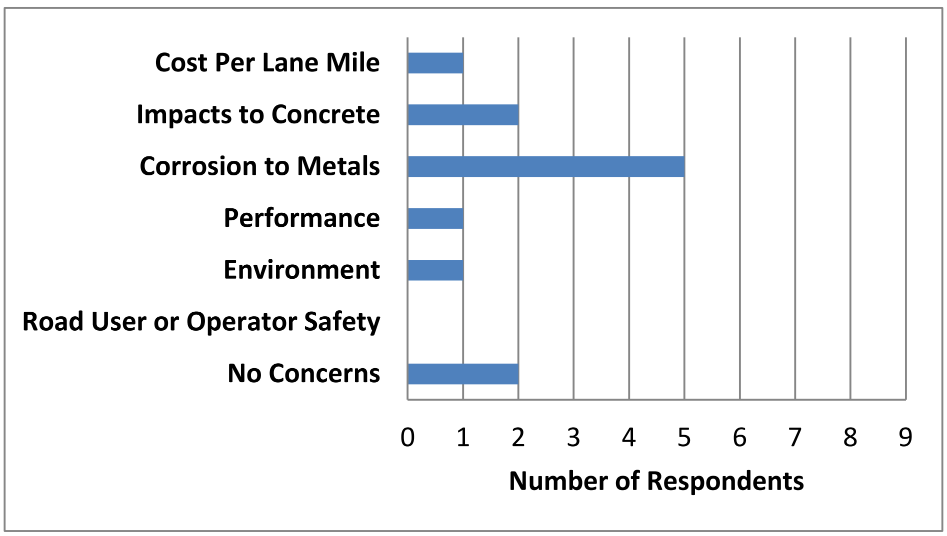


Figure 7. Concerns Associated With the Use of $MgCl_2$ in Winter Maintenance Operations

Finally, respondents were asked if, in their opinion, $MgCl_2$ should continue to be used in their district for winter highway maintenance for the next 10 years. All respondents replied yes, with one respondent adding the comment that, "If we can use more salt in addition to mag I think we would benefit."

Salt Brine

Methodology

In order to obtain specific information pertaining to the use and performance of salt brine in ITD Districts 1 and 5, an online survey was conducted and 12 responses were received. This survey is presented in Appendix B. The following sections summarize the results obtained from the survey regarding salt brine use.

Products, Form and Application Methods Used

Non-inhibited salt brine was listed as the most commonly used product by respondents, with the percent of time it is used ranging from 20 percent to 100 percent (20, 25, 40, 50, 99, 100 (%)) of the time. Two respondents indicated using corrosion-inhibited salt brine 80 and 100 percent of the time, respectively. One respondent indicated that they use corrosion-inhibited liquid $MgCl_2$ 100 percent of the time. The respondent that used non-inhibited salt brine 99 percent of the time also used KAc at an automated bridge deicing system, with estimated use at 1 percent. The respondent that used non-inhibited salt brine 40 percent of the time also stated that they used salt 60 percent of the time.

Non-inhibited salt brine was cited as being used by 9 respondents. Other products listed as being used include corrosion-inhibited salt brine (n=2), corrosion-inhibited liquid $MgCl_2$ (n=1), and other products such as salt (n=1) and KAc (n=1). The amount of time salt brine has been used ranged from less than 1 year to more than 5 years, with the majority of use being 3 to 5 years.

Three respondents stated that they make salt brine on site. One respondent stated that the brine was made in Pocatello and stored in a tank in their yard. Equipment used by 1 respondent was listed as the Varitech 1400-SS Brine Machine, where the location also has a salt tent, loader tractor and 20,000 gallons of storage. For respondents that do not make brine on site (n=8), the brine was made by:

- ITD in Coeur d'Alene (n=2)
- ITD in Pocatello (n=5), and now Soda Springs (n=2)
- Another district and hauled in.

Salt brine was listed as being using equally for anti-icing, deicing and pre-wetting (Figure 8). The respondent from the "Other" category indicated they no longer use salt brine.

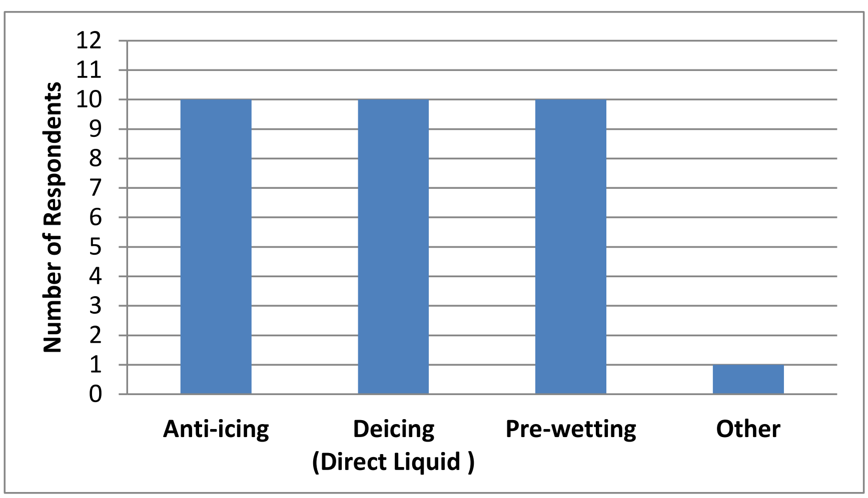


Figure 8. How Salt Brine is Used by Survey Respondents.

All respondents indicated that they use pre-wetting, with the exception of the one respondent that no longer uses salt brine. Definitions of pre-wetting provided by respondents include:

- “Pre wet salt as the sander is running it out the back at 18 gallons per ton (gpt).”
- “Apply before storm event.”
- “Adding salt solution to solid materials, anti-skid or solid salt, before application to the roadway.”
- “We use Magnesium Chloride to pre-wet anti-skid.”
- “Prewet salt to enhance brine making efficiencies.”
- “Applying solution to the road surface before a storm event, 72 hours or less.”
- “Injected into salt as it is dispensed.”
- “Brine sprayed onto the salt as it is falling from box to roadway.”
- “Spray on roadway ahead of storm event at about 25 gplm.”
- “Apply 20 to 30 gplm of brine to roadway before storm event.”

Based on the definitions of pre-wetting provided by the respondents, some clarification may be needed on the definition of pre-wetting versus anti-icing. Additional information would be useful on what is being pre-wet with what (liquid and/or solid, products, and application rates or percent added).

Salt Brine Application Rates

Table 8 presents the results of respondents regarding typical application rates for salt brine. For anti-icing, the application rate ranged between 15 and 50gplm. Application rates ranged between 5 and 40 gplm for pre-wetting, while “Other” application rates ranged from 25 to 35 gplm.

Table 8. Typical Application Rates for Salt Brine (NaCl, Liquid).

Anti-Icing (gplm)	Pre-Wetting	Other
20	18 (gpt)	-
32	-	32 (gplm, deicing)
≤40	5 to 8 (pglm)	25 to 35 (gplm)
35 to 50	5 to 7 (gpt)	-
40	40 (gplm)	-
20	14 (gpt)	-
15 to 18	35 to 40 (gplm)	-
20	20 (gplm)	-
≤15[1]	25 (gplm)	-
20 to 40	20 to 30 (gplm)	-

1. Depending on the storm.

When asked if typical application rates for salt brine deviated from FHWA or ITD guidelines the majority of responses was no, they do not, with two respondents stating that they never deviate from typical application rates of salt brine. When asked if changes in specific parameters cause deviations in typical application rates of salt brine, air temperature and pavement temperature, followed by humidity were listed more frequently (Figure 9). Respondent's comments from the "Other" category include:

- "We will vary application rates for noted conditions, but stay within the FHWA guidelines."
- "Ice build-up on road surface."

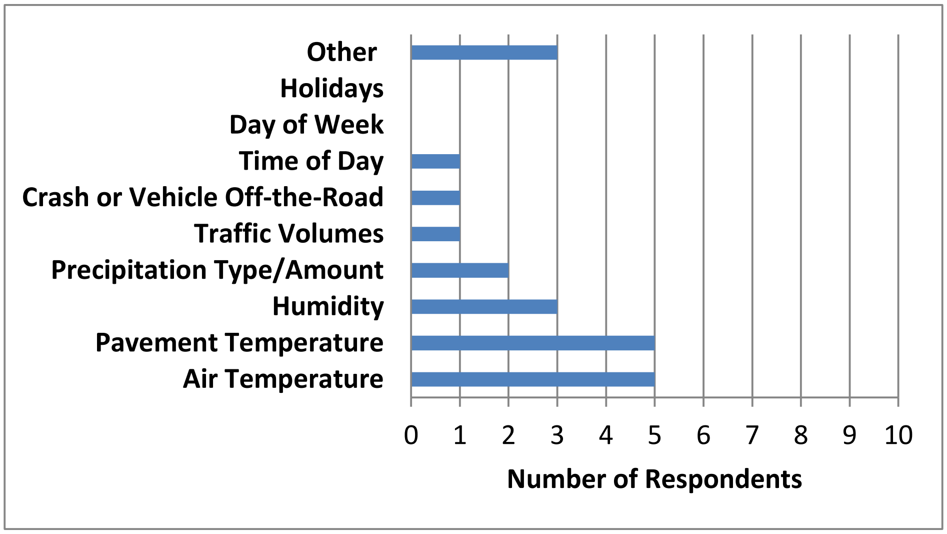


Figure 9. Parameters that Cause a Deviation in Typical Application Rates of Salt Brine.

A follow-up question asked respondents when application rates for salt brine are changed and what the decision was based on. The majority of respondents said experience (n=8) was the basis for changes, with ITD guidelines (n=2) and never changing application rates (n=2) also provided as responses. One comment made by a respondent indicated that the decision was based on experience and stated that "ITD has no real guidelines".

Survey respondents were asked who determines what application rates for salt brine are used, with responses shown in Figure 10. It is important to note that 7 of 12 respondents listed multiple options for who makes the decision on salt brine application rates.

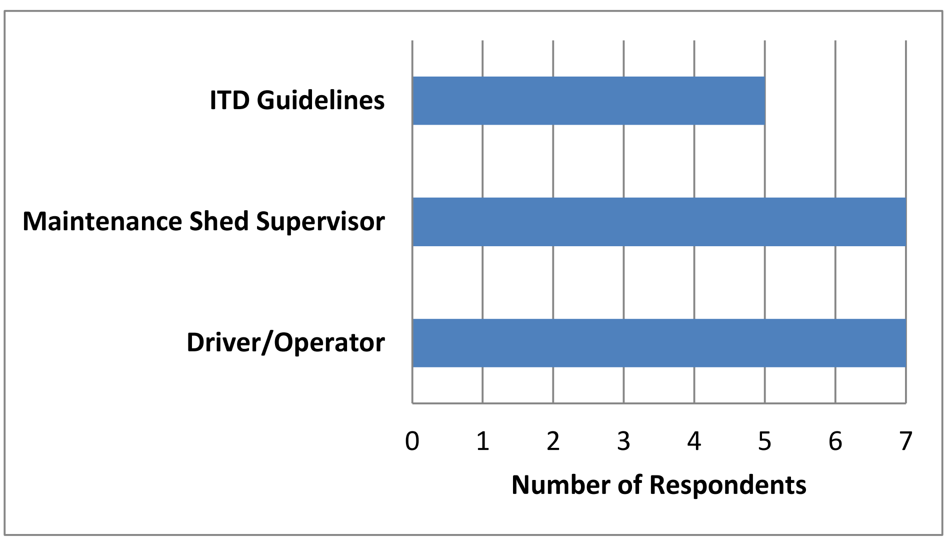


Figure 10. Who Determines the Application Rates for Salt Brine.

Respondents were asked to comment on how application rates for salt brine have changed over time. For anti-icing with salt brine, the majority of respondents (n = 8) stated that application rates have increased over time, with a smaller group (n = 3) saying there has been no change over time, and only 10 percent saying salt brine application rates have decreased over time. For pre-wetting, the majority of respondents (n = 9) stated that application rates have increased over time, with a minority (n = 3) saying pre-wetting application rates of salt brine have decreased over time. One respondent commented that for deicing, application rates have decreased over time.

Salt Brine Temperature Ranges for Application Type

Table 9 presents the results of typical temperature ranges for the application of salt brine. For both anti-icing and deicing, the application temperatures cited ranged between 15^o and 35^o F(-9^o and 2^o C). Pre-wetting applications were made at temperatures ranging from 15^o to 40^o F(-9^o and 4^o C).

Table 9. Typical Temperature Ranges for Salt Brine (NaCl, Liquid) Using Various Application Methods.

Anti-icing (°F)	Deicing (°F)	Pre-wetting (°F)
32 to 34	20 to 32	-
-[1]	15 to 30	15 to 20
20	20	15 to 20
15 to 30	15 to 30	-[2]
20 to 32	20 to 32	20 to 32
19 to 35	19 to 35	19 to 35
15 and rising	15 and rising	15 and rising
25 to 35	20 to 35	20 to 40

1. Trick question, before storm event, temperature is not a factor as during very cold conditions there are no storms so you do not use it, the road can be warm before a storm but you still use it because the road will cool during the storm event
2. Temperature does not dictate.

District Lane-miles Maintained with Salt Brine

Table 10 presents the results of responses for the number of lane miles being maintained through the use of salt brine. As the table indicates, responses to this question varied significantly, with the reported mileage ranging from between 200 and 2,000+. When identified, the portion of these lane miles that salt brine was applied to was over 40 percent, although in the case of pre-wetting, 1 respondent indicated it was used on only 20 percent of total lane miles.

Table 10. Lane-miles Per District Maintained for WMO and Estimated Percent of Treatment Type.

Lane-miles maintained per district for WMO	Anti-icing (%)	Deicing (%)	Pre-wetting (%)
172	50	50	-
1472	100	100	100
Over 2000	75	100	100
800	40	40	20
225	50	50 to 75	80
170	100	90	90
270	100	100	100
Not provided	50	40	60

Cost of Salt Brine

Respondents were asked to provide cost information for salt brine. Three respondents were able to provide cost data:

- $0.11 per gallon (2 respondents), use approximately 14,700 gallons per year.
- $0.19 per gallon

Issues With Salt Brine

Respondents were asked if they experienced any issues with storage, handling or costs to equipment (e.g., corrosion) from the use of salt brine. Five respondents replied yes and provided the following comments:

- “If you don’t clean the trucks they start to show corrosion.”
- “Vehicles must be washed on regular basis.”
- “There are transportation costs that are included in the noted price, we have no cost for water, corrosion costs exist but it is less than anti-skid. Salt residue is easier to remove than anti-skid, anti-skid is also abrasive on vehicle parts, anti-skid collects in difficult to reach areas and holds salt and moisture that results in greater corrosion.”
- “An algae that builds and plugs the applicator screens. In general the corrosive nature of the product and the lack of keeping things washed sufficiently.”
- “Problems with pumps binding because of corrosion.”

Amount of Salt Brine Used in a Typical Season

Respondents were asked the amount of salt bring used during a typical winter season, with the following responses provided:

- 3,000,000 gallons
- 2,000,000 gallons
- 2,500,000 gallons
- 18,000, 3 years ago, to over 75,000 gallons last year.
- 73,000 gallons
- 828,240 gallons
- Each year the total keeps going up, depending on the winter and the application to wider coverages.

Respondents were asked to comment on the typical road weather scenarios for winter highway maintenance in their district and the main challenges they face with the use of chemicals for snow and ice control. Responses included:

- Granular salt for snow floor situations, salt brine for deicing, anti-icing for black ice.
- Ice, slush, drifting snow, heavy traffic. The greatest challenge is getting the work done safely.
- Snow and black ice.
- Fog, wind, and ice conditions by our rivers. High winds and heavy snow in the mountain areas.
- We have a lot of wind. You must be careful not to apply brine when wind is an issue.
- Sometimes it is too cold for brine and sand is used.
- Cold with ice on roadway. We have problems with when to quit using chemical because of temperatures.

Respondents were asked if “trouble” spots, such as areas of frequent crashes or vehicles off the road, are identified at the District level and if so, are they treated differently. There were mixed responses of yes and no to this question, with respondent comments provided below.

For those respondents who replied in the affirmative:

- We treat bridges and ramps first.
- As best we can.
- They are identified, but have no idea if they are treated differently.

For those respondents who replied in the negative:

- Maintained by the area foreman.
- No, roadways are treated for full length.
- Not so much at the district level.

Respondents were then asked, once a crash has occurred or a vehicle has runoff the road, are additional resources sent to the site to apply more salt brine and if so, what typical application rates are used? For those who replied in the affirmative:

- We will apply 20 gplm several times.
- Apply at same rate, problems possibly occur from more moisture causing refreeze.
- Only if additional units are close by and their own areas are in good shape, but no salt brine.
- According to guidelines.
- If requested by law enforcement.

For those who replied in the negative:

- No, usually we will apply solid salt for traction improvement at 100 to 150 lb. per lane mile.
- We will not put any extra because it will cause the freeze point to rise.

Other comments provided include:

- At times law enforcement will request additional products, to help or appear to help at those locations.
- If available, they are at 20 gplm.

Salt Brine Performance

Respondents were asked how they define the performance of salt brine, with feedback indicating friction (n=3), bare pavement (n=3), and melting ability (n=4). In most cases more than one parameter to define product performance was selected.

Respondents were also asked to compare salt brine to other anti-icing, deicing and pre-wetting materials they have used during winter maintenance operations (Table 11). Two respondents provided the following comments:

- Easy to wash off vehicles.
- Relative to what? On a cost basis it is the best overall for our weather environment in D1 (District 1). Other products can work better at different criteria, but are too costly for our budget limitations.

Table 11. Respondents Rating of Salt Brine (NaCl, Liquid) Based on Performance Aspects.

	1 (best) %	2 %	3 %	4 %	5 (worst) %
Performance	44.4	22.2	22.2	11.1	0
Ease of Use	77.8	11.1	0	11.1	0
Safety	55.6	22.2	11.1	11.1	0
Operator Satisfaction	55.6	22.2	11.1	11.1	0
Road User Satisfaction	33.3	11.1	44.4	11.1	0

Respondents were asked if they have any concerns about the use of salt brine in winter maintenance operations. The majority of respondents had no concerns with the use of salt brine, with impacts to concrete and corrosion to metal being of concern to a small group of respondents (Figure 11).

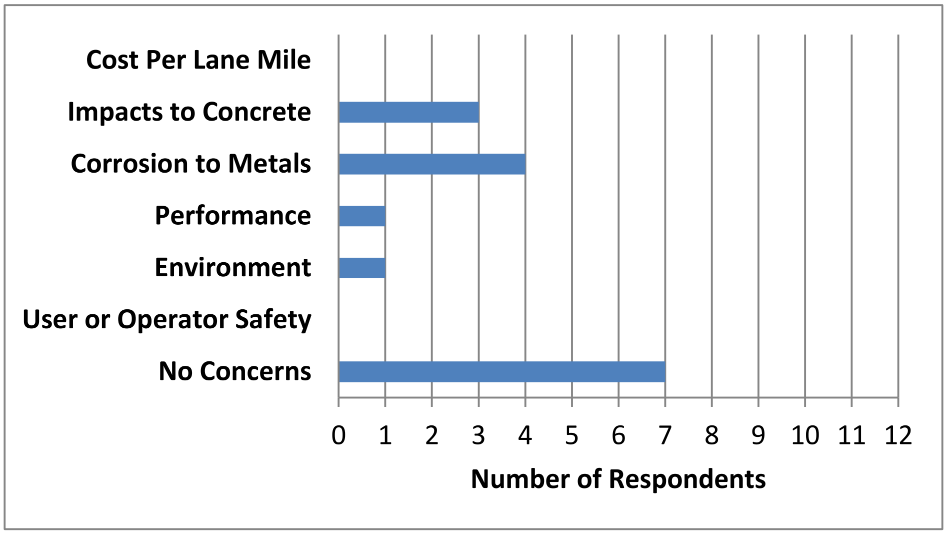


Figure 11. Concerns Associated With the Use of Salt Brine in WMO.

Respondents were asked if in their opinion salt brine should continue to be used in their district for winter highway maintenance for the next 10 years. All respondents replied yes, with one replying no and one comment made that it is too costly at this time.

Chapter Summary

This chapter has provided the results of surveys conducted with maintenance operators in different ITD districts regarding the use of $MgCl_2$ and salt brine. Eleven respondents from District 2 provided feedback on $MgCl_2$, indicating the product was most commonly used in anti-icing operations (liquid form). Application rates ranged from 10 to 40gplm, depending on the specific use (anti-icing, deicing or pre-wetting). Precipitation type and amount were the most common factors in deviating from normal application rates. Applications of $MgCl_2$ was cited as increasing over time, with typical application temperatures ranging between 15^o and 32^o F. $MgCl_2$ was indicated as being applied to at least 50 percent of the lane miles being maintained in the district.

A total of 12 respondents from Districts 1 and 5 provided information and feedback on salt brine usage. Salt brine was equally used in anti-icing, deicing and pre-wetting operations, with application rates ranging from 5 to 40gplm. Pavement and air temperature were the most common reasons for deviations from typical application rates. The typical temperature range for salt brine applications was between 15^o and 40^o F. Salt brine was indicated as being applied to at least 40 percent of the lane miles being maintained in the district.

Chapter 4
Evaluation of Snow and Ice Control Materials for Highway Maintenance Operations

This chapter presents a comprehensive and quantitative evaluation of snow and ice control materials currently used by various ITD districts for highway maintenance operations, including rock salts (mainly solid sodium chloride), IceSlicer products (solid NaCl with trace amounts of other chlorides), NaCl brines, a corrosion-inhibited $MgCl_2$ brine, and sand-salt mixtures. This case study is the first attempt to incorporate the most up-to-date information into a multi-criteria decision making framework for the data-driven evaluation of various snow and ice control materials used by a maintenance agency.

