Benefit-Cost of Various Winter Maintenance Strategies

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16. Various costs and benefits are incurred while performing winter maintenance operations. However, a summary of these costs and benefits for different maintenance scenarios has not been compiled to date. This report summarizes past work that documented the quantified and non-quantified costs and benefits of three different winter maintenance strategies of interest; use of abrasives, salts and other chemicals in solid and liquid forms, and snow plows. Basic strategies were defined as plowing and use of abrasives, intermediate strategies were defined as the use of rock salt and salt brine (NaCl), and advanced strategies were defined as the use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, and blended products. These approaches employ different components, both in terms of equipment as well as materials. Some components of the various strategies have better cost and benefit information available than others. This is particularly true of sanding/abrasives and salting. Other, more recently developed and employed approaches and materials have more limited cost and benefit information published. There are also a number of different environmental impacts associated with different components of each maintenance strategy. Using information gained from the literature review, surveys, and interviews summary benefit-cost matrices were developed for various winter maintenance strategies. Information and data gap analysis has aided in identification of areas for recommended research. This document is intended for use by transportation agencies, such as by maintenance supervisors, to aid in the decision making process in terms of the selection of winter maintenance strategies used to achieve a prescribed LOS.

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Final Report

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Executive Summary

Various costs and benefits are incurred while performing winter maintenance operations. However, a summary of these costs and benefits for different maintenance scenarios has not been compiled to date. This summary report provides all levels of decision-makers with information on which to base sound decisions. In doing so, agencies could better maximize the roadway level of service relative to the maintenance strategy's costs and have a mechanism to explain the available options, their costs, benefits, and consequences to various stakeholders, including DOT personnel, legislators, and the general public.

In order to facilitate that summary, it was necessary to identify past work that identified the quantified and non-quantified costs and benefits of three different winter maintenance strategies of interest to this project. The first strategy was basic and consisted of actions performed to maintain traveler mobility and safety, including plowing and the use of abrasives (sanding). A second, intermediate strategy reflected an improvement over the basic approach; it consists of plowing and the use of some abrasives in spot locations, but also relies on salt in solid or liquid forms for anti-icing and deicing. The third strategy uses magnesium chloride, calcium chloride, and blended products such as corrosion-inhibiting liquids and/ or treated or chemically enhanced solid chemicals in anti-icing and deicing to address the corrosion risks associated with untreated materials. This strategy allows for the selection of specific chemicals that will work best in a specific climatic region or temperature range, avoiding the overuse of salt or salt brine at colder temperatures as may be the case in the second strategy. Collectively, these three approaches employ various equipment and materials. Such components include materials such as abrasives, salts and other chemicals in solid and liquid forms, and snow plows. Literature related to these various components was identified and summarized during the course of a literature review, the results of which are presented in this document.

Some components of the various strategies of interest have better cost and benefit information available than others. This is particularly true of sanding/abrasives and use of road salt (sodium chloride). This may stem from the historical use over time, and because this has been the most common treatment used by maintenance agencies. Historically, salting approaches have provided benefits that generally exceed the quantified costs associated with them, not factoring in environmental impacts. For example, they have been shown to reduce crashes and improve or maintain mobility (travel time and speeds). The costs and benefits of snow plows, which represent the other common approach historically employed by agencies, have not been as well defined. It is possible that agencies have difficult separating the contribution of plowing versus material usage.

Other approaches developed and employed in the past two to three decades (e.g. prewetting and materials such as magnesium chloride and calcium chloride) have more limited cost and benefit information published. While the cost of the equipment and materials are available from agency records (although it did not appear in literature), benefit information is generally lacking outside of generalized terms. Such information gaps were addressed through an agency survey conducted by this project.

As one would expect, there are a number of different environmental impacts associated with different components of each maintenance strategy. This is particularly true of materials, each of which had negative impacts on the environment. In some cases, equipment, alternative materials

or practices can be employed to reduce this impact. For example, the use of prewetting can facilitate adhesion and enhance melting action of granular chemicals, such as salt and magnesium chlorides. Similarly, wetting abrasives with hot water can enhance adhesion to ice and snow covered pavements, reducing bounce and scatter into the roadside environment. Research has shown prewetting of sand to provide up to 25 percent material savings, and prewetting rock salt to provide 20 to 33 percent material savings. Additionally, one researcher found $CaCl_2$ to be 9.5 to 71.4 percent more effective as a prewetting agent and outperformed $MgCl_2$.