Previous research has demonstrated a framework to enable "a holistic approach to anti-icer procurement or design" and "to strike the right balance in meeting multiple goals of winter maintenance, including safety, mobility, environmental stewardship, infrastructure preservation, and economics".(131) In this ITD case study, the researchers further extended this framework for the evaluation of products beyond anti-icers. Instead, chemicals in liquid or solid forms and abrasive were assessed under the same framework. Other improvements have been made to advance the quantification of performance and risks of various products as well. For instance, friction coefficient measurements on the pavement before and after the anti-icing and deicing operations have been incorporated into the characterization of product performance. The corrosive effects of products on rebars and dowel bars have been incorporated into the characterization of risks, along with the damaging effects of products to asphalt (and concrete) pavements. Finally, for the first time, the environmental risks of various products have been quantified to the best possible extent, taking into account average aquatic toxicity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), emission factor for air quality impairment, and chloride emissions into the natural environment (soil, vegetation, surface water, groundwater, etc.).

Methodology

In this research, a total of 13 rock salts, 3 IceSlicer products, 8 NaCl brines, a corrosion-inhibited $MgCl_2$ brine, and two sand-salt (3:1 by weight) mixtures were examined. Samples of these 27 products were samples provided by various ITD districts to the research team for laboratory testing. In addition, the rock salt sample from Boise, ID was also made into a 23 percent salt brine and a 30 percent salt brine for laboratory testing and thus included in the comprehensive evaluation. Note that typically 23 percent salt brines are used for snow and ice control and the inclusion of a 30 percent brine into evaluation simply aims to provide additional insight into whether a saturated brine would provide any benefit.

The following sections briefly describe the laboratory tests conducted on the select ITD materials for snow and ice control. For simplicity, the term "deicer" is used from this point on to refer to the 27 aforementioned products.

Differential Scanning Calorimetry Thermograms

The performance characteristics of the 27 ITD deicers were assessed by measuring their Differential Scanning Calorimetry (DSC) thermogram with a TA Instruments Q200 apparatus. As the DSC provides fingerprint type information on the thermal properties of the products, the DSC thermograms were used as a tool to identify "outliers" in each category of deicers. In light of the substantial similarities between most products, the number of products for in-depth investigation was limited to a few in each category (as detailed later in this chapter). This approach offered the most flexibility and efficiency for comparing various properties of select deicers and allowed the analysis of numerous similar products within a short timeframe. The use of DSC to quantify deicer or anti-icer performance is relatively new and all solid products were made into a liquid at 23 percent by weight. (132) The thermograms were measured in the temperature range of 25° to -60° C (77° to -76° F) with a cooling/heating rate of 2° C (3.6° F) per minute. The liquid deicer was first diluted using the liquid deicer to deionized water volume ratio of 1:2. Subsequently, approximately 10 µL samples were pipetted into an aluminum sample pan and hermetically sealed for DSC measurements. At least three samples were run for each anti-icer to minimize data variability. The first peak at the warmer end of the heating cycle thermogram was used to derive the characteristic temperature of the liquid deicer tested (Tc), which along with the enthalpy of fusion (H, integrated surface area of the peak) are used to predict the ice melting capacity (IMC) of the liquid deicer at 60 minutes of application under 30° F (-1.1° C), using the following empirical equation (132):

$$IMC_{30^\circ F}(\%, \frac{\text{mL melt}}{\text{mL applied}}) = [-0.02265T_c + 1.965\log(\Delta H) + 0.03285t - 2.1761]/0.9 \cdot 100$$

$$(R^2 = 0.94)$$

Where:

IMC = Amount of ice melted per 0.9 ml (1 g) brine applied (%), assumed to be zero if predicted to be negative

ΔH = 345 J/g minus enthalpy of fusion (H in J/g) of characteristic peak from DSC (J/g)

Tc = characteristic temperature from DSC (°F)

t = time between 10 and 60 (minutes)

Figure 12. Predictive equation to derive ice melt from DSC parameters.

SHRP Ice Melting Test at 15°F

Laboratory measurements of ice melting capacity of various deicers were conducted following the SHRP (Strategic Highway Research Program) H205.1 and H205.2 test methods.(133) The SHRP H205.1 test measures the ice melting capacity of solid deicer pellets spread randomly across an ice surface of uniform thickness. The results of the test provide a measurement of the ice melting capacity of the deicer relative to the generated brine, or melted ice. The process was completed at -9.4° C (15° F). For liquid deicing solutions (SHRP H205.2), similar procedures were followed.(133)

PNS/NACE Corrosion Test

Deicer products have been reported to pose a significant risk to bare metals used in vehicles and the transportation infrastructure.(77) As such, the corrosive effects of various deicers to bare steel were tested following the NACE Standard TM0169-95 as modified by the PNS. It measures the weight loss of carbon steel coupon samples that are cyclically immersed in deicer solutions and reports the Percent Corrosion Rate (PCR) to indicate the corrosivity of the deicer solution relative to solid salt and deionized water. The metal coupons were purchased from Ad-Tek, Inc., and were 0.5 in flat steel washers (0.38 in. x 0.56 in. x 0.11 in. or 9.7 mm x 14.2 mm x 2.8 mm) with an average density of 7.85 g/cm^3. The metal coupons were cleaned by placing in 1+1 hydrochloric acid for 2-3 minutes. The coupons were rinsed in tap water, then de-ionized water, then wiped dry and placed in chloroform. The coupons were then placed in the fume hood and were allowed to dry for 15 minutes. The coupons were then weighed and placed on the corrosion testing machine (Corrosion Testing Machine CTM10- 10/50, AD-TEK, Inc.). The corrosion testing machine cyclically lowered the 3 metal coupons for 10 minutes into a 3 percent deicer solution and then raised the metal coupons into ambient air for 50 minutes. This cycle continued every hour for 72 hours. The solid deicers were 3 percent weight-to-volume solutions were made and for liquid deicers were 3 percent volume-to-volume solutions. The final weight of the coupons was recorded after 72 hours of cyclic testing and cleaning.

SHRP Test of Diluted Deicers on Freeze-Thaw Damage of PCC

Deicer products have been reported to pose a significant risk to PCC used in the transportation infrastructure.(77) The risks of diluted liquid deicers on concrete were assessed by conducting freeze-thaw tests of PCC samples in the presence of diluted deicers, following the SHRP H205.8 test method with minor modifications. (133) The test evaluates the combined effects of liquid chemicals and freeze-thaw cycling on the structural integrity of specimens of non-air-entrained concrete. Concrete samples were made in 2 in. diameter x 4 in. length (51 mm x 102 mm) poly (vinyl chloride) piping with a volume of 206 cm^3. The concrete mix design had a water-to-cement ratio of 0.55, a slump of 1 in. (25 mm) and air content of 2.5 percent. Samples were cured in the mold in the first 24 hours before being demolded and cured in open air for another 27 days with a relative humidity of 25±5 percent, the average 28-day compressive strength of 3 test cylinders was 4,933 psi (34.0 MPa). The concrete sampled were then further cured in a water bath at 68 ° F (20° C) for 7 days then at 140 ° F (60º C) for 24 hours. The average compressive strength increased to 7,474 psi (51.5 MPa). Before immersion in anti-icer solution, the concrete samples were cut to a final length of 3 in. (76 mm). The dry weight of each sample was recorded before placing it on a sponge inside a dish containing 310 mL of diluted (3 percent) anti-icer solution. The dish was covered in plastic wrap to press the concrete samples into the sponge. Three concrete specimens were tested in each anti-icer solution. There were 2 controls: 1) a 3 percent NaCl solution and 2) de-ionized water. A thermocouple was embedded in one of the control concrete samples to monitor temperatures during freeze-thaw cycling. The sealed dishes were placed in the freezer for 16 to 18 hours at -17.8 ± 2.7° C (0 ± 4.9° F), then placed in the laboratory environment at 23.0 ± 1.7° C (73.4 ± 3° F) for 6 to 8 hours. This cycle was repeated for 10 times. The test specimens were then removed from the dish and rinsed under running water to remove any scaled-off material. The specimens were air-dried overnight before the final weight of each was recorded.

Results

The following sections will provide the detailed analysis of the 27 ITD deicers, with sand also included in the analysis as a useful benchmark. The analysis will examine three aspects of using deicers, i.e., cost, performance (mainly for anti-icing and deicing), and risks. Subsequently, these data will be normalized between 0 and 100 and then used to calculate a "composite index" for each product. This index will be very valuable for the comprehensive evaluation of available options in the snow and ice control materials and for the collaborative decision-making by maintenance agencies such as ITD.

Based on the DSC measurements (parameters of T_c and H_c), three salts (American Falls (AF) Blackfoot (BLKFT), and Firth) were identified as outliers whereas the remaining 10 salts were considered "regular salt" (CW (ITD label with no detailed location), Kiln Salt Pocatello, Kiln Salt Mn St. (ITD label with no detailed location), Road Salt with Anti-Caking, Road Salt Bannock Creek, Road Salt Pocatello, Downey, Malad, McCammon, and Boise). Three IceSlicer products were individually tested, i.e., AF Slicer, IceSlicer BLKFT, and IceSlicer Malad, even though the last two had a similar DSC fingerprint. The DSC data also suggested 2 salt brines (BLKFT Brine and Pocatello Brine) as outliers whereas the remaining 7 brines were considered "regular brine" (AF Brine, Downey Brine, Malad Brine, McCammon Brine, Tank 5, CW Brine, and the 23 percent brine made from the Boise Salt). A 30 percent brine made from the Boise Salt was also included in some of the testing, along with a 30 percent corrosion-inhibited magnesium chloride liquid deicer from Boise. Furthermore, two sand-salt mixtures were tested, with one sampled from Boise and the other from the Simco stockpile. Also included in the quantitative evaluation was sand without any salt mixed, even though the analysis was purely based on conceptual interpretation instead of actual testing.

Relative Cost of ITD Deicers

The choice of different deicer products for winter highway operations is expected to significantly affect the overall cost of such activities, assuming that different products were used to achieve a similar level of service (LOS). It is well recognized that the direct costs include those for materials (storage cost, cost per ton, or per lane mile, or per storm), equipment (engine hours, fuel costs, etc.), and staffing (wages and benefits, overtime/standby time, training costs, etc.). In addition, the indirect costs of deicers mainly include those associated with negative impacts to motor vehicles, transportation infrastructure, and the natural environment.

Currently most agencies (including ITD) do not have accurate or systematic records of the cost items associated with specific winter maintenance products. In this context, the cost of deicers examined will be presented by deicer category, instead of being product specific. Fitch et al. (2013) reported the cost of using chemicals for highway winter operations, with solid salts at $3,149 per typical storm and salt brine at $3,343 per typical storm.(134). According to a recent survey of the winter road maintenance community, the vast majority of survey respondents reports a *typical* winter storm to feature a moderate pavement temperature (15 ºF to 25ºF) or warmer and a moderate snow precipitation intensity (1/2 to 2 inches per hour) or lighter. From the ITD survey results, the weighted average application rate for both the $MgCl_2$ liquid deicer and (23% NaCl) salt brines was approximately 28 gallons per lane mile and their average material cost can be estimated to be $0.72/gallon and $0.14/gallon respectively.

In this study, the cost of using various materials for highway snow and ice control was estimated by examining the documented labor, equipment and materials expenditures for select study routes. The annual (direct) cost per lane mile was estimated to average $123, $121, $263, $110, and $116 when using salt, salt brine, corrosion-inhibited magnesium chloride ($MgCl_2$) liquid deicer, sand, and sand-salt mixture on Idaho highways, respectively. If a highway segment relies solely on the use of sand to provide a reasonable LOS, it would require more frequent applications than those reported by ITD. Assuming the cost of additional applications and sand cleanup is three times of the recorded cost, the annual cost can be estimated to average $440 per lane mile. For the sand-salt (3:1) mixtures, their annual cost can be estimated by the weighted average of using salt or sand alone, i.e., $361. Assuming the cost of materials is one third of the total cost, one can derive the annual cost of using 30% NaCl brine from that of using 23% NaCl brine, i.e., $133 per lane mile.

Performance Characteristics of ITD Deicers

This section is devoted to the quantitative analysis of performance characteristics of various ITD deicers, focusing on the following 5 parameters:

1. Characteristic temperature measured from the DSC thermogram, T_c.
2. Effective temperature estimated from the eutectic curve of each product, T_e.
3. Ice melting capacity predicted from the DSC thermogram, $IMC_{30ºF, 60min}$.
4. Measured IMC, $IMC_{15ºF, 60min}$, as shown in Figure 13;
5. Friction coefficient averaged from field measurements on the treated asphalt pavements, f_c.

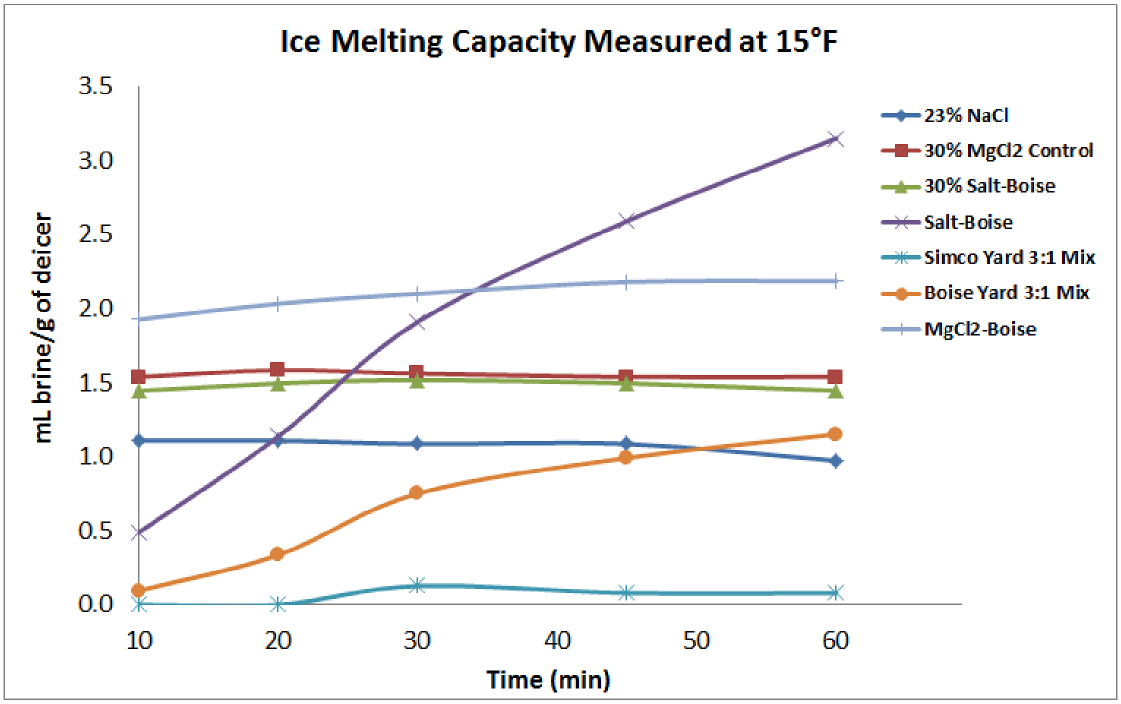


Figure 13. Ice Melting Behavior of Select ITD Deicers at 15°F.

As indicated in Figure 13, the data of most solid salts and most salt brines were grouped under "regular salt" and "regular brine" due to the great similarity within each group. The data illustrate the overall comparison in the performance of the select ITD deicers (along with sand). The lower the T_c and T_e, the more likely the deicer would work effectively under colder temperatures. The higher the IMC values are, the more powerful the deicer. The higher the f_c value, the more safety benefits the deicers would bring to asphalt pavement surface during snowy weather. Table 12 shows that among the ITD deicers, the $MgCl_2$ liquid deicer featured the lowest T_c and T_e values and the highest predicted $IMC_{30ºF,\ 60min}$, whereas the solid salts featured the highest $IMC_{15ºF,\ 60min}$ and friction coefficient values.

Note that for measuring the T_c and $IMC_{30ºF,\ 60min}$, the solids (salts, IceSlicers, sand-salt mixtures) were first made into a 23 weight percent liquid solution before their further dilution for DSC measurements. The solids, however, were not made into liquid form before measuring their $IMC_{15ºF,\ 60min}$. For estimating the T_e from the eutectic curve of each product, the following equation was used to assume a weighted average of freezing point temperature from three dilution scenarios:

$$T_e = (3\times FP_{25\%AAC} + 2\times FP_{50\%AAC} + FP_{AAC})/6$$

Where:

T_e = effective temperature estimated from the eutectic curve (ºF)

FP = freezing point temperature

AAC = as-applied concentration

Figure 14. Equation to Estimate the Effective Temperature from Eutectic Curve

The eutectic curve of the 30 percent $MgCl_2$ liquid deicer was provided by ITD for analysis, whereas that of salt brines was adopted from a web source.(135) For solid salt, both $FP_{50\%AAC}$ and FP_{AAC} was assumed to be 32º F since both concentrations exceeded the saturation point of NaCl brine, whereas $FP_{25\%AAC}$ (i.e., FP of 25 percent NaCl solution) was assumed to be 13.3º F. For sand, its T_c and T_e were both assumed to be 34º F. For the two sand-salt mixtures, their T_e was assumed to be equal to their T_c. Finally, the *fc* value of NaCl brines and 30 percent $MgCl_2$ liquid deicer was averaged from friction coefficient measurements on asphalt pavement during field operational tests conducted in Ohio in March 2013, with simulated traffic. Specifically, the *fc* value of each was averaged between anti-icing (5 measurements at 7 hours after anti-icer application and then at 30 minutes after snow being trafficked) and deicing scenarios (5 measurements at 30 minutes and then at 60 minutes after deicer application). The *fc* value of solid salts, in contrast, was only averaged from friction coefficient measurements at the two stages of deicer scenario. The *fc* value of sand treated pavement was assumed to be 50 percent that of the dry pavement. Table 12 also indicated that there is no significant benefit in making the salt into a 30 percent brine, relative to the regular 23 percent brine, as the latter features similar performance characteristics.

Table 12. Performance Characteristics of the ITD Deicers and Sand.

	T_c from DSC (°F)	T_e from Eutectic Curve (°F)	$IMC_{30°F, 60 min}$ (ml/ml, by Liquid DSC)	$IMC_{15°F, 60 min}$ (ml/g, by As-Received Deicer)	Average Friction Coefficient, f_c
AF Salt	21.7	22.7	3.55	3.15	0.33
BLKFT Salt	23.8	22.7	3.46		
Firth Salt	24.4	22.7	3.19		
Regular Salt	23.3±0.3	22.7	3.2±0.2		
AF Slicer	25.2	22.7	3.26	3.15	0.33
Ice Slicer BLKFT	24.7	22.7	2.87		
Ice Slicer Malad	24.8	22.7	2.85		
BLKFT Brine	23.2	18.1	3.23	1.1	0.32
Pocatello Brine	22	18.1	3.63		
Regular Brine	22.6±0.3	18.1	3.4±0.1		
30% Boise Salt Brine	23.8	21.2	3.4	1.45	0.32
30% $MgCl_2$ Boise	3.4	7	4.14	2.19	0.3
Sand-Salt Boise	26.9	26.9	2.19	1.15	0.33
Sand-Salt Simco	31.8	31.8	0	0.08	
Sand	34	34	0	0	0.34

Relative Risk of ITD Deicers on Infrastructures and Vehicles

This section is devoted to the quantitative analysis of how various ITD deicers affect the motor vehicles and transportation infrastructure, as characterized by the following 5 parameters:

1. Corrosion to bare carbon steel, in terms of *PCR* measured by the PNS/NACE test.
2. Average corrosion rate of rebar (steel bars in bridge or pavement concrete mixes) and dowel bar (MMFX and stainless steel tube in pavement concrete) after 254 days of continuous or cyclic immersion in deicers at 31 percent of as-applied concentration, i_{corr} (63)
3. Damage to non-air-entrained PCC by the combined action of diluted deicer (3 percent of as-applied concentration) and 10 freeze-thaw cycles, in terms of weight loss, *WLd*;
4. Damage to air-entrained PCC concrete by the combined action of concentrated deicer (14 percent $MgCl_2$ and 18 percent NaCl) and 300 freeze-thaw cycles, in terms of loss in the dynamic modulus of elasticity, *MLc* (74); and
5. Loss in the Marshall stability of asphalt concrete in the presence of deicer solution, *MSL* (136).

The data shown in Table 13 illustrate the overall risks to vehicles and infrastructure associated with the use of the select ITD deicers (along with sand). The lower the *PCR* and i_{corr}, the less likely the deicer would cause corrosion to the bare steel or bars embedded in concrete. The lower the *WLd* and *MLc* values, the less negative impacts the deicer would likely cause to PCC that is a crucial construction material for bridges and other infrastructure. The lower the *MSL* values, the less negative impacts the deicer would likely cause to asphalt concrete that is the most common material used for pavement infrastructure. Table 13 shows that among the ITD deicers, the $MgCl_2$ liquid deicer featured the lowest *PCR, WLd* and *MSL* values, whereas the sand-salt mixtures featured the lowest i_{corr} and *MLc* values.

Table 13. Vehicle and Infrastructure Implications of ITD Deicers and Sand.

	Corrosion to Bare Steel, *PCR*	Corrosion Rate of Rebar or Dowel Bar, i_{corr} ($\mu A/cm^2$)	Damage to Concrete, *WLd* (%)	Damage to Concrete, *MLc* (%)	Effect on Asphalt Pavement, *MSL* (%)
AF Salt	81.8	2.09	10.4	5	13.7
BLKFT Salt	70.7		21.1		
Firth Salt	73.6		39.4		
Regular Salt	86.3		34.2		
AF Slicer	72.6	2.09	35.4	5	13.7
Ice Slicer BLKFT	78.3		19.5		
Ice Slicer Malad	76.5		37.3		
BLKFT Brine	84.6	2.01	15.7	5	10.3
Pocatello Brine	85.8		18.2		
Regular Brine	85.8		18.2		
30% Boise Salt Brine	85.8	2.26	17.5	5	10.3
30% $MgCl_2$ Boise	16	0.95	0.2	50	1.4
Sand-Salt Boise	84.9	0.52	35.4	1.25	11.2
Sand-Salt Simco	103.3	0.52	7.6		
Sand	0	0	1.8	0	15.5

Note that for measuring the *PCR*, the solids (salts, IceSlicers, sand-salt mixtures) were made into a 3 percent weight-to-volume solution whereas the liquid deicers were made into 3 percent volume-to-volume solutions. For sand, its *PCR*, i_{corr} and *MLc* were assumed to be zero and its *WLd* and *MSL* were assumed to be equal to that of deionized water. For the 2 sand-salt mixtures, their i_{corr} was assumed to be 25 percent that of salt since they contain 25 percent salt and 75 percent sand by weight.(66) For the 30 percent NaCl brine, its *WLd* value was interpolated from that of solid salt and 23 percent NaCl brine. In light of the lack of available data, the *MLc* value of all solid salts and salt brines were assumed to be equal to that of 18 percent NaCl, whereas the *MLc* value of the 30 percent $MgCl_2$ liquid deicer was assumed to be equal to that of 14 percent $MgCl_2$.(74) Finally, the *MSL* value of salt brines, sand-salt mixtures, and solid salts was assumed to equal to that of 1M NaCl, 3M NaCl and 4M NaCl solutions, respectively, whereas the *MSL* value of the 30 percent $MgCl_2$ liquid deicer was assumed to be that of 1M $CaCl_2$ solution.(136)

Relative Risk of ITD Deicers on the Natural Environment

This section is devoted to the quantitative analysis of how various ITD deicers affect the natural environment, as characterized by the following 5 parameters:

1. Average aquatic toxicity (*LCIC*).
2. Chemical oxygen demand (*COD).*
3. Biochemical oxygen demand (*BOD).*
4. Risk to air quality, in terms of average aggregate emission factor (EF_a), where *EF* was "calculated by dividing the total flux of PM perpendicular to the road by the number of vehicles passing the (sampling) tower".(137)
5. Chloride anion emission (*ClE*), which was estimated for the amount released per lane mile "during a typical storm in the piedmont region of Virginia".(**Error! Bookmark not defined.**)

Note that chloride anions are not degradable in the environment and their accumulation over time thus poses a significant risk not only to vehicles and infrastructure but also to soil, vegetation, wildlife habitat, and possibly human health.

The data shown in Table 14 illustrate the overall risks to the natural environment associated with the use of the select ITD deicers (along with sand). The higher the *LCIC*, the less likely the deicer would pose toxicological effects to aquatic species. The lower the *COD* and *BOD*, the less likely the deicer would lead to significant reduction in the concentration of dissolved oxygen in the surrounding environment such as receiving soil and water bodies. Finally, the *EF* and *ClE* indicate the air quality risk and the amount of chloride emissions into the environment, respectively, and lower values are desirable. Table 15 shows that among the ITD deicers, the salt brines featured the lowest *COD*, *BOD*, and *EF* values, the magnesium chloride brine featured the lowest *ClE* values, whereas the sand-salt mixtures featured the highest *LCIC* values.

Table 14. Risk of ITD Deicers and Sand On the Natural Environment.

	Average Aquatic Toxicity (g/L)	Chemical Oxygen Demand (mg/L)	Biochemical Oxygen Demand (mg/L)	Air Quality (emission factor, mg/km)	Cl^- emissions (Kg, per lane mile)
All Salts	3.04	6209	1085	26.4	204
All IceSlicers	3.04	6209	1085	26.4	204
All 23% Salt Brines	13.22	3725	651	6.1	130
30% Boise Salt Brine	10.13	3951	691	7.9	137
30% $MgCl_2$ Boise	2.58	27800	4860	7.9	61.2
Sand-Salt 3:1 Mixtures	10.28	76552	7771	65.9	153
Sand	50.00	100000	10000	79.00	1.00

Note that for estimating the *LCIC*, the following 5 parameters were averaged for each deicer, i.e., LC_{50} (96hr, *Trout*), IC_{25} (7d, *Ceriodaphnia*), IC_{50} (7d, C.), IC_{25} (7d, *Selanastrum*), and IC_{50} (7d, *S.*). These aquatic toxicity data for solid salts and the 30 percent corrosion-inhibited $MgCl_2$ liquid deicer were provided by the ITD. For the 23 percent and 30 percent salt brines, their *LCIC* was estimated by dividing that of solid salt by their NaCl weight concentration, respectively. For sand, a relatively high *LCIC* of 50 g/L was assumed since typical winter traction sand contains only trace amounts of toxic substances yet a high sand content in the stormwater runoff may cause toxic effects to aquatic species as abrasives “can reduce oxygen in stream beds and cause increased turbidity”.(101) The *LCIC* value of the sand-salt mixtures was derived from interpolating its toxicity from that of salt and sand. The BOD and COD data for the 30 percent corrosion-inhibited $MgCl_2$ liquid deicer were provided by the ITD. For simplicity, the BOD data recently reported by Fitch et al. (134) were adopted for solid salts and salt brines, and their missing COD data were infilled assuming that their COD to BOD ratio follows that of the $MgCl_2$ liquid deicer.

For estimating the EF_a from the PM_{10} and $PM_{2.5}$ data, the following equation was used to assume a weighted average of *EF* from these two groups of particulate matters:

$$EF_a = [(EF_{2.5}-76)\times(1/6.25)+(EF_{10}-229)\times(1/100)]/(1/6.25+1/100)$$

Where:

EF_a = average emission factor (mg/km)

EF_{10} and $EF_{2.5}$ = emission factor of PM_{10} and $PM_{2.5}$ particles after the deicer application, with their baseline concentration before any deicer application being 229 mg/km and 76 mg/km, respectively.

1/6.25 and 1/100 = decision weights of the two types of particles based on their relative exposed surface area, with smaller particles posing bigger risk to air quality.

Figure 15. Equation to Estimate Aggregate Emission Factor.

The baseline concentrations and EF data of solid salts and sand were obtained from a case study reported by Gertler et al. (137). For simplicity, the EF_a value of the 23 percent and 30 percent salt brines and the 30 percent $MgCl_2$ liquid deicer was estimated by multiplying that of solid salt by their weight concentration, respectively. For sand, a high *COD* of 100 g/L and high *BOD* of 10 g/L were assumed considering their presence in the stormwater runoff has been reported to cause oxygen depletion in the receiving water bodies.(138) The *COD*, *BOD*, *EF* and *ClE* values of the sand-salt mixtures was derived from interpolating those of salt and sand. The *ClE* data of solid salts and 23 percent salt brines were adopted from those recently reported by Fitch et al., whereas the ClE value of the 30 percent salt brine and the 30 percent $MgCl_2$ liquid deicer were derived from their relative Cl^- loading relative to that of 23 percent NaCl. (134)) A low *ClE* of 1 kg per lane mile was assumed for the use of sand for winter operations since typical winter traction sand contains only trace amounts of chlorides.

Collaborative Decision-making for Deicer Selection

This section is devoted to the comprehensive assessment of the deicer performance and risks by normalizing the aforementioned data on the sixteen selected parameters as shown in Table 15 and then integrating them into a single composite index as shown in Table 16. This approach enables collaborative decision-making for deicer selection as the normalized data present a holistic overview on the multiple dimensions of this crosscutting issue. Different from the researchers' previous studies, this study assumes equal user priority within each deicer dimension and between the four select dimensions (Table 16).(12, 131) This is based on the general observation obtained from the results of surveying the ITD district highway winter maintenance practitioners, in which the economics, performance (safety and mobility), infrastructure preservation, and environmental stewardship were considered equally important. In other words, if an ITD district or maintenance shed would consider a different set of assumptions and user priorities for its specific region or road segments, the calculation of the values in all the tables (including the composite index) would change accordingly. Furthermore, *"what-if"* analysis can be conducted to demonstrate how the deicer selection can be changed as a function of assumptions and/or user priorities.

Table 15. Normalized Assessment of ITD Deicers and Sand By the Select 16 Parameters.

Normalized Data	Cost per Lane Mile	T_c	T_e	IMC30°F, 60 min	IMC15°F, 60 min	Avg. friction	Corrosion to Steel	Corrosion of Bars	Damage to Concrete (Diluted)	Damage to Concrete (Concentrated)	Effect on Asphalt Concrete	Aquatic Toxicity	COD	BOD	Air Quality	Cl^- Emissions
AF Salt		36		59			49		80							
Salt BLKFT		30		58			56		58							
Salt Firth		28		53			54		21							
Regular Salt	89	31.5±0.4	33	55.2±1.1	63	58	46	48	32	92	11	28	60	57	67	2
AF Slicer		26		54			55		29							
Ice Slicer BLKFT		27		48			51		61							
Ice Slicer Malad		27		48			52		26							
BLKFT Brine		32		54			47		69							
Pocatello Brine	88	35	47	60	22	56	46	50	64	92	34	66	71	70	93	38
Regular Brine		33.5±0.9		57.6±0.9			46		64							
30% Salt Brine	80	30	38	57	29	56	46	43	65	92	34	59	70	68	91	34
30% $MgCl_2$ Boise	63	90	79	69	44	50	90	76	100	17	91	24	28	18	91	0
Sand-Salt Boise	53	21	21	37	23	59	47	87	29	98	27	60	6	6	17	27
Sand-Salt Simco	53	7	7	0	2	59	35	87	85	98	27	60	6	6	17	27
Sand	0	0	0	0	0	59	100	100	97	100	0	100	0	0	0	100
Max	$ 440	34°F	34°F	6 ml/ml	5 ml/g	0.5	160	4 μA/cm2	50%	60%	15%	50 g/L	100 g/L	10 g/L	79 mg/km	208 kg/l-mi
Min	$ 121	0°F	0°F	0 ml/ml	0 ml/g	0.1	0	0 μA/cm2	0%	0%	0%	1 g/L	1 g/L	0.2 g/L	1 mg/km	1 kg/l-mi

Table 16. Normalized Assessment of ITD Deicers and Sand By the 4 Select Dimensions and the Composite Indices Calculated From Them.

Normalized Data	Cost per Lane Mile	Average Performance	Infrastructure/Vehicle Impacts	Environmental Impacts	**Composite Index**
AF Salt		50	56		59
Salt BLKFT		48	53		58
Salt Firth		47	45		56
Regular Salt	89	48	46	43	56
AF Slicer		47	47		56
Ice Slicer BLKFT		46	53		58
Ice Slicer Malad		46	46		56
BLKFT Brine		42	58		64
Pocatello Brine	88	44	57	68	64
Regular Brine		43	57		64
30% Salt Brine	80	42	52	65	60
30% $MgCl_2$ Boise	63	66	75	32	59
Sand-Salt Boise	53	32	58	23	41
Sand-Salt Simco	53	15	67	23	39
Sand	0	12	79	40	33
Max	89	66	79	68	64
Min	0	12	46	23	33

Four different methods were utilized to normalize the experimental or estimated data for each deicer, using the maximum and minimum values shown in Table 15 for each select parameter. The ultimate goal is to ensure that a deicer with a desirable attribute (e.g., low effective temperature) would have a reasonably high score and a deicer with an undesirable attribute (e.g., high corrosivity) would have a reasonably low score on the specific parameter of interest.

First, the $IMC_{30ºF,\,60min}$, $IMC_{15ºF,\,60min}$ and *fc* values were normalized via $X_{normalized} = [(X-X_{min})/(X_{max}-X_{min})] \times 100$.

Second, the *COD* and *BOD* values were normalized via $X_{normalized} = 100-[(\lg X-\lg X_{min})/(\lg X_{max}-\lg X_{min})] \times 100$.

Third, the *LCIC* values were normalized via $X_{normalized} = [(\lg X-\lg X_{min})/(\lg X_{max}-\lg X_{min})]\times 100$.

Finally, all the other values were normalized via $X_{normalized} = 100-[(X-X_{min})/(X_{max}-X_{min})] \times 100$.

Figure 16. Equations to Normalize Data for Each Deicer.

Table 16 presents the final results of the quantitative analysis. Under the established evaluation framework, one can conclude that the ITD salt brines featured the highest composite index of 64 and thus should be considered a best practice. In contrast, the use of sand without salt would lead to the lowest composite index of 33 and thus should be avoided in highway winter operations. The use of the 2 sand-salt mixtures featured low composite indices of 41 and 39 respectively and also should be avoided wherever possible.

Arguably, brines, solid salts, and sand-salt mixtures are integral components of the highway winter maintenance toolbox and they are best suited for different application scenarios. For instance, for anti-icing on relatively warm pavement (18ºF or above), NaCl brine is likely the best product to use; yet $MgCl_2$ brine may be a better choice to use for cold pavements (10ºF to 15ºF). For extremely cold pavement (below 10ºF), the use of liquid deicer is risky and needs to be validated before implementation and prewet salt may be used for deicing. Avoid anti-icing below 20°F when there are strong winds, heavy snowfall, or freezing rain conditions. In cases where the removal of snow and ice on the pavement would require too much chemical or the pavement temperature is too cold for common chemicals to work (e.g., 5ºF or below), the use of sand-salt mixture is the last resort to obtain safe traction levels.

Discussion

Currently there are considerable data gaps when it comes to the quantification of deicer performance and impacts and their comprehensive assessment for decision-making. Nonetheless, this work is an important step in the right direction, aimed to enable maintenance personnel to make informed and defensible decisions following an established methodology to balance the multiple dimensions of using chemicals and abrasives for winter highway operations. Note that the quantitative evaluation of various materials were made possible by adopting data either from laboratory testing or field testing conducted by the researchers at the Western Transportation Institute, from the survey of ITD practitioners, or from recently published literature, among other sources. Furthermore, whenever necessary, reasonable assumptions were made in order to bridge the data gaps that currently exist in certain aspects related to the performance or risks of the select snow and ice control materials. In other words, there are caveats in the quantitative analysis in light of discrepancies inherent in extending data from laboratory testing or from field studies in other regions to Idaho road weather scenarios. In addition, it is known that the performance and impacts of snow and ice control products tends to be site-specific and can vary as a function of the localized pavement conditions, the prevailing climatic conditions, the receiving water body, the traffic volume, the nearby infrastructure, among other site characteristics.

In light of the data gaps identified through this work, additional research is needed for better quantification of cost-effectiveness (e.g., cost per lane mile by deicer type), performance (e.g., friction behavior at different times of anti-icing, deicing, and sanding practices as a function of pavement type and deicer type), infrastructure impacts (e.g., field risk to bare metals, rebars, dowel bars as a function of deicer type), and environmental impacts (e.g., aquatic toxicity and air quality risks by deicer type and deicer longevity on the road surface and dilution dynamics).

Chapter 5
Review of Historical Crash Data and Data Reduction

To evaluate the influence of winter chemical usage on road safety, several routes were selected after discussions with ITD, including I-90, I-15, I-84, I-86, US-12, US-95. The location of these routes is shown in Figure 17. The historical crash data of these selected routes was provided by ITD for review and analysis. As will be shown in the next chapter, due to the lack of weather and/or material usage data, only a few routes had compete datasets for benefit-cost analysis. This chapter provides a review of historical crash data on the six selected routes.

Figure 17. Selected Routes in Idaho.

Identification of Route Segments

The initial step in completing the crash data and chemical evaluations was to identify the road segments that would be considered. These routes would be examined for the impacts of different winter chemicals on traffic safety (i.e. reducing crashes) as data permitted. The routes of interest for this research were identified by the project technical advisory committee (TAC) and District personnel based on their firsthand experience with the roadways being maintained and the availability of information related to the types of treatment materials being used, functional classification , crash and traffic data, historical road weather data, and geometric design data for each route. Based on consultation and input from ITD, the following routes were identified for inclusion in the research:

- I-90 (mileposts 0.00 – 73.88) – District 1
- US-95 (mileposts 371 – 538.5) – District 1
- US-12 (mileposts 14.9 – 66) – District 2
- I-84 (mileposts 60 – 82) – District 3
- I-15 (mileposts 0.00 – 111.86) – District 5
- I-86 (mileposts 14.8 – 60) – District 5

As indicated, the routes came from four different districts and passed through a variety of terrains and environments. Collectively, they comprised a significant mileage of roadway, providing adequate crash data to support the overall analysis.

Review of Historical Crash Data and Data Reduction

Crash Data Collection

Historical crash data for the six selected routes were requested and provided by ITD. The datasets covered the years of 2000 through 2012. Note that only data through 2010 is presented in the following descriptions, as this data was available to the researchers throughout the course of the project, whereas later data was only available in parcels toward the end of the project. Each dataset contains comprehensive information about crashes events, with approximately 50 data elements used to describe the events. Some of the data elements include the date of accident, crash severity, mile point (MP), road surface condition, description of events (e.g., ran-off-the-road, loss of control, overturn), weather condition, and event serial number. The crash data provided by ITD were stored in Microsoft Excel files for the data analysis aspects of the work.

Crash Data Reduction

Data reduction was performed to identify the crash events in which winter road weather conditions were reported to play a role. Such crashes were retained for the subsequent data analysis. Screening criteria were developed for this data reduction and included:

1. Crash events occurring during winter season (established as November 1 to March 31 of the following year) were retained. Those crashes that happened during the months of April, May, June, July, August, September, and October were removed. In total, 12 winter seasons of crash data were obtained, including the 2000-2001 through 2011-2012 winter seasons (although crash data during the 2010-2011 and 2011-2012 seasons were not complete and not available for this portion of the analysis). Additionally, crash data from the October 2012 – December 2012 period was also available for the analysis.
2. Crash events that occurred under normal road weather condition (“Dry”) were removed from consideration, while those with road surface conditions of ice, slush, snow, and wet (or water standing) were retained. Crashes during dry conditions were eliminated as these would not represent a roadway surface state treated by winter maintenance chemicals, the interaction of which is of interest to this research.
3. As crashes may occur due to a combination of factors, crash data were further reduced to exclude those events that road weather conditions did not play a role, such as “animal-wildlife” collisions and drowsy/impaired driving.
4. Some crash events involved more than one vehicle, and in such cases, two or more records related to that crash event existed. These records had a same “serial number”, linking them together as being the same event. Thus, further actions were taken to remove duplicates so that each crash event corresponded to one record.

Summary of Crash Data

Table 17 presents the reduced crash data for the 6 selected routes. A total of 6,333 crashes events remained after data reduction, with 4,228 Property Damage Only (PDO) (66.8 percent of total crashes), 2,056 injury (32.5 percent), and 49 fatal crashes (0.8 percent). The total number of crashes during each winter season is also provided in the rightmost column for reference. It was found that the winter seasons of 2003-04 and 2001-2002 had 1,000 and 950 crash events respectively, which was much higher than other winter seasons. The winter season of 2009-2010 had the fewest crashes (372). An overview of crash counts for each of the selected routes is presented in this section. The review does not take other factors (e.g., traffic volume, geometric design) into account.

Table 17. Summary of Crash Counts for Selected Routes.

Winter Season	I-90 (MP 0- MP 73.88)	I-15 (MP 0- MP 111.86)	I-84 (MP 60 – MP 82)	I-86 (MP 14.8 - MP 60)	US-12 (MP 14.9 – MP 66.8)	US-95 (MP 371 – MP 538.5)	Total
2000-01	204	163	31	46	17	126	587
2001-02	379	219	39	66	35	212	950
2002-03	127	96	9	35	23	146	436
2003-04	277	319	35	114	33	222	1000
2004-05	139	168	26	57	18	91	499
2005-06	179	195	41	66	28	142	651
2006-07	218	89	39	27	27	158	558
2007-08	240	187	45	46	26	160	704
2008-09	170	153	55	46	23	129	576
2009-10	82	101	38	29	20	102	372
Total	2015	1690	358	532	250	1488	6333

Summary of I-90 Crash Data

The I-90 route segment starts at milepoint (MP) 0.0 and ends at 73.88. During 10 winter seasons, 2,015 crashes were associated with winter road weather, of which 1,440 were PDO (71.5 percent), 568 were injured crashes (32.2 percent), and 7 were fatal crashes (0.7 percent). The histogram of crashes for this route segment is shown in Figure 18, with MP as the horizontal axis, and crash count and cumulative probability as the vertical axis. The number of crashes that occurred between MP 29.0 and 32.1 was the highest (52 crash events), followed by the segment between MP 16.2 and 19.3 (40 crash events).

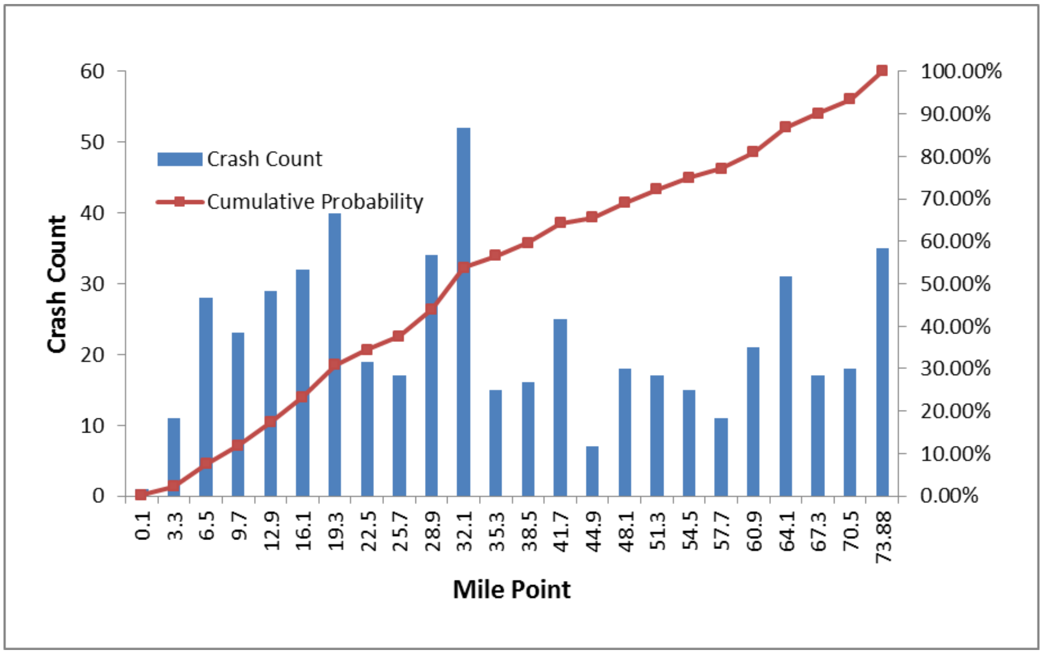


Figure 18. Histogram of Crashes on I-90.