The results of the survey and interviews have been incorporated into the benefit-cost matrices. In general, the survey and interviews identified Basic and Intermediate Activities as the most commonly used winter maintenance strategies. This includes plowing, use of abrasives, use of solid and liquid salt (sodium chloride) for deicing and anti-icing. Less commonly reported was the use of the Advanced Activities including the use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, or blended products. This may be indicative of these winter maintenance strategies being less commonly employed, a result of who responded to the survey and interviews, or the result of survey fatigue. Gathering information on costs associated with the various winter maintenance strategies from the individuals surveyed and interviewed was a challenge. This may be due to a lack of available data, a lack of ability to access the data, or a lack of available time for interviewees to spend gathering the data. This highlights the need for easy to use cost-tracking tools for use by winter maintenance professionals.

The information gathered in the literature review, surveys, and interviews was used to populate the developed benefit-cost matrix. The matrix is presented as three sub-matrices Basic Activities, Intermediate Activities, and Advanced Activities. Within each sub-matrix information is reported on the cost, benefits, effectiveness in achieving LOS, positive and negative impacts, pros and cons, respective performance, environmental impacts, and the calculated benefit-cost ratio where possible. Benefit-cost ratios were calculated for all winter maintenance strategies with the exception of the use of corrosion inhibitors because not enough information was available to successfully calculate a ratio as shown in Table 1.

Table 1. Summary of winter maintenance strategies and the calculated benefit-cost ratios.

Activities	Winter Maintenance Strategy	Benefit/Cost Ratio
Basic	Plowing	5.3
	Abrasives	0.2
Intermediate	Rock salt (solid NaCl)	2.4
	Salt brine (liquid NaCl)	3.8
Advanced	Corrosion inhibitors	8.0-13.2*
	Inhibited salt brine	3.8
	Magnesium Chloride ($MgCl_2$)	3.6
	Calcium Chloride ($CaCl_2$)	3.8
	Blended products	3.8 - 4.0

*The B/C ratios represent the use of proactive maintenance and corrosion prevention. Calculated by Shi et al., 2013a; Honarvarnazari et al., 2015.

Knowledge gaps and future research recommendations include the need to support winter maintenance agencies in keeping detailed cost data. Specifically, a cost analysis of corrosion inhibitors and agriculturally derived products is needed.

Chapter 1
Introduction

Highway agencies such as Departments of Transportation (DOTs) are tasked with numerous responsibilities, including winter maintenance operations. When completing winter maintenance, agencies employ a suite of approaches customized to their local snow and ice control needs and funding, staffing, and equipment constraints.

This can include, but is not limited to the following options depending on the road weather scenarios, resources available, and local rules of practice:

- Anti-icing, deicing, and sanding
- Mechanical removal (e.g., snowplowing)
- Snow fencing

On average, state DOTs expend roughly 20% of their budgets on such activities, with a direct cost of $2.3 billion and an indirect (infrastructure and environmental) cost of $5 billion annually (FHWA, 2014).

Typically, the strategies employed by agencies come with many tradeoffs. The costs include resources expended by the agency, corrosion and abrasive wear, and potential environmental impacts. Benefits can include economic impacts to society and increased safety and mobility for travelers. In light of these costs and benefits, it is necessary to assess and communicate how different strategies can produce the most cost-effective winter maintenance approach.

A helpful analogy is to think of winter maintenance as a staircase. The ***initial step*** consists of the most basic activities that can be performed in order to maintain traveler mobility and safety. The first step consists of activities such as plowing and the use of abrasives (sanding). These activities can have some effectiveness in terms of maintaining mobility and safety. Vehicles are provided with traction, but travel speeds are greatly reduced, and snow and ice are still likely to build up on the roadway surface. Additionally, this strategy can result in the need for more operator time to maintain a reasonable level of service (LOS), potential damage to vehicles (e.g., windshield), and cleanup of the abrasives between storms or at the end of the season.