Summary of I-15 Crash Data

This route segment starts at MP 0.0 and ends at 111.86. A total of 1,690 crashes occurred that were associated with winter road weather in the 10 winter seasons, with 1,134 PDO (67.1 percent), 544 injury (32.2 percent), and 12 fatal crashes (0.7 percent). The histogram of crashes for this route segment is shown in Figure 19. Based on the slope of the cumulative probability curve, the amount of crashes between MP 0.0 and 43.7 was generally lower than the rest of the route. The segment between MP 54.7 and 57.3 had the highest number of crashes (101 crash events).

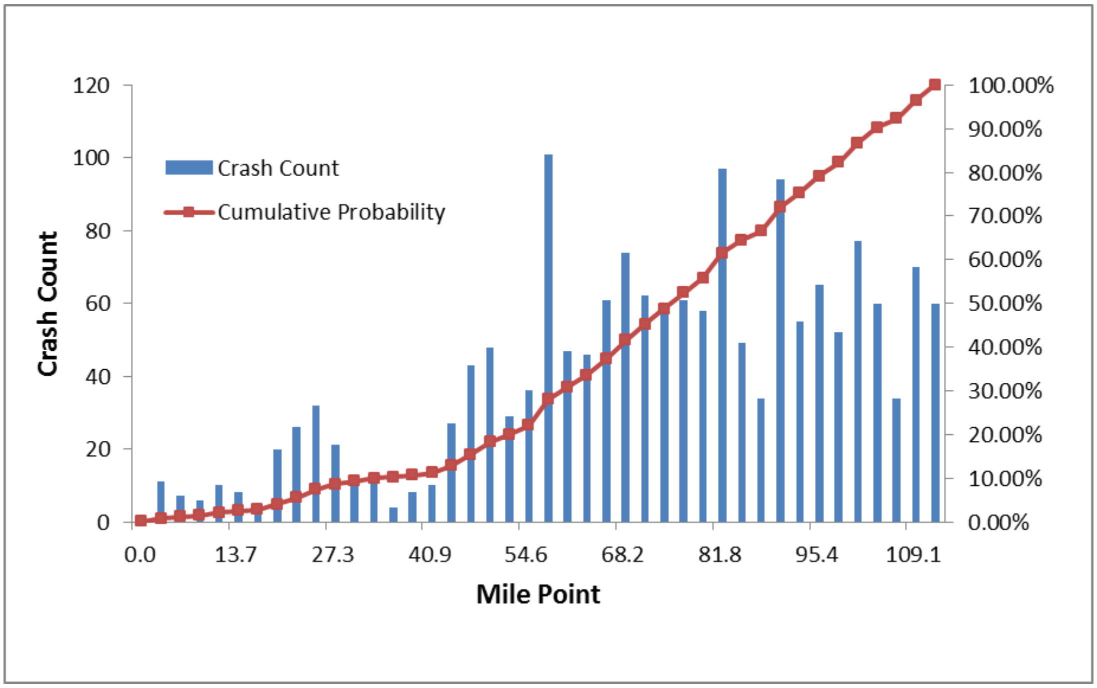


Figure 19. Histogram of Crashes on I-15.

Summary of I-84 Crash Data

This route segment starts from MP 60.0 and ends at 82.0. The length of this segment is 22 miles. A total of 358 crashes associated with winter road weather occurred on this route over the 10 winter seasons, with 206 PDO (57.5 percent), 148 injury (41.3 percent), and 4 fatal crashes (1.1 percent). As shown in Figure 20, this route had the fewest crashes (9 events) during the winter season of 2002-2003. The distribution of crashes is generally even as the slope of the cumulative probability curve tends to be straight. The section of MP 73.6 - 74.7 had the highest number of crashes (38 events), while MP 66.3 - 67.4 had the fewest number of crashes (5 events).

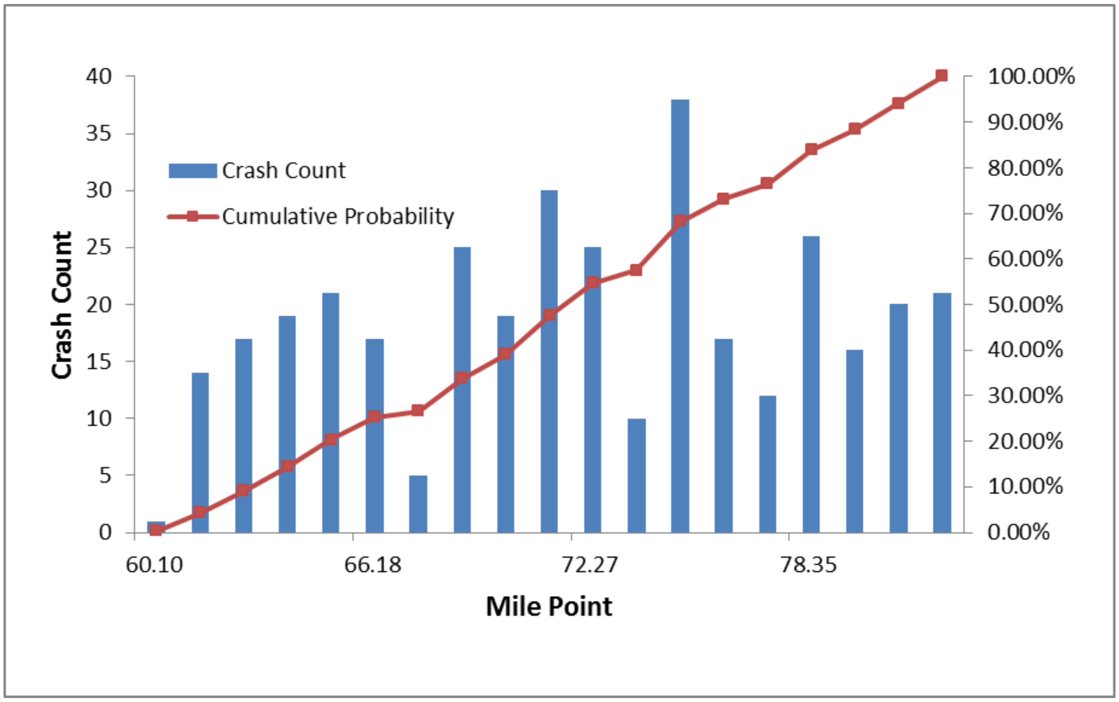


Figure 20. Histogram of Crashes on I-84.

Summary of I-86 Crash Data

The I-86 route segment starts at MP 14.8 and ends at 60.0. The length of this segment is 45.2 miles. A total of 532 crashes associated with winter road weather occurred over 10 winter seasons, with 371 PDO (69.7 percent), 156 injury (29.3 percent), and 5 fatal crashes (0.9 percent). The distribution of crashes is generally even, except at 2 consecutive sections (MP 32.6 - 34.4 and MP 34.4 - 36.4) with crash counts of 51 and 57 respectively.

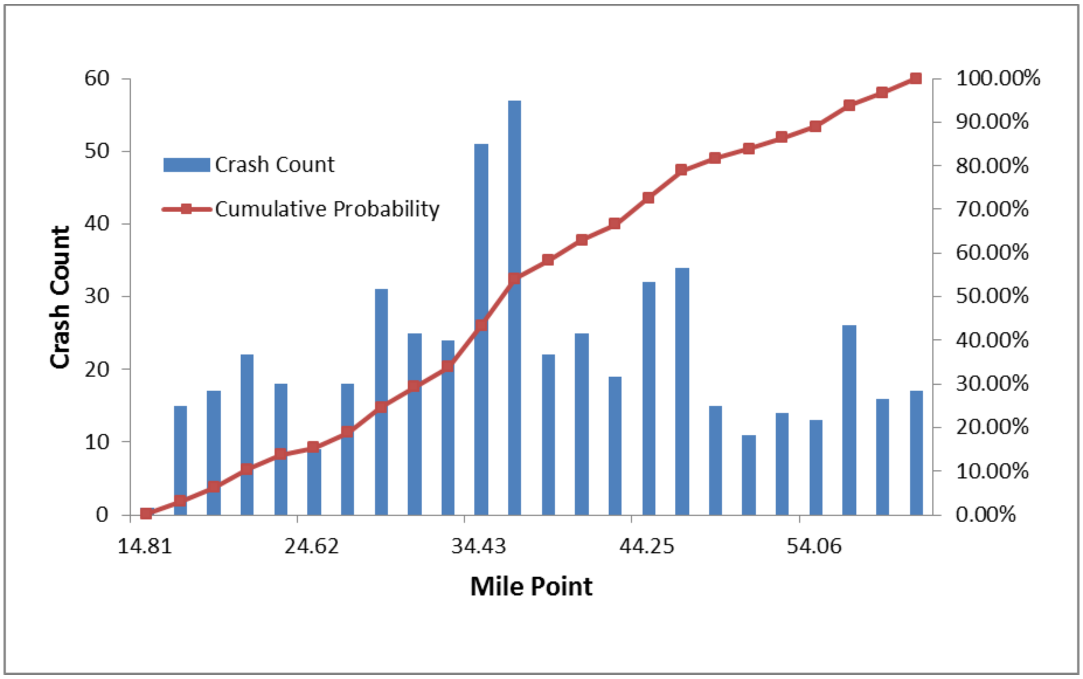


Figure 21. Histogram of Crashes on I-86.

Summary of US-12 Crash Data

This route segment starts at MP 14.9 and ends at 66.8. The length of this segment is 51.9 miles. During the 10 winter seasons, a total of 250 crashes associated with winter road weather occurred on this route, with 135 PDO (54.0 percent), 110 injury (44.0 percent), and 5 fatal crashes (2.0 percent). The section between MP 49.2 and 66.8 had fewer crashes than the section between MP 14.9 and 29.2. The section of MP 25.2 - 28.6 had the highest number of crashes (32 events).

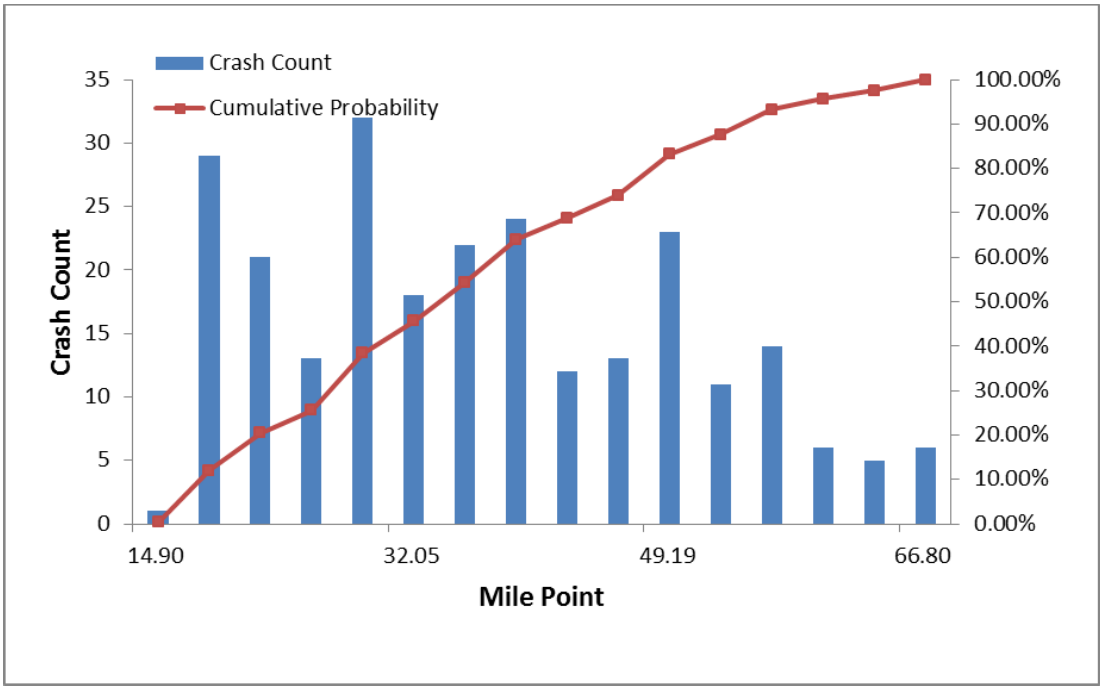


Figure 22. Histogram of Crashes on US-12.

Summary of US-95 Crash Data

This route segment starts at MP 371.0 and ends at 538.5. The length of this segment is 167.5 miles. A total of 1,488 crashes associated with winter road weather occurred on the route in 10 winter seasons, with 942 PDO (63.3 percent), 530 injury (35.6 percent), and 16 fatal crashes (1.1 percent). As shown in Figure 23, the section of MP 428.8 - 433.2 had the highest number of crashes with 145 events. Other sections with relatively high number of crashes included MP 472.5 - 476.9 (102 events), MP 433.2 - 437.5 (98 events), and MP 424.4 - 428.8 (82 events). The section after MP 476.9 appears to have a smaller number of crashes compared with the section between MP 371.0 and 476.9.

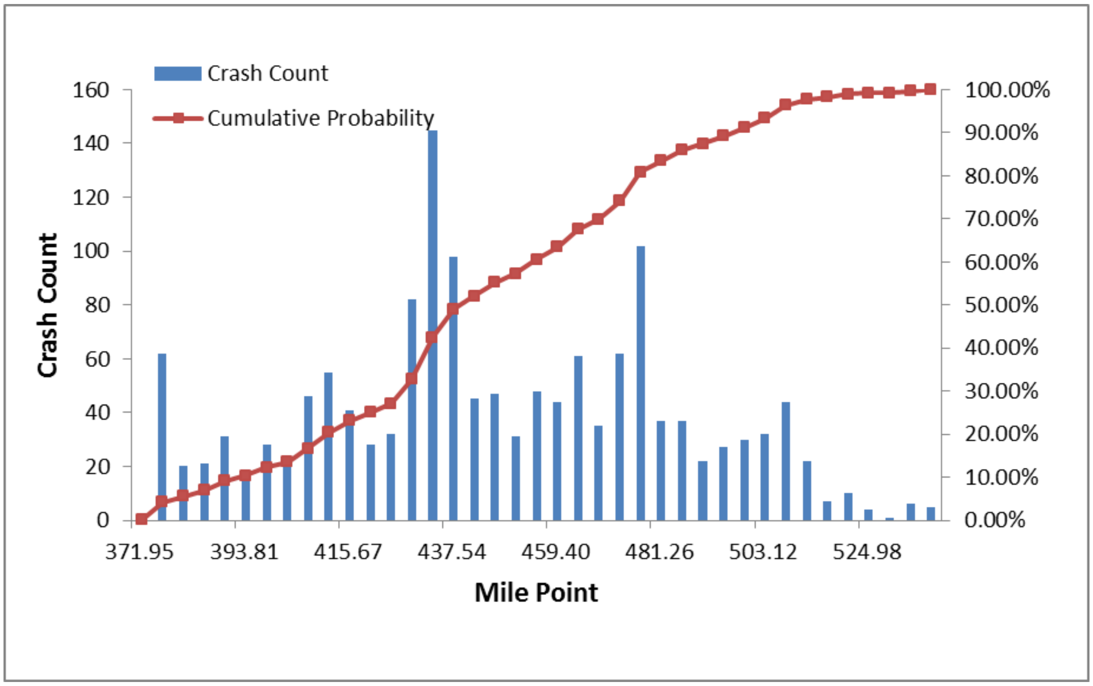


Figure 23. Histogram of Crashes on US-95.

Chapter Summary

This chapter has presented an overview of general crash trends along the study routes identified by ITD. A total of 6,333 crashes were identified as being winter-related, with a breakdown of 4,228 PDO (66.8 percent of total crashes), 2,056 injury (32.5 percent), and 49 fatal crashes (0.8 percent). It was found that the winter seasons of 2003-2004 and 2001-2002 had 1,000 and 950 crash events respectively, which was much higher than other winter seasons.

An investigation was conducted to identify the causes of the accidents happened during the 10 winter seasons (Figure 24). As shown in this figure, “speed too fast for conditions” was the main factor associated with winter accidents. Other factors such as “inattention” and “following too close” also contributed to winter accidents.

In addition, the distribution of crashes observed along each route was typical, with some locations exhibiting a higher number of crashes due to factors such as terrain, speed, road geometric factor and design defects.

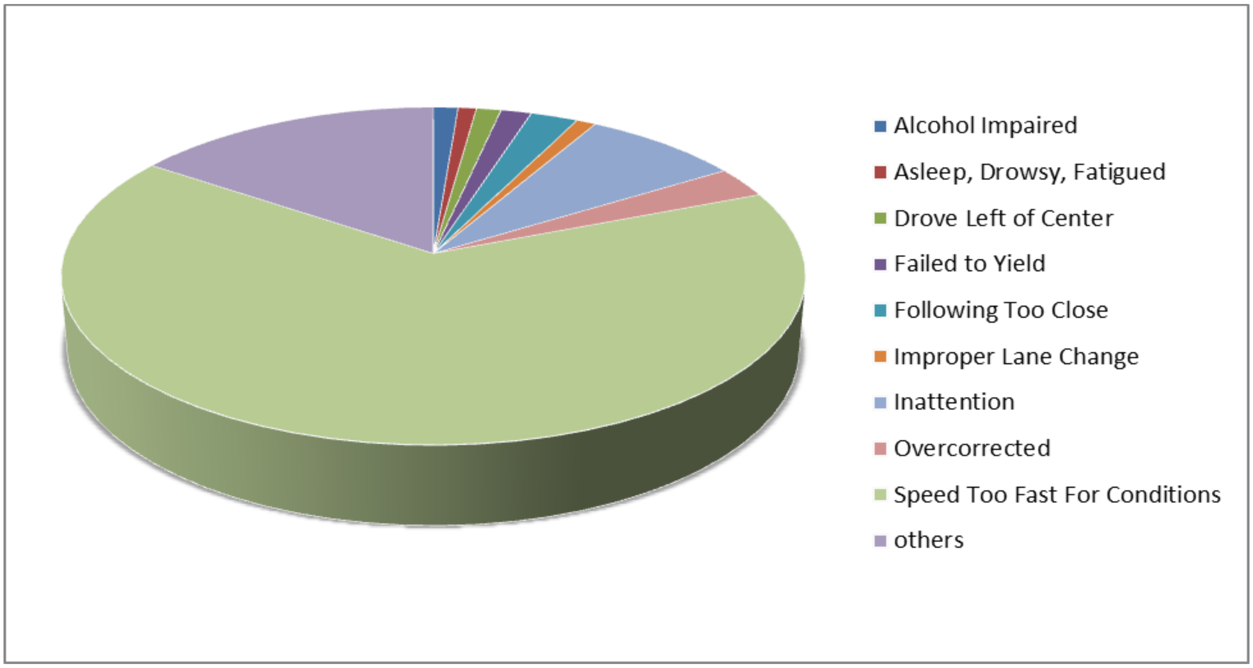


Figure 24. Causes of Winter Accidents.

Chapter 7
Benefit-Cost Analysis of Winter Chemicals

The previous chapters reviewed and documented the effects of different winter chemicals for winter maintenance. The usage of different winter chemicals ($MgCl_2$ and salt brine) was reviewed through the survey. Also, the reduction and preliminary analysis of crash data were provided. Finally, the performance of many materials presently used by ITD was examined. The objective of this chapter was to analyze the benefits and costs associated with the use of winter chemicals.

This chapter first presents a model that established the relationship between winter crashes and associated independent variables such as chemical usage, traffic volume, and weather condition. Then, a methodology consisting of Artificial Neural Network (ANN) and sensitivity analysis methods was used to estimate the benefits associated with winter chemicals. The methods were then applied to different routes to investigate the tangible benefits and costs. Finally, a determination of the annual costs per lane mile of several materials was made.

Winter Chemical Usage Model

To estimate the safety benefits of winter chemical usage, it is important to establish the relationship between safety (in terms of crash frequency in this study) and explanatory variables like AADT, maintenance costs, and WSI. This relationship is usually referred to as Safety Performance Function (SPF), as shown in Figure 25. The established SPF can be used to evaluate the effect of independent variables (e.g., winter maintenance in this study) on traffic safety.

$$\text{crash} = f(\text{AADT}, \text{Length}, \text{WSI}, \text{chemical usage})$$

Where

Crash = the crash number of different road segments

AADT = the annual average daily traffic of the road segment

Length = the length of the road segment

WSI = the winter severity index of the road segment

Chemical usage = the chemical cost used in the road segment

Figure 25. Safety Performance Function Equation.

Methodology

Neural Networks

A neural network is a modeling technique that is used to mimic the performance of a system based on observed behavior of neurons. It is in the borderline area of artificial intelligence and approximation algorithms. There are hundreds of types of neural networks using different algorithms. Among these, the Back-propagation Neural Network (BPNN) is the most popular one due to its simplicity and effectiveness.

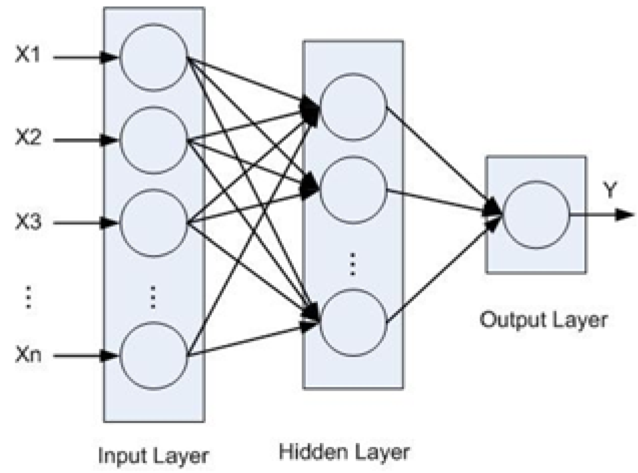


Figure 26. Architecture of the Neural Network Model With One Hidden Layer.

A BPNN , illustrated in Figure 26, usually consists of 3 layers: the input layer, the hidden layer and the output layer. A BPNN can have one or more hidden layers or outputs. Thus, the complexity of the BPNNs usually depends on the number of hidden layers and neurons. The input variables are sent to the input layer and be summed with weights. After that is complete these variables are passed to the hidden layer. Then, the sums in the hidden layer are weighed, passed to the output layer, and finally generate the prediction. The back-propagation algorithm develops the input-to-output mapping by minimizing a mean square error (MSE) function:

$$\mathrm{MSE} = \frac{\sqrt{\sum_{i=1}^{n}(y_i - E(i))^2}}{n}$$

Where

n = sample size of the training data set

y_i = model output related to the sample i(i=1,…,n)

$E(i)$ = estimated output

Figure 27. Mean Square Error Function.

Sensitivity Analysis

Sensitivity analysis is a method to study, qualitatively or quantitatively, how the uncertainty in the model output is attributed to different sources of variation (139). In this study, the objective of the sensitivity analysis is to find the subset of input variables that are most responsible for variation in model output. In real-world applications, it is common that the sample size for network training is limited and the dataset includes many input variables, which may present challenges for appropriate training. Hence, it is important to limit the number of inputs in the network model since some of the inputs may have negligible impacts (very low sensitivities), which in turn reduces the complexity of network and training time.

Before conducting sensitivity analysis, preparations need to be made. First, the input and output data must be normalized. Normalization of data means that the parameters are scaled equally so that the sensitivities of input variables can be compared. Second, data from all normalized input variables are used to train the network. Sensitivity analysis is conducted based on the trained network.

To normalize the dataset, a minimum–maximum method was used. The minimum–maximum normalization preprocesses the network training set by normalizing the inputs and outputs so that they fall in the interval [-1, 1]. Through normalization, the input parameters are scaled equally. The minimum–maximum normalization can be realized through the following equation:

$$Pn = 2\times(P - MinP\times OneQ)./((MaxP - MinP)\times OneQ) - 1$$

Where

P = a $R\times Q$ matrix of input (or output) vectors

$MinP$ = a $R\times 1$ vector containing minimums for each *P*

$MaxP$ = a $R\times 1$ vector containing maximums for each *P*

$OneQ$ = a $1\times Q$ vector containing 1s

Pn = a $R\times Q$ matrix of normalized input (or output) vectors

Figure 28. Equation for Minimum–Maximum Normalization.

It should be noted that in the normalization, a system (i.e., cost model in this study) is assumed: $y = f(x_1, x_2, ..., x_n)$, where y is the output (or result) and $x_1, x_2, ...x_n$ denotes the inputs of the system.

Once the network is properly trained, sensitivity analysis can be realized through the following steps:

1. Estimate mean and standard deviation for each variable $x_i (i = 1, 2, ..., n)$.
2. For x_1, evenly divide the interval $[\overline{x}_1 - \sigma(x_1), \overline{x}_1 + \sigma(x_1)]$ (σ is the standard deviation) into *k* sub-intervals. Thus, there are *k+1* input values $x_1^1, x_1^2, ..., x_1^{k+1}$. This study uses *k=100*, which means that the length of each interval (Δx_i) is less than $2/100 = 0.02$. One should be aware of the possibilities that $\overline{x}_1 - \sigma(x_1) < -1$ and $\overline{x}_1 + \sigma(x_1) > 1$, under which the input values outside the range of [-1, 1] will be excluded.
3. Calculate the results ($y_1^1, y_1^2, ..., y_1^{k+1}$) of the system for each element of the sample; other inputs are fixed at their respective means.

4. Analyze sensitivity of x_1 by using partial derivatives: $S_1 = \partial y_1 / \partial x_1$, which is a $1 \times k$ vector. The calculation of sensitivity is approximated by the first order of the Taylor series:
   $S_1^i = \frac{\partial y_1^i}{\partial x_1^i} \approx \frac{y_1^i(x_i + \Delta x_i) - y_1^i(x_i)}{\Delta x_i}$ For each $i = 1, 2, ..., k+1$
   Where S_1^i is the sensitivity of x_1^i.
5. Calculate the average sensitivity (which is a positive value) for x_1: $S_1 = \left| \frac{1}{k} \sum_{i=1}^{k} S_1^i \right|$
6. Repeat steps 1 through 4 for the rest of the input variables.
7. Obtain $S_1, S_2, ..., S_n$ for all input variables. Normalize the sensitivity values so that $\sum_{j=1}^{n} \hat{S}_j = 1$,

   where $\hat{S}_j = S_j / \sum S$. The final sensitivity values are $\hat{S}_1, \hat{S}_2, ..., \hat{S}_n$. These values can then be

   used to analyze their relative importance in the output variable, and to select key factors for the system.

Case Studies

Study Data

Weather Severity Index

Historical weather data from Road Weather Information System (RWIS) stations along the study routes were requested from and provided by Vaisala. The weather stations and associated information (latitudes, longitudes, routes, and mile post (MP)) are presented in Table 18. Observed data from each weather station were stored in a ".dsv" file. The datasets included air temperature, precipitation, rain state (light, medium, and heavy precipitation), and other parameters. Among the stations, 5 were located in Districts 1 and 5, respectively, with 2 in District 2.

Table 18. Road Weather Stations.

Station Name	Latitude	Longitude	Route	MP
D1 - 4th of July Pass	47.622	-116.525	I-90	28
D1 - Vets Memorial Bridge	47.650	-116.716	I-90	17.7
D1 - Wallace Viaduct	47.475	-115.906	I-90	62.3
D1 - Railroad Bridge Deck	47.712	-116.952	I-90	4.47
D1 - Five Mile Hill	48.932	-116.331	US-95	526
D2 - Cottonwood Creek	46.500	-116.714	US-12	19.1
D2 - Kamiah	46.247	-116.042	US-12	64.5
D5 - Cold Water	42.612	-113.153	I-86	18.9
D5 - Arbon Valley	42.879	-112.663	I-86	50.5
D5 - Blackfoot Rest Area	43.302	-112.272	I-15	101
D5 - Malad Summit	42.343	-112.227	I-15	24
D5 - Pocatello (Monte Vista)	42.851	-112.415	I-15	68

A database was created in MS Access to facilitate data processing and analysis. The ".dsv" files were imported into this database and weather data from each station were stored in a separate table.

Figure 29 shows partial data of the table for the station "D1-4th of July Pass." The columns include parameter code, data value, time, etc. Different parameters such as air temperature (T), precipitation in the past hour (PR1H), rain state (RS) are denoted by parameter code.

D1_4th_july_pass_531952

PARAMETER_	PARA_NO	SITE_NO	DATA_VALUI	DATA_TIME (GMT)
PR1H	1	1	0	30-MAR-09 11:05
PR1H	1	1	0	30-MAR-09 11:20
PR1H	1	1	0	30-MAR-09 11:35
PR1H	1	1	0	30-MAR-09 11:50
PR1H	1	1	0	30-MAR-09 12:05
PR1H	1	1	1	30-MAR-09 12:20
PR1H	1	1	2	30-MAR-09 12:35
PR1H	1	1	2	30-MAR-09 12:50
PR1H	1	1	2	30-MAR-09 13:05
PR1H	1	1	0	30-MAR-09 13:20
PR1H	1	1	0	30-MAR-09 13:35
PR1H	1	1	0	30-MAR-09 13:50
PR1H	1	1	0	30-MAR-09 14:05
PR1H	1	1	0	30-MAR-09 14:20
PR1H	1	1	0	30-MAR-09 14:35

Figure 29. Snapshot of the Weather Data Table.

Queries in MS Access were created to filter out the parameters that would not be used for later data analysis. Air temperature (T) and precipitation in the past 1 hour (PR1H) were retained. Moreover, observations during the winter season (established as November 1 to March 31 of the following year) were retained. Those observations recorded during the months of April, May, June, July, August, September, and October were removed. The available winter seasons for "T" and "PR1H" for the stations are shown in Table 19. It can be seen that the majority of stations had air temperature for 4-5 winter seasons, except the "Railroad Bridge Deck" in District 1, which had 2 seasons of data available. The numbers of available winter seasons with precipitation data available were less than those of air temperatures. Most of the stations had 2 to 3 winter seasons of precipitation data available. No precipitation data were available for 2 stations in District 1 ("Vets Memorial Bridge" and "Wallace Viaduct"). The limited precipitation data availability may be the result of some of the RWIS sites on the study routes either being installed or upgraded within recent years.

Table 19. Available Winter Seasons for Air Temperature and Precipitation.

Station Name	Available Winter Seasons (T)	Available Winter Seasons (PR1H)
D1 - 4th of July Pass	2008-09,2009-10, 2010-11, 2011-12	2008-09,2009-10
D1 - Vets Memorial Bridge	2008-09,2009-10, 2010-11, 2011-12	No precipitation Data
D1 - Wallace Viaduct	2008-09,2009-10, 2010-11, 2011-12	No precipitation Data
D1 - Railroad Bridge Deck	2010-11, 2011-12	2010-11, 2011-12
D1 - Five Mile Hill	2008-09,2009-10, 2010-11, 2011-12	2008-09,2009-10
D2 - Cottonwood Creek	2008-09,2009-10, 2010-11, 2011-12	2008-09,2009-10
D2 - Kamiah	2008-09,2009-10, 2010-11, 2011-12	2008-09,2009-10
D5 - Cold Water	2007-08, 2008-09,2009-10, 2010-11, 2011-12	2007-08,2008-09,2009-10
D5 - Arbon Valley	2007-08, 2008-09,2009-10, 2010-11, 2011-12	2007-08,2008-09,2009-10
D5 - Blackfoot Rest Area	2007-08, 2008-09,2009-10, 2010-11, 2011-12	2007-08,2008-09,2009-10
D5 - Malad Summit	2007-08, 2008-09,2009-10, 2010-11, 2011-12	2007-08,2008-09,2009-10
D5 - Pocatello (Monte Vista)	2007-08, 2008-09,2009-10, 2010-11, 2011-12	2007-08,2008-09,2009-10

The last step in the data preprocessing was to generate hourly weather data. Generally, 3 to 4 records were observed during each hour for each weather parameter. For example, as shown in Figure 29, there are 4 records of precipitation in 1 hour. Thus, the values of the records within the same hour were averaged to obtain an hourly record. This step was carried out for the two weather parameters separately. The software Matlab was used to process the raw data. The generated data were exported and stored in MS Excel spreadsheets and were used for further data analysis (calculation of weather severity index).

The records of air temperature (T) and precipitation in the past 1 hour (PR1H) should be averaged for each month from November 1st to March 31st to eliminate the influence of the month length. WSI was calculated by the following Figure 30 (140):

$$\mathrm{WSI} = \mathrm{a}\sqrt{\mathrm{TI}} + \mathrm{b}\ln\left(\frac{\mathrm{S}}{10} + 1\right) + \mathrm{c}\sqrt{\left(\frac{\mathrm{N}}{\mathrm{R}+10}\right)} + \mathrm{d} \qquad (8)$$

Where

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

Snow fall (s): mean daily values in millimeters.

Number of air frosts (N): mean daily values of days with minimum air temperature at or below 32 ° F (0° C) (0≤N≤1).

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

Figure 30. Weather Severity Index Equation.

With reference to the US climate data, and considering potential application of the index in cost analysis, the coefficients of Figure 30 are derived by taking into account the critically significant level of each parameter to winter maintenance cost, and solving a set of simple equations. The resulting coefficients are:

a = -25.58

b = -35.68

c = -99.5

d = 50.0

The resulting weather severity index is：

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

The WSI has a range from -50 (most severe weather and maximum level of snow and ice control), through 0 (not too severe weather and mean level of snow and ice), to 50 (warm weather and no need of snow and ice control). The results were stored in MS Excel spreadsheets, and Figure 31 shows partial results of the spreadsheet.

Note that the availability of weather data was an issue in some cases. One challenge encountered for some sites was the number of winter seasons that had associated weather information was limited. In other cases, some of the study routes only had one RWIS station located along them (ex. US.-95). In such cases, the influence of winter weather on different route segments would be difficult to take into consideration. The calculation of WSI would be meaningless for such conditions.

E	F	G	H	I	J	K	L	M
N		R		S		TI		WSI
0.5714		5.5		3.1463		0.6786		0.063332
1		4.8214		5.9567		1.75		-26.3573
0.9333		4.6667		8.5369		1.5333		-28.7954
0.963		6.4444		1.7106		1.1852		-7.56073
0.9667		6.1		7.0972		1.2333		-21.9251
0.8519		5.2222		4.4285		1.1481		-14.0283
0.9355		4.8065		1.7884		1.6774		-14.0106
0.8667		4.3333		2.6893		1.1667		-10.5952
0.8929		5.8571		1.1855		0.9286		-2.25813
0.8065		9.0323		2.4073		0.9032		-2.48894

Figure 31. Snapshot of the Analysis of WSI.

Annual Average Daily Traffic

The AADT for the six selected routes were requested and provided by ITD. The dataset covered the years of 2008 through 2011, as these were the years which had material use records available, and contained comprehensive information about the AADT. Each of the six selected route was divided into several segments, and within each segment the AADT was consistent. Thus, an Excel spreadsheet was created to store AADT, chemical usage, WSI, etc. for each road segment. The benefit-cost analysis was conducted based on the data provided in this spreadsheet.

Chemical Usage

The chemical usage means the total cost of each winter chemical. Data provided by ITD from historical paper records (scanned to .pdf) only included the chemical usage of I-90, US-12 and US-95. The chemical usage of the remaining three routes was unavailable for this study. Hence, benefit-cost analysis of winter chemicals can be only conducted for the three routes with chemical data. As the chemical usage data were stored in ".pdf" files, the date, location, chemical type, amount of usage, etc. were manually entered into Excel spreadsheets. The amounts of usage and types of chemicals were aggregated by road segment and winter season.

Data Availability for Benefit Analysis

After the data processing, data for four different variables (AADT, WSI, Chemical Usage, and crash data) were available, as presented in Table 20. Unfortunately, the majority of winter seasons did not have complete datasets for analysis. In order to evaluate the effectiveness of winter maintenance chemicals, all four of these pieces of information were necessary. Traffic and crash data are integral components in understanding and modeling crashes, while WSI and chemical usage are vital to understanding the interaction of weather conditions and treatments on crash occurrence. Issues with the completeness of RWIS data limited some of the seasons that could be evaluated. Similarly, ITD records of chemical usage were incomplete, particularly for earlier years of the prospective analysis (primarily 2007-2008 and earlier). The paper-based nature of files from this era made the identification and scanning of complete records for research use a significant challenge.

Complete data were available for 2 winter seasons on I-90, 2 winter seasons on US-95, and 1 winter season on US-12, as highlighted in Table 20. The analysis of these three routes was conducted and presented in the following sections. Note that weather, crash and chemical usage data for the last 2 months of 2012 were also provided by ITD during the course of this research. As traffic volumes during these months were not available, the AADT in 2011 was used so that further benefit-cost analysis could be conducted. It was assumed that significant changes in traffic volumes between 2011 and 2012 had not occurred, allowing for this data to also be used. Since this part of the analysis did not include an entire winter season, the analysis was done independently and presented as such.

Table 20. The Detailed Data Information for the Selected Road.

Winter Season	I-90				I-15				I-84				I-86				US-12				US-95			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
2000-01	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2001-02	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2002-03	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2003-04	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2004-05	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2005-06	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2006-07	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2007-08	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√	×	×	×	√
2008-09	√	√	√	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√	√	√
2009-10	√	√	√	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√	√	√	√	√	√	√
2010-11	√	×	√	√	√	×	×	√	√	×	×	√	√	×	×	√	√	×	√	√	√	×	√	√
2011-12	×	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√	×	√	√	√

1—AADT 2—WSI 3—Chemical Usage 4—Crash Data "×"—Not Available "√"—Available

I-90 Analysis

The I-90 route segment started at MP 0.0 and ended at MP 40.391, and 2 winter seasons from 2008 - 2009 to 2009 - 2010 were chosen for network training and testing. The network consisted of an input layer with 5 input variables, a hidden layer with 4 nodes, and an output layer with 1 output variable. The 5 input variables include AADT, Length, WSI, C1 and C2, among these C1 represents the cost of liquid deicer and C2 represents the cost of salt. The BPNN was used to train the dataset. As shown in Figure 32, the MSE values were very low in the analysis, so it was found that 1,000 epochs (a single pass through the entire training set, followed by testing of the verification set) was adequate for network training because the improvement in *MSE* was minimal beyond that number.

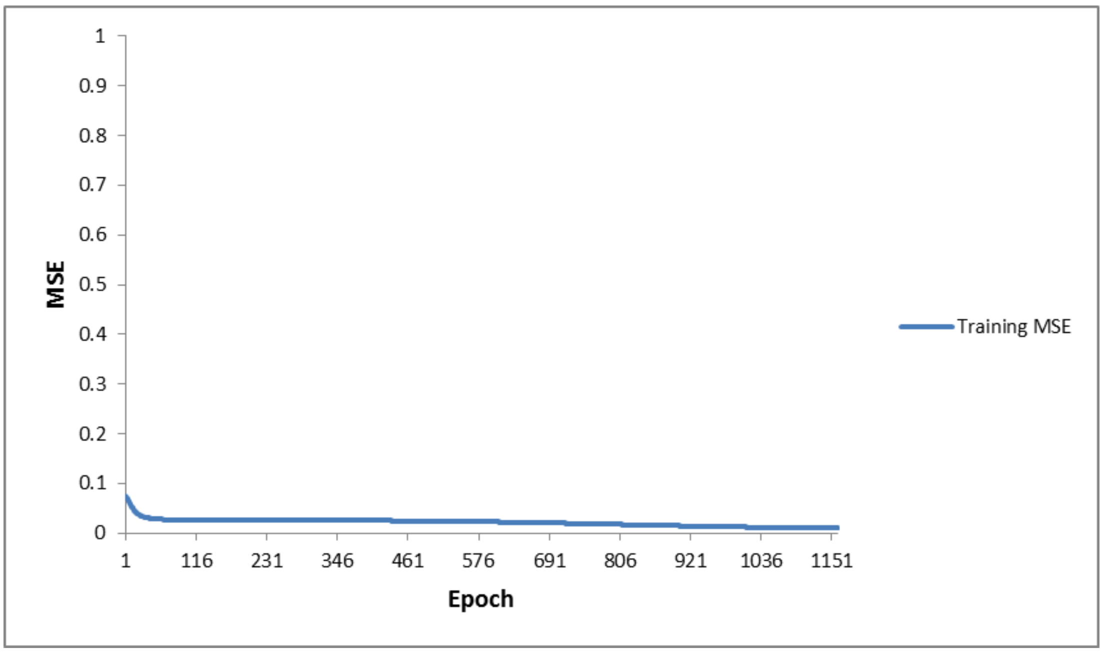


Figure 32. MSE Curves.

The value of R-square was used for the research team to evaluate the accuracy of network training. After network testing, the value of R^2 was shown as 0.75, which represents a strong relationship between input variables and the output variable (crash).

Sensitivity Analysis

Sensitivity analysis was conducted for each of the five variables. The variables of AADT and Length had positive relationship with crashes, while the other 3 (WSI, C1, and C2) had a negative relationship. The result of sensitivity analysis is shown in Figure 33. Obviously, among these five inputs, length of the road segments had the highest sensitivity to crash numbers. In addition, it is easy to determine that the costs of Chemical Type 1 (liquid deicer) and Chemical Type 2 (NaCl - salt) both had high sensitivities to crash numbers. The sensitivity values of C1 and C2 are 0.22 and 0.21, respectively. Liquid deicer and salt both had a significant effect on reducing crashes during winter seasons. The results of sensitivity analysis, however, do not imply that one type of chemical is better than the other.

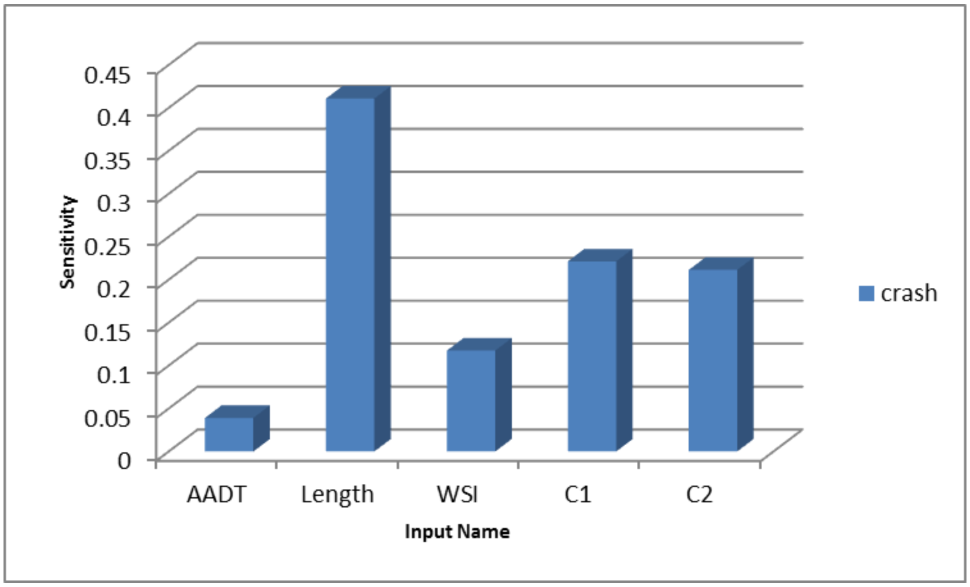


Figure 33. Sensitivity Analysis of Input Variables (I-90).

Safety Benefits of Winter Chemical Usage

The analysis of safety benefits included 2 scenarios:

1. the present case with winter maintenance performed
2. the base case without winter maintenance, that is, the cost of winter chemicals is zero

In the first scenario with chemicals used, 319 crashes occurred on I-90 for the study period. To estimate the number of crashes that would have happened under the second scenario (no chemicals used), the previously trained network was used by setting chemical usage as zero to predict the number of crashes, leaving other variables unchanged. After the analysis, it was found that 519 crashes could have happened if there were no use of winter chemicals. In other words, 200 crashes have been prevented by the application of winter chemicals. The average Idaho crash cost is $42,796 in 2012 dollars, while the average cost of injury and property damage crashes in Idaho is.(141) This difference of 200 crashes, multiplied by an average crash cost, resulted in safety benefits of $8,559,200.

Costs of Winter Chemical Maintenance

The cost of winter chemical maintenance includes chemical cost, equipment cost and labor cost. The chemical costs were calculated by multiplying the usage and the price ($/yd^3 or $/gallon). The chemical costs of I-90 was $1,487,572 during the studying period.

Based on information provided by ITD, the average equipment cost for applying liquid deicer and salt was $2.61 per mile and $1.81 per mile, respectively. The equipment cost was calculated by multiplying the average equipment cost (per hour) by the number of miles maintained, resulting in a cost of $24,840.

Information provided by ITD indicated that labor costs averaged $21 per hour and department personnel generally can maintain 25 miles of roadway in a hour. The maintenance mileage was 4,670 miles during the studying period. Thus, the number of labor hours was 187 hours (4,670/25).The total labor cost was $3,927. Thus, the total cost of winter chemical maintenance was $1,516,339. Note that the equipment and labor costs for this portion of roadway may seem low, until one recalls that the segment length being examined was approximately 40 miles.

Benefit-Cost Analysis

Given the safety benefits and various costs, a benefit-cost analysis for winter maintenance on I-90 was conducted. Table 21 shows that the safety benefits of using winter chemical are greater than winter chemical maintenance costs, with a benefit–cost ratio of 5.54. The results show that the use of winter chemical had positive and significant effects on improving safety under adverse weather conditions.

Table 21. Benefit-Cost Analysis of I-90.

Benefits ($)		**$8,559,200**
Costs ($)	**Chemical Cost**	$1,487,572
	Equipment Cost	$24,840
	Labor Cost	$3,927
Benefit-Cost Ratio		**5.64**

US-12 Analysis

The US-12 route started at MP 14.901 and ended at MP 66.946 (52.045 miles), and the 2009 - 2010 winter season was chosen for network training and testing. The network consists of an input layer with 4 input variables, including AADT, WSI, Length and C (cost of liquid deicer), a hidden layer with 4 nodes, and an output layer with 1 output variable. The chemical usage data provided by ITD indicated that no salt was used for the winter road maintenance during the particular study season (2009-2010). After the network training and testing, the value of R^2 was 0.617, which represents a relatively strong relationship between input and output variables

Sensitivity Analysis

Sensitivity analysis showed that the variables of AADT and Length had positive effect on safety, while WSI and C had negative effects. The result of the sensitivity analysis is shown in Figure 34. In this case, Length and WSI had higher sensitivities values than the other two variables.

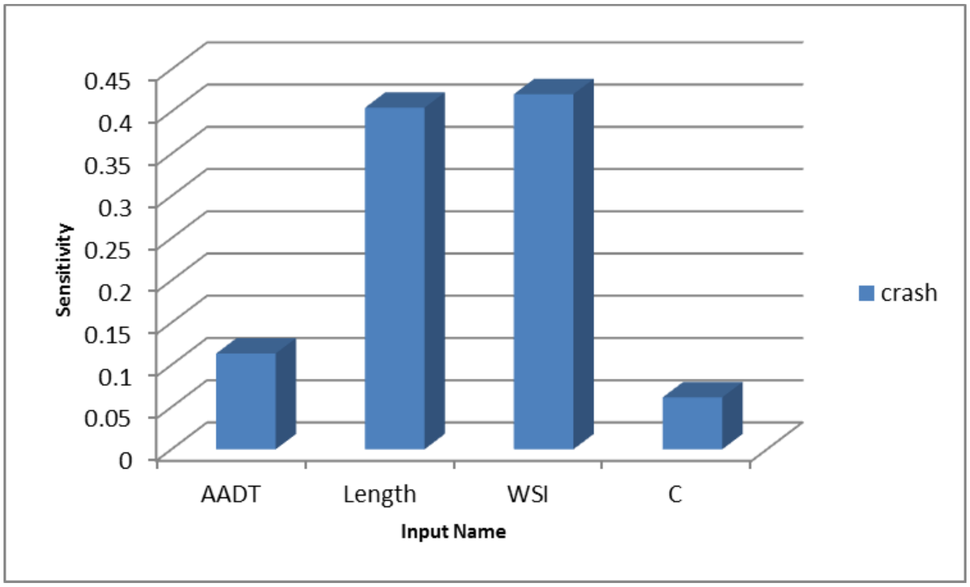


Figure 34. Sensitivity Analysis of Input Variables (US-12).

Safety Benefits of Winter Chemical Maintenance

It was found that the expected number of crashes that would have occurred without chemical usage was 58, compared with the 42 that was actually observed under the winter chemical maintenance conditions. This difference of 16 crashes, when multiplied by the average crash cost of $42,796, produced safety benefits of $684,726 during the winter season.

Cost of Winter Chemical Maintenance

Similar to the analysis for I-90, the cost of winter chemical maintenance consists of chemical costs, equipment costs and labor costs. Based on information provided by ITD, the final chemical cost of US-12 during the study period was $87,433.

The average equipment cost of US-12 was $0.91 per mile. The maintenance route miles were 2214.51 according to maintenance records. Thus, the total equipment cost of US-12 was $2015. The labor cost was $1693. Finally, the total cost of winter chemical maintenance on the selected route was $91,141 during the 2009-2010 winter season.

Benefit-Cost Analysis

Table 22 shows the benefits and costs of using winter chemicals. The benefit-cost ratio is 7.76. Again, this case study indicates that the use of winter chemical on US-12 produced more safety benefits than associated costs.

Table 22. Benefit-Cost Analysis of US-12.

Benefits ($)		$684,726
Costs ($)	Chemical Cost	$87,433
	Equipment Cost	$2015
	Labor Cost	$1693
Benefit-Cost Ratio		**7.51**

US-95 Analysis

The researchers also conducted an analysis on road US-95. The US-95 route segment starts at MP 418.7 and ends at MP 458.58 (39.88 miles). Two winter seasons from 2008 - 2009 to 2009 - 2010 were chosen for network training and testing. The network consisted of an input layer with 4 input variables, a hidden layer with 4 nodes, and an output layer with 1 output variable. The results of network testing showed that the coefficient R^2 value was only 0.17, which indicated that the input and output variables did not have a strong relationship. For this reason, crash analysis and the determination of a benefit-cost analysis for US-95 was not pursued.

Winter Chemical Costs

In addition to examining the general benefits of winter maintenance chemicals on crashes, it is also useful to examine the total estimated costs associated with their use from the perspective of the material, labor and equipment. To this end, estimates were made for each of the previously identified study routes examining the annual cost per lane mile that was associated with each type of material. This cost included labor, equipment and material expenses.

In conducting the evaluation, various assumptions were employed. First, given an efficiency of 25 miles per hour (mph) for maintenance vehicles, it was assumed that a specific roadway section was maintained once per storm. In reality, maintenance vehicles patrol and maintain most highway segments multiple times per storm; however, this low speed factor was viewed to incorporate this higher frequency of maintenance. Consequently, the 3 mph efficiency figure was employed for Idaho, as well as comparison state calculations. In terms of material usage, it was not possible to analyze the myriad of material combinations that can be used during the course of any particular storm or winter season. As a result, the analysis presented in this section uses the simplified approach of examining the use of only one material type for treatment during all storms during the study year (2010, based on available storm records from ITD). While this assumption does not represent reality, it is believed that it provides at least an initial understanding of how the costs of different materials compare to one another. An average cost per vehicle per mile was developed from individual figures provided by ITD by vehicle type. The costs associated with the cleanup of a material, for example sand, are not factored in to these calculations, as such information was not available. Finally, when calculating the costs from comparison states, the Idaho study routes were employed, with changes only made to material, equipment and labor costs for the respective comparison state.

All study segment, storm, material use and cost data was provided by ITD staff during the course of the project. Data from three comparison states was available to the researchers: Kansas, Washington and North Dakota. Each state shares at least some characteristics (traffic volumes, materials used, terrains, population centers, etc.) with Idaho, allowing for an initial understanding of how Idaho's current estimated costs compare to other agencies. In some limited cases, costs associated with vehicles per lane mile were assumed. Such assumptions are noted in the summary tables.

Table 23 presents the material cost and application rate data employed in the analysis. As one will likely note, in many cases, Idaho has lower costs for labor, equipment and materials than other states. In the case of materials, costs for a specific material will vary significantly depending on region, so this observation is not surprising. Additionally, in the case of salt and salt brine in Washington, the cost includes the use of corrosion inhibitors, resulting in a significantly higher cost compared to the other states. These differences in costs will be quite evident in the analysis of particular materials, especially when application rates also differ significantly.

Table 23. Cost and Application Rate Data.

Element	Idaho	Kansas	Washington	North Dakota
Equipment cost/mile	$1.90	$2.06	*$3.00*	*$3.00*
Loaded Labor cost	$21.00	$38.45	$35.63	$42.88
Salt (cost/ton)	$59.43	$44.07	$114.41	$66.58
Salt Brine (cost/gallon)	$0.14	$0.04	$0.51	$0.08
MgCl2 (cost/gallon)	$0.72	N/A	$0.79	N/A
Sand (Cost/ton)	$11.15	$11.43	$9.72	$8.81
Sand Salt (cost/ton)	$13.63	$13.19	$40.29	$23.44
Application Rates				
Salt (lb/lane mi)	200	200	200	300
Salt Brine (gallon/lane mi)	45	50	40	40
MgCl2 (gallon/lane mi)	35	N/A	20	N/A
Sand (lb/lane mi)	800	200	150	500
Sand Salt (lb/lane mi)	300	400	200	500
Italics indicate assumed value				

Salt

Table 24 presents the results of cost calculations for granular salt materials. Note that a specific product/brand was not examined; rather, a general cost for the material was obtained from each state. When examining the annual costs per lane mile for salt, it is evident that the number of storms has a direct bearing on the resulting calculation, as does the lane mileage being maintained. Salt is a relatively cost effective treatment strategy in Idaho, with an average cost per lane mile of $81.79 and a range between $60.78 to $112.88. This $112.88 figure is slightly skewed by the overall cost computed for the I-15 segment, which experienced a larger number of storms than the other routes. This skew will appear again in the other calculations made in this section. Overall, Idaho's cost per lane mile for maintenance using salt is somewhat lower than comparison states, with the exception of Kansas. In part, this is due to the lower costs of salt reported by ITD, as well as differences in labor rates, but the application rates used in Idaho generally matched those reported in other states. Regardless, salt appears to be a cost-effective treatment particularly compared to Washington and North Dakota.

Table 24. Cost Per Lane Mile Comparison for Salt (2010).

Route	Storms (2010)	Lane Miles	Equipment Cost	Labor Cost	Material Cost	Total Costs	Annual Cost per Lane Mile (Idaho)	Annual Cost per Lane Mile (Kansas)	Annual Cost per Lane Mile (Washington)	Annual Cost per Lane Mile (North Dakota)
I-90	9	294	$5,031.03	$2,224.24	$15,736.52	$22,991.79	**$78.15**	$72.05	$142.80	$132.32
US-95	8	435	$6,611.70	$2,923.07	$20,680.69	$30,215.45	**$69.46**	$64.04	$126.93	$117.62
US-12	8	116	$1,769.83	$782.45	$5,535.83	$8,088.11	**$69.46**	$64.04	$126.93	$117.62
I-84	7	141	$1,875.30	$829.08	$5,865.74	$8,570.12	**$60.78**	$56.04	$111.06	$102.92
I-15	13	478	$11,806.60	$5,219.76	$36,929.80	$53,956.16	**$112.88**	$104.07	$206.26	$191.13
I-86	7	192	$2,548.73	$1,126.81	$7,972.17	$11,647.71	**$60.78**	$56.04	$111.06	$102.92
TOTALS		**1656**	**$29,643.18**	**$13,105.41**	**$92,720.75**	**$135,469.34**	**$81.79**	**$69.38**	**$137.51**	**$127.42**

Notes: Number of storms reported by ITD data
Lane miles are the total miles of lane for all segments (ex. 1 mile of roadway with 2 lanes is 2 lane miles)
Average efficiency in maintenance operations = 25 miles per hour

Salt Brine

Table 25 presents the results of cost calculations for salt brine. On a cost per lane mile basis, salt brine was variable compared to other states. It is a relatively cost effective treatment strategy, with an average annual cost of $81.36 per lane mile and a range between $63.28 and $117.52. This average is again skewed by the overall cost computed for the I-15 segment, which experienced a larger number of storms than the other routes. Idaho's cost per lane mile for maintenance using salt brine is generally higher than comparison states. While Kansas and North Dakota produced comparable costs, Washington's cost for salt brine was significantly higher. This was in part, due to the use of corrosion inhibitors by WSDOT. Additionally, one should also recall from the earlier cost table that Washington pays over two times as much for salt as Idaho due to the use of corrosion inhibitors.

Table 25. Cost Per Lane mile Comparison for Salt Brine (2010).

Route	Storms (2010)	Lane Miles	Equipment Cost	Labor Cost	Material Cost	Total Costs	Annual Cost per Lane Mile (Idaho)	Annual Cost per Lane Mile (Kansas)	Annual Cost per Lane Mile (Washington)	Annual Cost per Lane Mile (North Dakota)
I-90	9	294	$5,031.03	$2,224.24	$16,681.82	$23,937.09	**$81.36**	$50.38	$223.43	$71.24
US-95	8	435	$6,611.70	$2,923.07	$21,922.99	$31,457.75	**$72.32**	$44.78	$198.60	$63.32
US-12	8	116	$1,769.83	$782.45	$5,868.37	$8,420.65	**$72.32**	$44.78	$198.60	$63.32
I-84	7	141	$1,875.30	$829.08	$6,218.10	$8,922.48	**$63.28**	$39.19	$173.78	$55.41
I-15	13	478	$11,806.60	$5,219.76	$39,148.20	$56,174.56	**$117.52**	$72.77	$322.73	$102.90
I-86	7	192	$2,548.73	$1,126.81	$8,451.06	$12,126.60	**$63.28**	$39.19	$173.78	$55.41
TOTALS		**1656**	**$29,643.18**	**$13,105.41**	**$98,290.55**	**$141,039.13**	**$85.16**	**$48.52**	**$215.15**	**$68.60**

Notes: Number of storms reported by ITD data
Lane miles are the total miles of lane for all segments (ex. 1 mile of roadway with 2 lanes is 2 lane miles)
Average efficiency in maintenance operations = 25 miles per hour

$MgCl_2$ Brine

Table 26 presents the results of cost calculations for $MgCl_2$ brine. On a cost per lane mile basis, $MgCl_2$ brine is quite expensive, particularly when compared to salt brine. $MgCl_2$ brine is a strategy that is accompanied by a significant cost, with an average annual cost in Idaho of $250.00 per lane mile and a range between $185.78 and $345.02. Idaho's annual cost per lane mile for maintenance using $MgCl_2$ is higher than Washington (note that Kansas and North Dakota did not report use of $MgCl_2$) on account of the higher average application rate of ITD . The overall higher cost of $MgCl_2$ underscores its use in specific situations or locations rather than as a wholesale treatment strategy. The costs associated with $MgCl_2$ illustrate the need for careful consideration of the appropriate time and location of a particular treatment in order to obtain the maximum benefit for the cost expended.

Table 26. Cost Per Lane Mile Comparison for $MgCl_2$ Brine (2010).

Route	Storms (2010)	Lane Miles	Equipment Cost	Labor Cost	Material Cost	Total Costs	Annual Cost per Lane Mile (Idaho)	Annual Cost per Lane Mile (Kansas)	Annual Cost per Lane Mile (Washington)	Annual Cost per Lane Mile (North Dakota)
I-90	9	294	$5,031.03	$2,224.24	$63,020.21	$70,275.48	**$238.86**	N/A	$182.03	N/A
US-95	8	435	$6,611.70	$2,923.07	$82,820.19	$92,354.95	**$212.32**	N/A	$161.80	N/A
US-12	8	116	$1,769.83	$782.45	$22,169.41	$24,721.69	**$212.32**	N/A	$161.80	N/A
I-84	7	141	$1,875.30	$829.08	$23,490.60	$26,194.98	**$185.78**	N/A	$141.58	N/A
I-15	13	478	$11,806.60	$5,219.76	$147,893.20	$164,919.56	**$345.02**	N/A	$262.93	N/A
I-86	7	192	$2,548.73	$1,126.81	$31,926.22	$35,601.76	**$185.78**	N/A	$141.58	N/A
TOTALS		**1656**	**$29,643.18**	**$13,105.41**	**$371,319.84**	**$414,068.43**	**$250.00**	**N/A**	**$175.29**	**N/A**

Notes: Number of storms reported by ITD data
Lane miles are the total miles of lane for all segments (ex. 1 mile of roadway with 2 lanes is 2 lane miles)
Average efficiency in maintenance operations = 25 miles per hour

Sand

The use of sand is of course limited to spot treatments in order to provide traction. Consequently, the full-route calculations presented in Table 27 should be viewed with some caution, as they represent the use of sand over the entire distance of each route. In actual practice, straight sand applications are rarely used, as abrasives are normally mixed with salt. However, the cost per lane mile calculations provide a better indication of what the spot treatment costs of sand may represent. On a cost per lane mile basis, sand is the most inexpensive material examined, with an average annual cost for Idaho of $67.82 per lane mile and a range between $50.40 and $93.60. Idaho's cost per lane mile for maintenance using sand is higher than those of comparison states, but ITD also reported a higher application rate than those states. Recall that any cleanup costs associated with sand use, nor the potential for recycling, have not been considered. Additionally, sand is a single purpose material which provides traction but cannot contribute to the deicing of the roadway surface.

Table 27. Cost Per Lane Mile Comparison for Sand (2010).

Route	Storms (2010)	Lane Miles	Equipment Cost	Labor Cost	Material Cost	Total Costs	Annual Cost per Lane Mile (Idaho)	Annual Cost per Lane Mile (Kansas)	Annual Cost per Lane Mile (Washington)	Annual Cost per Lane Mile (North Dakota)
I-90	9	294	$5,031.03	$2,224.24	$11,809.67	$19,064.94	**$64.80**	$42.67	$46.39	$49.49
US-95	8	435	$6,611.70	$2,923.07	$15,520.09	$25,054.85	**$57.60**	$37.93	$41.23	$43.55
US-12	8	116	$1,769.83	$782.45	$4,154.44	$6,706.71	**$57.60**	$37.93	$41.23	$43.55
I-84	7	141	$1,875.30	$829.08	$4,402.02	$7,106.40	**$50.40**	$33.19	$36.08	$38.11
I-15	13	478	$11,806.60	$5,219.76	$27,714.44	$44,740.80	**$93.60**	$61.63	$67.00	$70.77
I-86	7	192	$2,548.73	$1,126.81	$5,982.81	$9,658.35	**$50.40**	$33.19	$36.08	$38.11
TOTALS		**1656**	**$29,643.18**	**$13,105.41**	**$69,583.47**	**$112,332.05**	**$67.82**	**$41.09**	**$44.67**	**$47.27**

Notes: Number of storms reported by ITD data
Lane miles are the total miles of lane for all segments (ex. 1 mile of roadway with 2 lanes is 2 lane miles)
Average efficiency in maintenance operations = 25 miles per hour

Sand-Salt

The final material cost calculations made were for sand-salt mixtures. Table 28 presents the results of these comparisons. On an annual cost per lane mile basis, sand-salt mixtures are relatively inexpensive, particularly when compared to the costs of straight sand. The cost per lane mile for the use of sand-salt mixtures in Idaho averaged $45.07 per lane mile and a range between $33.49 and $62.20. The difference of these costs to straight sand is not surprising, as the use of a small portion of salt introduced into the mixture allows for a lower application rate. Idaho's annual cost per lane mile for maintenance using sand-salt is also lower than those of comparison states by a wide margin. Recall that Washington's high cost for salt per ton is at least partially responsible to the higher cost per lane mile figure for that state.

Table 28. Cost Per Lane Mile Comparison for Sand-Salt (2010).

Route	Storms (2010)	Lane Miles	Equipment Cost	Labor Cost	Material Cost	Total Costs	Annual Cost per Lane Mile (Idaho)	Annual Cost per Lane Mile (Kansas)	Annual Cost per Lane Mile (Washington)	Annual Cost per Lane Mile (North Dakota)
I-90	9	294	$5,031.03	$2,224.24	$5,413.65	$12,668.92	**$43.06**	$56.12	$76.09	$95.18
US-95	8	435	$6,611.70	$2,923.07	$7,114.53	$16,649.29	**$38.28**	$49.89	$67.63	$84.60
US-12	8	116	$1,769.83	$782.45	$1,904.43	$4,456.70	**$38.28**	$49.89	$67.63	$84.60
I-84	7	141	$1,875.30	$829.08	$2,017.92	$4,722.30	**$33.49**	$43.65	$59.18	$74.03
I-15	13	478	$11,806.60	$5,219.76	$12,704.52	$29,730.88	**$62.20**	$81.07	$109.90	$137.48
I-86	7	192	$2,548.73	$1,126.81	$2,742.57	$6,418.11	**$33.49**	$43.65	$59.18	$74.03
TOTALS		**1656**	**$29,643.18**	**$13,105.41**	**$31,897.62**	**$74,646.21**	**$45.07**	**$54.05**	**$73.27**	**$91.65**

Notes: Number of storms reported by ITD data
Lane miles are the total miles of lane for all segments (ex. 1 mile of roadway with 2 lanes is 2 lane miles)
Average efficiency in maintenance operations = 25 miles per hour

Discussion

As the comparisons of annual costs per lane mile have shown, sand and sand-salt mixtures are the lowest cost materials available to ITD. However, these materials come with associated costs that could not be incorporated into the calculations, namely post-season cleanup, as well as any prospective recycling effort that may be used in the future. The use of salt in Idaho as a treatment material was higher in terms of costs to sand-salt, making that material a less attractive option, although in reality straight sand is rarely used. Similarly, salt brines compared favorable in terms of costs, with only a slightly higher expense than granular salt. $MgCl_2$ brines were the most expensive treatment material compared by a significant margin. This underscores the importance of using such a material in more specific applications and locations to maximize the benefits achieved given its significant costs.

The data and records employed in this research did not allow a straightforward identification of the number of treatments/passes that were made by a plow on a particular segment. Consequently, it was assumed when comparing the annual costs per lane mile that a single pass had been made for each lane to treat and plow the roadway. Consequently, the costs per lane mile have likely been underestimated. Still, even when considering a single pass for a specific material, the results of the various comparisons allow for general conclusions to be drawn regarding the costs of various treatment materials.

When compared to the annual costs per lane mile that other states would experience for these same routes, Idaho performed quite favorably. This was in part due to lower equipment and labor costs, as well as lower costs for many of the materials being compared. In no case did Idaho appear to be paying an excessive amount for a given material.

Chapter Summary

This chapter presented a model that established the relationship between winter crashes and associated independent variables including chemical usage, traffic volume, and weather conditions. An Artificial Neural Network (ANN) was employed to estimate the benefits associated with winter chemicals. Sensitivity analysis was employed to determine how uncertainty in the model output was attributed to different sources of variation (ex. chemical costs by type). The methods were then applied to different routes for which complete data was available to investigate the tangible benefits and costs of winter maintenance.

When completed for routes that had complete datasets available (I-90 MP 0.0 – 40.391 and -2 MP 14.901 – 66.946), benefit-cost analysis showed that the use of winter chemicals produces greater benefits than costs incurred. When identifying the safety benefits of winter chemical use on I-90, it was determined that a reduction of 200 crashes had been achieved over 2008-2010 winter seasons through the use of liquid deicer and salt. Sensitivity analysis was unable to establish which of these materials was more preferable in reducing crashes however. Based on crash reduction estimates, a savings of $8,559,200 was achieved, compared to a cost of chemicals, labor and equipment of $1,545,108. This resulted in a benefit-cost ratio for the I-90 study segment of 5.54. A follow-up study using data from November and December of 2012 on I-90 found a reduction of 6 crashes through the use of chemicals, resulting in a savings of $256,776. Given the cost of chemicals used on the route, $229,863, this resulted in a benefit-cost ratio of 1.12. Note that in this latter case, labor and equipment costs were not available, so the true benefit-cost ratio may be lower.

When identifying the safety benefits of winter chemical use on US-12, it was determined that a reduction of 16 crashes had been achieved through the use of liquid deicer during the 2009-2010 season. Sensitivity analysis was unable to establish which of these materials was more preferable in reducing crashes however. Based on the crash reductions estimate, a savings of $684,726 was achieved, compared to a cost of chemicals, labor and equipment of $88,281. This resulted in a benefit-cost ratio for the US 12 study segment of 7.76.

When identifying the safety benefits of winter chemical use on US-95, it was determined that a reduction of 11 crashes had been achieved through the use of chemicals during the final months of 2012. Based on the crash reduction estimate, a savings of $470,756 was achieved, compared to a cost of chemicals of $100,795. This resulted in a benefit-cost ratio for the US-95 study segment of 4.67. Note that in this latter case, labor and equipment costs were not available, so the true benefit-cost ratio may be lower. Collectively, all of these results indicate that winter chemical maintenance plays a very important role on road safety.

The reader should note that the benefit-cost analysis only considered equipment costs, labor costs and chemical costs. The costs of winter chemicals have on surrounding environment and corrosion costs were not incorporated in this research. That means the cost of winter chemical maintenance may be higher than those taken into account here. In addition, the benefits and costs associated with winter chemicals presented here were computed for only a limited number of specific winter seasons. The collective benefits and costs produced from winter chemical usage will vary from season to season and are dependent on factors including, but not limited to winter storm severities, traffic volumes, and so forth.

Comparisons of the annual costs per lane mile found that sand and sand-salt mixtures were the lowest cost materials available to ITD. However, these materials come with costs that could not be incorporated into the calculations, namely post-season cleanup. The use of salt as a treatment material was comparable in terms of costs to sand and sand-salt, making that material an attractive option. Similarly, salt brines compared favorably in terms of costs, with only a slightly higher expense than granular salt. Consequently, it would appear from this evidence that salts and salt brines are the most cost effective treatment materials available for use, although one must take into consideration other aspects such as their effective working temperatures before their selection over other materials. $MgCl_2$ brines were the most expensive treatment material which underscores the importance of using such a material in more specific applications and locations. When compared to the annual costs per lane mile that other states would experience for these same routes, Idaho performed quite favorably.

Chapter 8
Conclusions and Recommendations

The purpose of this project was to compare the safety impacts and cost effectiveness of NaCl and $MgCl_2$ and identify best practices for performing winter maintenance based on safety and the cost-effectiveness of these materials. In the previous chapters, the research team reviewed literature regarding the positive and negative aspects of winter chemical use, surveyed the current practices and uses of different winter chemicals in ITD districts, summarized the crash data and completed data reduction for selected road segments throughout the state and analyzed the benefits and costs associated with using winter chemicals. This chapter summarizes the key findings and conclusions of this research study. The researchers also provide recommendations for using winter chemicals in winter maintenance.

Findings and Conclusions

The findings and conclusions of this research project are summarized in the following paragraphs. The literature review of winter chemical maintenance shows that sodium chloride is the most widely used chemical due to its abundance and low cost. But it is rarely used and minimally effective below pavement temperature of 10°F (-12.2°C). $CaCl_2$ and $MgCl_2$ exhibit better ice-melting performance than NaCl brine at cold temperatures. However, $CaCl_2$ and $MgCl_2$ are more costly and their residue on roads can attract more moisture than salt, resulting in slippery pavement conditions in some cases. In addition to chlorides, acetates are used for anti-icing and they are generally much more expensive. However, they can be more effective, less corrosive and not as environmentally harmful as chlorides.

The survey of salt brine operations in ITD Districts 1 and 5 found that non-inhibited salt brine was listed as the most commonly used product by respondents and salt brine has been used the majority of the time in the last 3 to 5 years. Furthermore, salt brine was listed as being using equally for anti-icing, deicing and pre-wetting. In addition, changes in air temperature and pavement temperature, followed by humidity cause deviations in typical application rates of salt brine more frequently. When application rates for salt brine are changed, the majority of respondents said experience was the basis for changes. Moreover, the majority of respondents stated that application rates have increased over time. [Note that a review of material use data from ITD records indicates that application rates for solids and liquids generally remained the same over time. Based on this observation, it appears that respondents were referring to product use increasing over time as a function of the number of storms per season and their severity.] In most cases, parameters like friction, bare pavement, and melting ability were selected by respondents to define the performance of salt brine. In addition, most respondents had no concerns with the use of salt brine, with impacts to concrete and corrosion to metal being of concern to a small group of respondents.

The survey of $MgCl_2$ operations in ITD Districts 2 and 3 found that corrosion-inhibited liquid $MgCl_2$ was listed as the most commonly used product. Other products including corrosion-inhibited solid $MgCl_2$

were also being used. All but 1 respondent have been using $MgCl_2$ for more than 5 years. Precipitation type and amount caused deviations in typical application rates of $MgCl_2$ most frequently, followed by changes in pavement temperature and air temperature. When application rates for $MgCl_2$ were changed, the respondents said that it was determined based on experience. Friction, bare pavement and melting ability were used to define the performance of $MgCl_2$. In addition, all respondents recommend that $MgCl_2$ should continue to be used in winter highway maintenance. However, the potential corrosion to metal caused by $MgCl_2$ was a concern.

Evaluation of snow and ice chemicals through laboratory testing yielded a number of conclusions. Under the established evaluation framework, one can conclude that the ITD salt brines featured the highest composite index of 64 and thus should be considered a best practice. (Recall that the composite index is a range from 0 to 100 that provides a normalized rating of a material based on its cost, performance and risks.) In contrast, the use of sand without salt lead to the lowest composite index of 33 and thus should be avoided in highway winter operations. The use of the 2 sand-salt mixtures featured low composite indices of 41 and 39 respectively and also should be avoided wherever possible. Arguably, brines, solid salts, and sand-salt mixtures are integral components of the highway winter maintenance toolbox and they are best suitable for different application scenarios.

When completed for routes that had complete datasets available (I-90 MP 0.0 – 40.391 and US-12 MP 14.901 – 66.946), benefit-cost analysis showed that the use of winter chemicals produces greater benefits than costs incurred. When identifying the safety benefits of winter chemical use on I-90, it was determined that a reduction of 200 crashes had been achieved through the use of liquid deicer and salt. Sensitivity analysis was unable to establish which of these materials was more preferable in reducing crashes however. Based on the crash reduction estimate, a savings of $8,559,200 was achieved, compared to a cost of chemicals, labor and equipment of $1,545,108. This resulted in a benefit-cost ratio for the I-90 study segment of 5.54. Crash savings on US-12 totaled $684,726, compared to chemical, equipment and labor costs of $88,281, producing a benefit-cost ratio of 7.76. For a limited case study using data from November and December 2012, crash savings on I-90 totaled $256,776 compared to chemical costs $229,863, producing a benefit-cost ratio of 1.12. A similar case study on US-95 for the same months found a crash savings of $470,756 compared to chemical costs $100,795, producing a benefit-cost ratio of 4.67.

Collectively, the benefit-cost analysis showed that the use of winter chemicals resulted in more benefits than costs. The benefits and costs associated with winter chemicals are summarized in Table 29. The benefits of using winter chemicals were much larger than winter chemical maintenance costs in all cases.

Table 29. Summary of Benefit-Cost Analysis.

Cases		I-90 (2008-10)	US-12 (2009-10)
Benefits ($)		$8,559,200	$684,726
Costs ($)	**Chemical Cost**	$1,487,572	$87,433
	Equipment Cost	$24,840	$2015
	Labor Cost	$32,696	$1693
Benefit-Cost Ratio		5.54	7.51

The benefit-cost analysis only considered equipment costs, labor costs and chemical costs, except for the I-90 and US-95 case studies from November-December 2012. The costs of winter chemicals have on surrounding environment and corrosion costs were not incorporated into this research. At the same time, other benefits (e.g., reduced travel time) were also not taken into account. Consequently, the total values of costs and benefits associated with winter chemicals would be higher than shown here.

Comparisons of the annual costs per lane mile found that sand and sand-salt mixtures were the lowest cost materials available to ITD. However, these materials come with costs that could not be incorporated into the calculations, namely post-season cleanup. The use of salt as a treatment material was comparable in terms of costs to sand and sand-salt, making that material an attractive option. Similarly, salt brines compared favorable in terms of costs, with only a slightly higher expense than granular salt. Consequently, it would appear from this evidence that salts and salt brines are the most cost effective treatment materials available for use, although one must take into consideration other aspects such as their effective working temperatures before their selection over other materials. $MgCl_2$ brines were the most expensive treatment material, which underscores the importance of using such a material in more specific applications and locations. When compared to the annual costs per lane mile that other states would experience for these same routes, Idaho performed quite favorably.

Level of Service

From the benefit-cost analysis, current winter maintenance practices seem reasonable. Consequently, ITD’s current LOS approach can be concluded as effective in quickly restoring roadway conditions from the perspective of reducing crashes and minimizing delays. The findings of this research can still be used in revising LOS guidance for the state in the future, should the need arise. For example, the findings of the materials evaluation in Chapter 4 could be used to develop more refinements to application rates. The approach in developing a revised LOS would likely be iterative, using input and feedback from ITD maintenance staff to adjust current procedures to account for different parameters including material cost and effectiveness, as well as priorities, such as those discussed in the next paragraph.

When considering LOS, more than simply system performance outcomes should be considered. For example, intangible costs and benefits can also be incurred and accrued through winter maintenance.

Intangible costs are costs that are incurred but that a value cannot or has not been assigned to. For example, the improved productivity drivers achieve through mobility on roads that are free of snow and ice is presently intangible, as existing research has not yet developed an approach to estimating its value. Intuitively, we know that delaying drivers through reduced mobility on winter roads impacts productivity, but this is difficult to measure and quantify. Similarly, indirect benefits, or savings accrued as a result of winter maintenance are also difficult to measure. For example, improved maintenance using chemicals rather than abrasives can reduce broken windshields. The benefit to motorists is time savings in not having to have repairs made, while the benefit to insurers (and sometimes the transportation agency) is reduced payment of claims. However, estimates of these types of benefits are difficult to make, particularly when private party information from insurance companies is involved. Potentially intangible costs and benefits stemming from the selection of different treatment materials include:

- Mobility
    - Reduced road closures
    - Improved productivity for the public (drivers)
- Safety
    - Decreased insurance claims (partially quantified in prior chapter as part of crash costs)
- Productivity (not quantified specifically to chemicals or LOS to date)
- Reduced Maintenance Costs (overtime, materials) (partially identified in cost comparisons of prior chapter)
- Reduced Clearance Times
- Environmental Quality
    - Reduced impact on roadside environment
    - Improved air quality (reduced abrasives)
- Other/Indirect
    - Reduced asset damage (vehicles, equipment)

To an extent, the contribution of some of these items has been touched upon throughout this report. In other cases, there is no suitable approach at present to begin assigning a value for the contribution (cost or benefit) a specific treatment material might have on an item. Consequently, this remains one area where future research is still needed. Regardless of whether a tangible value exists for the items listed above, there remains a need to take them into account when selecting specific materials to achieve a particular LOS.

When considering the socio-economic costs of different treatment strategies, particularly over a long time horizon such as a decade, it is difficult to estimate the various costs of alternative maintenance methods and materials. Over such a timeframe, sustainable winter operations should ideally maximize the use of existing materials and/or infrastructure, reduce the waste and minimize the carbon/environmental footprint of maintenance as much as possible. The best sustainable choices would reduce the social and economic and environmental impacts over the entire life cycle, while not sacrificing performance or cost effectiveness of the winter maintenance practices. As one can surmise, applying a fixed dollar cost to these different (and sometimes competing) aspects for estimation purposes is difficult. Many of the requisite values needed for estimation have not been quantified through research. To estimate the long term socio-economic costs of alternate maintenance methods in the next ten years, the following list of socio-economic and environmental costs to transportation agencies, road users and society would need to be better understood and quantified.

1. Transportation Agencies
    a. Costs of materials/infrastructure purchased and technologies installed/implemented, energy costs/fuel use (and efficiency)
    b. Costs of labor/staff training
    c. Costs of corrosion to roadway and infrastructure
2. Road users
    a. Costs of travel time delays
    b. Road closure costs
    c. Safety/crash reductions and corresponding costs
    d. Costs of vehicle corrosion
3. Society/Environment
    a. Environmental risks/damages
    b. Increased vehicle emissions

As one can see from this list, there are a large number of variables that all play a part in the socio-economic costs of winter maintenance. The quantification of these variables is a challenge, particularly when it is not known what future energy costs, laws (particularly environmental), material availability/costs, and other changes will occur over a long timeframe. Consequently, while the different categories of impacts can be established, the costs associated with different winter maintenance methods are not easy to establish.

General Recommendations

Based on the findings of this work, the researchers have developed recommendations for the use of chemicals in winter maintenance. Although data limitations such as limited material usage records precluded more detailed case studies of the selected routes to determine the impacts of using specific winter maintenance chemicals, meaningful recommendations for winter maintenance strategies can still be provided. The recommendations of this study are as follows:

1) For high traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: anti-ice using a salt brine at 20-30 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or an engineered salt brine at 20 gallons per lane mile. For low traffic volume roads under light snowfall, pavement temperature 15°F - 20°F: use an engineered salt brine to anti-ice at 30-50 gallons per lane mile or de-ice using a salt brine at 30-60 gallons per lane mile or de-ice at 35-70 gallons per lane mile. The upper limit of the recommended application rates corresponds to the lower limit of the target pavement temperature range. For colder pavements (10ºF to 15ºF), $MgCl_2$ brine may be a better choice to use for either anti-icing or liquid deicing. For extremely cold pavement (below 10ºF), the use of liquid deicer is risky and needs to be validated before implementation and prewet salt may be used for deicing. To achieve the friction benefits of anti-icing or deicing on pavement, plowing is highly recommended once sufficient time has been allowed

for the chemical to interact with snow precipitation and traffic. Avoid anti-icing below 20°F when there are strong winds, heavy snowfall, or freezing rain conditions.

2) The use of solid salts, brine and sand-salt mixtures in deicing depend on how quickly bare pavement is desired and whether a temporary traction layer is needed. Salt brines are generally most effective, with a composite index of 64, while sand and sand-salt mixtures are less desirable, with composite indexes of 33 (sand) and 39 to 41 (sand-salt). However, in cases where the removal of snow and ice on the pavement would require too much chemical or the pavement temperature is too cold for common chemicals to work (e.g., 5ºF or below) , the use of sand-salt mixture is the last resort to obtain safe traction levels.
3) Different types of winter chemicals may have different impacts on road safety, which means the use of improper winter chemicals may cause various kinds of problems on road safety (e.g., slippery pavement surface). Different winter chemicals should be chosen for winter maintenance in various conditions with this potential in mind. For instance, for pavement temperature higher than 20°F, the use of magnesium or calcium chloride brine is not recommended as the use of salt brine can work at least as effectively and avoid potential risk of slippery pavement. For pavement temperature lower than 10ºF, the use of salt brine is generally not recommended as it may lead to refreeze unless unusually high application rates are used.
4) The case studies show that the crashes decrease with the increase of winter chemical usage. Winter chemicals play an important role on road safety, and the results of the analysis show their necessity as part of the overall winter maintenance strategy employed.
5) In all of the case studies performed, NaCl brine and $MgCl_2$ liquid deicers and granular NaCl and $MgCl_2$ were the chemicals used to treat the roadways segments. Each was found effective in reducing crashes to varying extents, depending on the specific study roadway. From the results of sensitivity analysis, it would appear that liquid deicers are slightly more effective in reducing crashes. However, it must be stressed that both materials were effective in reducing crashes overall, which one would expect. It is difficult to determine which material was more capable of reducing crashes than the other given the data that was available.
6) Based on the results of lab tests and the observations of the case studies, it would appear that the use of NaCl brine is preferable to $MgCl_2$ in many winter maintenance applications, provided the effective temperature range for a specific product is taken into account.
7) From the review of winter maintenance chemicals, it is known that some may cause corrosion to the equipment and may influence the surrounding environment. The addition of corrosion inhibitors and other additives may effectively address these risks but may increase the direct cost of the materials significantly. Proactive maintenance and other best practices can help mitigate the corrosive effects of deicers on vehicles and infrastructure. For specific highway segments where corrosion and other environmental risks are of a significant concern (e.g., where historical landmark bridge or sensitive species are present), consider the use of a more engineered material to minimize the risks.
8) In terms of future evaluations, complete material use records, as well as transportation agency costs (materials, equipment, technology, fuel use, labor, training and corrosion), road user costs (delays, road closures, safety, corrosion) and societal and environmental costs (damage, emissions) are

needed to provide more comprehensive guidance on when and where specific materials may be used.

9) ITD's recent use of Automatic Vehicle Location (AVL technology, which has enabled the collection of specific material usage data by location will be a significant benefit to future evaluations. This data will allow a direct comparison to be made between material type, use and timing and storm-related crashes.

A further discussion related to recommendations on chemical types is presented in the next section. In addition to the recommendations made regarding chemical treatments, it is also recommended that ITD take steps to better inform decision-makers and the general public about the different approaches used in performing winter maintenance. To this end, a later section of this chapter discusses initial thoughts and concepts on how that outreach might be accomplished.

Chemical Types

Based on the findings of the lab analysis of material samples provided by ITD, a number of recommendations can be drawn regarding the types of chemicals that should be used. One can conclude that the ITD salt brines which featured the highest composite index of 64 should be considered a best practice. However, the use of sand without salt lead to the lowest composite index of 33 and thus should be avoided in highway winter operations. The use of sand-salt mixtures featured low composite indices of 41 and 39 respectively and also should be avoided wherever possible. The specific use of brines, solid salts, and sand-salt mixtures are of course suitable for different application scenarios.

Based on the results of the lab tests, it would be advisable to employ products such as NaCl and $MgCl_2$ brines under their appropriate temperature requirements. Both liquid brines and granular salts were found to be effective in preventing crashes in deicing applications, so their use should continue. Currently the ITD districts generally rely on either NaCl or $MgCl_2$ brines rather than having both at their arsenal, it is desirable to have both types of brines available. It would take initial equipment investment and sustained training to obtain and optimize the ability to switch from one type of brine to another type in light of changing road weather scenario. However, this ability would help reduce the amount of chemicals required to maintain a reasonable level of service on winter highways, thus significantly reducing the direct and indirect costs associated with snow and ice control.

The future use of sand-salt mixtures may continue, although careful consideration of their use should be made given the low composite indices associated with these materials. Limited spot use for improved traction (ex. intersections) may be the most advisable overall use of these treatments. When considering the results of the safety analysis, no firm conclusions can be drawn regarding the use of chemicals for anti-icing, as inadequate usage records were available in support of the analysis.

Recommendations related to appropriate application rates cannot be developed based on the information available for analysis. However, it would appear from the general crash trends observed over time and the overall results of the analysis, that ITD staff have done an effective job of reaching an appropriate selection of materials and application rates for different chemicals over time. This could be characterized as "self-adjusting practices" where changes have been made based on local needs and observations by ITD staff that has led the most appropriate material applications being made. However, given the limited nature of the case study analysis that could be completed, a confirmation of whether this is in fact the situation statewide on multiple routes could not be made. However, one would expect that given the current practices and policies in place by ITD, this is likely to be the case. In the future, as detailed records stored in an electronic format expand, namely data from the Transportation Asset Management System (TAMS) and AVL, assessment of applications rates should become more straightforward.

Public Awareness

Based on the findings presented in this chapter and discussed elsewhere in this report, the positive benefits attained through the use of chemicals in winter maintenance should be highlighted in various ways. The following sections provide initial thoughts and concepts for approaches to conveying information on ITD practices to the public and decision-makers.

Brochures

One low cost approach to alerting the public to winter crashes and the chemicals used in maintenance is through brochures. Such brochures can be distributed at locations such as rest areas and Division of Motor Vehicle offices (particularly as a handout with annual renewals of license plates) to increase public awareness of the hazards of winter driving, the benefits that winter maintenance chemicals produce and other relevant information. By increasing awareness via this mechanism, the public will have a better understanding of what ITD is doing to enhance winter driving safety and become more aware of the justifications for winter maintenance expenditures.

During the course of this project, an understanding has developed regarding the prospective reductions in crashes that result from the use of winter maintenance chemicals. While the specific reductions were not estimated on a statewide basis nor broken out by a specific treatment type, initial estimates have provided an indication of the potential reductions that winter chemicals produce in general terms. This provides a talking point that can be presented in an informational brochure, along with general crash trends during winter months and facts about the chemicals ITD uses. The following is a mock-up of such a prospective brochure; note that a more finalized version of such a brochure would need to have updated facts and figures based on the current information and practices used by ITD.

Keeping Idaho's Roads Clear!

In Idaho, winter weather is a fact of life. The Idaho Transportation Department (ITD) faces the challenge of maintaining roads during the winter by performing snow and ice control to ensure travelers remain safe, mobile and productive.

ITD's snow and ice control methods have had a major, positive impact on traveler safety and mobility. In a case study for selected routes in the state, it was observed that *the use of winter maintenance chemicals reduced crashes by 38 percent, and keeping roads clear allows for reduced delay*.

What types of winter maintenance does ITD perform?

ITD uses traditional (e.g., snowplowing, sanding and salting) and enhanced (e.g., anti-icing) methods to maintain roads.

- *Plowing* – Removal of snow and ice buildup from road surfaces.
- *Apply abrasives* – Spread sand (sometimes mixed with salt) to provide traction.
- *Apply chemicals* – Anti-icing or deicing to prevent or melt snowpack or ice.

What types of winter maintenance chemicals does ITD use?

Salt – Granular chlorides used on winter roadways to either prevent the bonding of ice to the roadway (anti-icing) or break the bond between ice and the roadway (deicing)

Liquid Salt Brine – Brine solution serving as a liquid roadway treatment similar to granular salt.

Liquid Magnesium Chloride – Brine solution for anti-icing, which exhibits better ice-melting performance than salt brine at cold temperatures.

Sand (sometimes with salt) – abrasive material applied to roadway to increase traction.

What are the impacts of these treatments?

The treatments used by ITD may cause damage to vehicles or the environment in some cases. Chemicals such as road salt are generally corrosive if a corrosion inhibitor is not added. Regular vehicle washing aids in reducing corrosion. Air quality, water quality along with endangered species can be harmed by the traditional use of abrasives, especially when used in large quantities or in sensitive locations.

Note that the images presented in the brochure are from ITD's current winter maintenance website. The intent of the images is to present views related to the general topic of winter maintenance, and these can be changed to match the general tone and focus of the brochure as it is more fully developed.

Winter Maintenance Website

At present, ITD maintains a winter maintenance-specific website at http://itd.idaho.gov/highways/WinterMaintenance/WinterMaint-Home.htm. The website provides a good overview of Idaho's winter maintenance activities in a manner that can be readily understood by the general public. The information presented on the website provides an overview of activities, specifics on liquid deicers, responsibilities of winter drivers, a winter driving checklist and regulations on studded snow tires.

Inclusion of an additional page providing supplemental information/brochures on specific topics, such as the benefits and costs of winter maintenance or more details on other winter maintenance chemicals should also be considered. This information would further public awareness of winter maintenance chemicals and the benefits they provide. The information presented would provide an overview of the different treatment materials being used in Idaho, their benefits (and impacts) and a discussion on how they improve safety. A brochure such as the one discussed in the prior section would also be provided on this portion of the site. Finally, a separate section could be developed discussing the general trends and specific types of winter crashes observed in Idaho, as well as tips for avoiding being in those types of crashes. This information would supplement that which is already provided by ITD's website, rather than replace it.

Changeable Message Sign Messages

Another prospective approach to increasing public awareness is the use of Changeable Message Sign (CMS) message sets throughout the winter season. From past experience, it has been recognized that messages must be succinct in order for a driver to read and comprehend them. Consequently, the use of CMS signs to present facts on winter maintenance chemicals, crash trends or other information is not practical. Rather, CMS messages should focus on conveying messages to drivers that increase their alertness and encourage safer driving. Based on this, prospective messages that could be employed in Idaho include:

- "Ice & Snow Take It Slow" (Developed by ClearRoads pooled fund and used nationally) – used during a storm event.
- Slow Down Under Winter Road Conditions – used before or during a storm event.
- Take Care Driving in Snow - used before or during a storm event.
- Crashes Increase on Slick Roads Slow Down - used before or during a storm event.

In all cases, these messages must be reviewed by proper staff to ensure that they are compliant with existing ITD practices and will not present any potential legal issues to the department. While CMS messages cannot present exact facts on winter crashes or chemicals, they can still provide points for drivers to consider before and during storm events that can have a positive impact on safety.

Appendix A
Survey: Evaluating the Effectiveness of Winter Chemicals on Reducing Crashes in Idaho-Magnesium Chloride

This survey is being undertaken by the Western Transportation Institute, Montana State University, and is part of work being sponsored by the Idaho Transportation Department. The purpose of the survey is to obtain specific information pertaining to the use and performance of Magnesium Chloride in your District. If you would like to participate, please take a few minutes and answer the questions below. This survey is estimated to take between 5 and 10 minutes to complete. Participation is voluntary. You can choose to not answer any question that you do not want to answer, and you can stop at any time.

Your contact information will only be used by the researchers for the purposes of this study. The researchers may contact you for clarification, and your contact information will not be released or shared for any reason. If you have any questions about the survey, please contact WTI at laura.fay@coe.montana.edu or call (406) 600-5777. If you have any questions concerning your rights as a human subject and/or the use of your contact information, please contact:

Institutional Review Board
Montana State University
P.O. Box 173610
Bozeman, MT 59717-3610
Phone: (406) 994-6783
Fax: (406) 994-4303

Survey directions
In order to progress through this survey, please use the navigation links presented on the survey pages:
- Use the Next button to continue to the next page.
- Use the Previous button to return to the previous page.
- Use the Exit the Survey link to exit the survey.
- Use the Submit button on the last page to submit your survey responses.

Note: Clicking the Back button in your browser before a page is completed will clear all data entered on the current page. You may not leave a survey session and start up again where you left off.

Please click the Next button to proceed to the survey:

1. Does your district use the following products in your Winter Maintenance Operations? If so, please provide an estimated percentage of use next to each option.

Corrosion-inhibited salt brine	
Non-inhibited salt brine	
Corrosion-inhibited Magnesium Chloride liquid (MgCl2)	
Non-inhibited MgCl2 liquid	
Corrosion-inhibited Magnesium Chloride solid (MgCl2)	
Non-inhibited MgCl2 solid	
Other (please specify)	

2. How many years have you been using Magnesium Chloride (MgCl2) in your Winter Maintenance Operations?

- 1 year or less
- 3 years or less
- 5 years or less
- More than 5 years

3. Which vendor, makes the Magnesium Chloride (MgCl2) you use? Where is it delivered from?

4. How do you use Magnesium Chloride (MgCl2) in your Winter Maintenance Operations?

- ☐ Deicing (solid product)
- ☐ Anti-icing (liquid product)
- ☐ Pre-wetting (liquid)
- ☐ Other (please specify)

5. If you use pre-wetting in you Winter Maintenance Operations, please provide your definition of pre-wetting.

- ○ We do NOT use pre-wetting
- ○ We use pre-wetting (provide definition below)

Definition of pre-wetting

6. Please provide typical application rates used for Magnesium Chloride (MgCl2) during Winter Maintenance Operations for:

Deicing

Anti-icing

Pre-wetting

Other (please explain)

7. Do your typical application rates for Magnesium Chloride (MgCl2) used in Winter Maintenance Operations deviate from the FHWA and ITD guidlines? If so why?

8. Changes in what parameters would cause you to deviate from your typical Magnesium Chloride (MgCl2) application rates?

- ☐ We NEVER deviate from our typical application rates.
- ☐ Air temperature
- ☐ Pavement temperature
- ☐ Humidity
- ☐ Precipitation type/amount
- ☐ Traffic volumes
- ☐ A crash or vehicle off the road
- ☐ Time of day
- ☐ Day of week
- ☐ Holidays
- ☐ Other (please specify)

9. When application rates for Magnesium Chloride (MgCl2) are changed the decision is based on:

- ☐ We NEVER change application rates.
- ☐ Experience
- ☐ ITD guidelines

Other (please specify)

10. Who determines what application rates for Magnesium Chloride (MgCl2) are used?

- ☐ Driver/Operator
- ☐ Maintenance Shed Direction
- ☐ ITD guidelines
- ☐ Other (please specify)

11. How have application rates for Magnesium Chloride (MgCl2) changed over time?

	Increased	Decreased	No change in application rates over time.
Deicing	☐	☐	☐
Anti-icing	☐	☐	☐
Pre-wetting	☐	☐	☐

Other (please specify)

12. Under what temperature ranges do you typically use Magnesium Chloride ($MgCl_2$) for winter maintenance operations and in what form (liquid vs. solid)?

Deicing

Anti-icing

Pre-wetting

Other (please specify)

13. What is the coldest temperature you will apply Magnesium Chloride ($MgCl_2$) during Winter Maintenance Operations?

Deicing

Anti-icing

Pre-wetting

Other (please specify)

14. What is the warmest temperature you will apply Magnesium Chloride ($MgCl_2$) during Winter Maintenance Operations?

Deicing

Anti-icing

Pre-wetting

Other (please specify)

15. How many lane miles does your district maintain during the winter season?

16. What percentage of total district-wide lane miles are the following techniques used for snow and ice control?

Anti-icing

Deicing

Pre-wetting

17. How much does the Magnesium Chloride ($MgCl_2$) you use cost? (Please provide the data as detailed as possible, for example: per gallon, per storm, total cost per year, etc. Consider not only the materials costs but also the storage/handling, labor and equipment costs.)

- I have this information.
- I do NOT have this information.

Please provide cost data for solid or liquid $MgCl_2$ here.

18. Do you experience any issues with the storage and handling of $MgCl_2$, or its costs equipment (e.g., due to corrosion)? If so, please provide any cost information you may have in these aspects.

- Yes
- No

If yes, please explain.

19. How much Magnesium Chloride ($MgCl_2$) do you use in a typical winter season? Please provide an estimate or preferably the actual usage data for the past years.

20. Please comment on the typical road weather scenarios for winter highway maintenance in your district and your main challenges with the use of chemicals for snow and ice control.

21. Are "trouble" spots, areas of frequent crashes or vehicles off the road identified at the District level and treated differently?

Yes (please explain)

No

22. Once a crash has occurred, or a vehicle has run off the road, are additional resources sent to the site to apply more Magnesium Chloride ($MgCl_2$)? If yes, what are typical application rates for this situation (liquid and/or solid product)?

Yes

No

Other (please specify)

23. How do you define the performance of Magnesium Chloride (MgCl2)?

- ☐ Friction measurements
- ☐ Bare pavement
- ☐ Melting ability

Other (please specify)

24. Compared to other deicing, anti-icing and pre-wetting materials you have used during Winter Maintenance Operations, rank Magnesium Chloride (MgCl2) on a scale of 1-5, 1 being best, 5 being the worst.

	1 (best)	2	3	4	5 (worst)
Performance	☐	☐	☐	☐	☐
Ease of use	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Operator satisfaction	☐	☐	☐	☐	☐
Road user satisfaction	☐	☐	☐	☐	☐

Other (please specify)

25. Do you have any concerns about the use of Magnesium Chloride (MgCl2) in Winter Maintenance Operations? If so please explain.

- ☐ I have NO concerns about the use of MgCl2.
- ☐ Road User or Operator Safety
- ☐ Environment
- ☐ Performance
- ☐ Corrosion to metals
- ☐ Impacts to concrete
- ☐ Cost per lane mile
- ☐ Other areas of concern or further explain conerns checked above.

26. In your opinion, should your district continue the use of MgCl2 for winter highway maintenance in the next ten years? Please comment on other alternatives as well.

- ○ Yes
- ○ No

Other (please specify)

27. Please indicate what District you work in.

- ○ 1
- ○ 2
- ○ 3
- ○ 5

28. Please provide your contact information if you are willing to be contacted with follow-up questions or if you are able to provide cost data for Magnesium Chloride (MgCl2).

Name:
Company/Title:
Address 1:
Address 2:
City/Town:
State/Province:
ZIP/Postal Code:
Country:
Email Address:

Appendix B
Survey: Evaluating the Effectiveness of Winter Chemicals on Reducing Crashes in Idaho – Salt Brine

This survey is being undertaken by the Western Transportation Institute, Montana State University, and is part of work being sponsored by the Idaho Transportation Department. The purpose of the survey is to obtain specific information pertaining to the use and performance of Salt Brine/Magnesium Chloride in your District. If you would like to participate, please take a few minutes and answer the questions below. This survey is estimated to take between 5 and 10 minutes to complete. Participation is voluntary. You can choose to not answer any question that you do not want to answer, and you can stop at any time.

Your contact information will only be used by the researchers for the purposes of this study. The researchers may contact you for clarification, and your contact information will not be released or shared for any reason. If you have any questions about the survey, please contact WTI at laura.fay@coe.montana.edu or call (406) 600-5777. If you have any questions concerning your rights as a human subject and/or the use of your contact information, please contact:

Institutional Review Board
Montana State University
P.O. Box 173610
Bozeman, MT 59717-3610
Phone: (406) 994-6783
Fax: (406) 994-4303

Survey directions
In order to progress through this survey, please use the navigation links presented on the survey pages:
- Use the Next button to continue to the next page.
- Use the Previous button to return to the previous page.
- Use the Exit the Survey link to exit the survey.
- Use the Submit button on the last page to submit your survey responses.

Note: Clicking the Back button in your browser before a page is completed will clear all data entered on the current page. You may not leave a survey session and start up again where you left off.

Please click the Next button to proceed to the survey:

1. Does your district use the following products in your Winter Maintenance Operations? If so, please provide the estimated percentage of use next to each option.

Corrosion-inhibited salt brine	
Non-inhibited salt brine	
Corrosion-inhibited Magnesium Chloride liquid(MgCl2)	
Non-inhibited MgCl2 liquid	
Other (please specify)	

2. How many years have you been using Salt Brine in your Winter Maintenance Operations?

- ○ 1 year or less
- ○ 3 years or less
- ○ 5 years or less
- ○ More than 5 years

3. Do you make salt brine on-site?

- ○ Yes
- ○ No

If Yes, please describe the equipment you have on-site to make Salt Brine.

[ ]

4. If you answered No to Question 3. does ITD or a vendor make Salt Brine at another location and deliver it?

- ○ Yes
- ○ No

If yes, who makes it, where is it made and delivered from?

[ ]

5. How do you use Salt Brine in your Winter Maintenance Operations?

- ☐ Anti-icing
- ☐ Deicing (Direct Liquid Application)
- ☐ Pre-wetting
- ☐ Other (please specify)

[ ]

6. If you use pre-wetting in your Winter Maintenance Operations, please provide your definition of pre-wetting.

- ○ We do NOT use pre-wetting
- ○ We use pre-wetting (provide definition below)

Definition of pre-wetting

[ ]

7. Please provide typical application rates used for Salt Brine during Winter Maintenance Operations for:

Anti-icing	
Pre-wetting	
Other (please explain)	

8. Do your typical application rates for Salt Brine used in Winter Maintenance Operations deviate from the FHWA and ITD guidlines? If so how and why?

9. Changes in what parameters would cause you to deviate from your typical Salt Brine application rates?

- ☐ We NEVER deviate from our typical application rates.
- ☐ Air temperature
- ☐ Pavement temperature
- ☐ Humidity
- ☐ Precipitation type/amount
- ☐ Traffic volumes
- ☐ A crash or vehicle off the road
- ☐ Time of day
- ☐ Day of week
- ☐ Holidays
- ☐ Other (please specify)

10. When application rates for Salt Brine are changed the decision is based on:

- ☐ We NEVER change application rates.
- ☐ Experience
- ☐ ITD guidelines

Other (please specify)

11. Who determines what application rates for Salt Brine are used?

- ☐ Driver/Operator
- ☐ Maintenance Shed Direction
- ☐ ITD guidelines
- ☐ Other (please specify)

12. How have application rates for Salt Brine changed over the past years in your district?

	Increased	Decreased	No change in application rates over time.
Anti-icing	○	○	○
Pre-wetting	○	○	○

Other (please specify)

13. Under what temperature ranges do you typically use Salt Brine for Winter Maintenance Operations?

Anti-icing

Deicing

Pre-wetting

Other (please specify)

14. What is the coldest temperature you will apply Salt Brine during Winter Maintenance Operations?

Anti-icing

Deicing

Pre-wetting

Other (please specify)

15. What is the warmest temperature you will apply Salt Brine during Winter Maintenance Operations?

Anti-icing

Deicing

Pre-wetting

Other (please specify)

16. How many lane miles does your district maintain during the winter season?

17. What percent of total district-wide lane miles are the following techniques used for snow and ice control?

Anti-icing

Deicing

Pre-wetting

18. How much does the Salt Brine you use cost? (Please provide the data as detailed as possible, for example: per gallon, per storm, total cost per year, etc. Consider not only the materials costs but also the storage/handling, labor and equipment costs).

- ◯ I have this information.
- ◯ I do NOT have this information.

Please provide cost data for salt brine here.

19. Do you experience any issues with the storage and handling of salt brine, or its cost to equipment (e.g., due to corrosion)? If so, please provide any cost information you may have in these aspects.

- ◯ Yes
- ◯ No

If yes, please explain.

20. How much Salt Brine does your district use in a typical winter season? Please provide an estimate or preferably the actual usage data for the past years.

21. Please comment on the typical road weather scenarios for winter highway maintenance in your district and your main challenges with the use of chemicals for snow and ice control.

22. Are "trouble" spots, areas of frequent crashes or vehicles off the road identified at the District level and treated differently?

Yes (please explain)

No

23. Once a crash has occured, or a vehicle has run off the road, are additional resources sent to the site to apply more Salt Brine? If yes, what are typical application rates for this situation (liquid and/or solid product)?

Yes

No

Other (please specify)

24. How do you define the performance of Salt Brine?

- ☐ Friction measurements
- ☐ Bare pavement
- ☐ Melting ability

Other (please specify)

25. Compared to other deicing, anti-icing and pre-wetting materials you have used during Winter Maintenance Operations, rank Salt Brine on a scale of 1-5, 1 being best, 5 being the worst.

	1 (best)	2	3	4	5 (worst)
Performance	☐	☐	☐	☐	☐
Ease of use	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Operator satisfaction	☐	☐	☐	☐	☐
Road User satisfaction	☐	☐	☐	☐	☐

Other (please specify)

26. Do you have any concerns about the use of Salt Brine in Winter Maintenance Operations? If so please explain.

- ☐ I have NO concerns about the use of Salt Brine.
- ☐ Road User or Operator Safety
- ☐ Environment
- ☐ Performance
- ☐ Corrosion to metals
- ☐ Impacts to concrete
- ☐ Cost per lane mile
- ☐ Other areas of concern or further explain conerns checked above.

27. In your opinion, should your district continue the use of salt brine for winter highway maintenance in the next ten years? Please comment on other alternatives as well.

- ○ Yes
- ○ No

Other (please specify)

28. Please indicate which District you work in.

- ○ 1
- ○ 2
- ○ 3
- ○ 5

29. Please provide your contact information if you are willing to be contacted with follow-up questions or if you are able to provide cost data for Salt Brine.

Name:

Company/Title:

Address 1:

Address 2:

City/Town:

State/Province:

ZIP/Postal Code:

Country:

Email Address:

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