As a result of the limitations produced by this first strategy, agencies typically ***move upward another step,*** to a strategy of plowing and the use of some abrasives in spot locations, which largely incorporates and relies on salt in solid or liquid forms. This approach may also incorporate some anti-icing materials applied in advance of a storm event. Salt brine can be used in this strategy for anti-icing and pre-wetting, whereas the solid salt is typically used for deicing practices. The use of these materials either prevents or weakens the bond of snow and ice to the pavement surface under ideal temperature ranges. While this strategy permits greater mobility and safety through the provision of bare or wet pavement, it has drawbacks. Namely, salt and salt brine do not incorporate corrosion inhibitors (as inhibitors are typically much more costly than salt brine), which can result in significant corrosion to infrastructure and vehicles. In addition, these products only work effectively above a certain temperature range (e.g., 15°F), below which the road can refreeze or a higher application rate would be required. In other words, if a temperature is colder than the effective range of a product, more of that product may be needed in order to facilitate the mechanical removal of snow and ice from the pavement, or an alternative product or treatment strategy should be considered. In summary, this strategy produces bare or wet pavement and facilitates mobility and safety, but at the cost of potential corrosion to critical infrastructure and with some environmental risk associated with the use of chemicals.

In order to maintain or enhance the mobility and safety benefits produced by treatment materials from this second strategy, many agencies move on to the ***third step*** of the staircase, the use of magnesium chloride, calcium chloride, and blended products such as corrosion-inhibited liquids and/ or treated or chemically enhanced solid chemicals. This approach uses inhibitors to address the corrosion risks associated with the untreated materials. The use of inhibitors and other additives can extend beyond direct liquid and solid products that incorporate inhibitors to the treatment or enhancement of solid chemicals. The prewetting of non-inhibited solid chemical with inhibited liquid chemical may partially reduce the corrosiveness of the latter. The strategy allows for the selection of specific chemicals that will work best in a specific climatic region or temperature range, avoiding the overuse of salt or salt brine at colder temperatures as was the case in the second strategy. Consequently, this final strategy sits atop the staircase of winter maintenance approaches by addressing corrosion impacts of chemicals while reducing the amounts of materials being used, resulting in prospective savings to an agency. In the course of meeting these goals, a high LOS is met, maintaining mobility and safety for the public.

As the discussions of these strategies indicate, various costs and benefits are incurred while performing winter maintenance operations. However, the absence of guidance regarding these costs and benefits of different maintenance scenarios is a significant void for the winter maintenance community. Therefore, efforts are necessary to address this gap and develop initial guidance for different scenarios in order to provide all levels of decision-makers with information on which sound decisions can be based. In doing so, agencies can better maximize the LOS they achieve for the costs of a strategy employed. Furthermore, winter maintenance professionals will be provided with another tool in their toolbox that can be used to explain the available options, their costs, benefits, and consequences to various stakeholders, including DOT personnel, legislators, and the general public. This would include: agency costs in achieving a specific LOS; economic impacts of different maintenance strategies; corrosion and abrasive impacts on highway users, equipment and infrastructure; safety benefits achieved through different strategies; and environmental impacts resulting from different strategies.

Consequently, the overall objective of this project is to identify the costs and benefits previously cited in literature, to identify and address any gaps in the cost and benefit information previously documented through a survey of practitioners, and to analyze and organize the available information into a format ready to be communicated to stakeholders. To this end, the information presented within this document identifies and summarizes the costs and benefits of winter maintenance previously discussed in literature. Prior to moving on to an examination of that information, it is first necessary to define what is meant by the costs and benefits of winter maintenance.

Defining Winter Maintenance Costs and Benefits

The winter maintenance community has recognized the need to better establish and understand the various costs and benefits of different aspects of their operations. This ranges from understanding the collective costs and benefits of winter maintenance (Kuemmel and Hanbali, 1992; Hanbali, 1994; Qiu and Nixon, 2009; Ye et al., 2012) as well as understanding specific costs and benefits of different equipment, materials, and operations (Veneziano, et al., 2010a; Veneziano, et al., 2013). These efforts have shed light on the costs and benefits of winter maintenance, but they do not necessarily consider general scenarios that employ different combinations of strategies, such as those outlined in the previous paragraphs. Consequently, there remains a need to develop an understanding of the different costs and benefits collectively associated with such scenarios and develop a mechanism to present that information not only to winter maintenance professionals, but also the many stakeholders that are involved in, or impacted by, these operations.

The costs and benefits of winter maintenance may be quantifiable or qualitative. Quantifiable benefits are those that a specific value can be assigned to. In some cases, the quantified value can take the form of a percentage; in other cases, it may take on a dollar value or other numerical form. Qualitative benefits are those which are numerically non-quantifiable, but still produce some tangible benefit. For example, the use of a specific technology in maintenance operations such as Automatic Vehicle Location (AVL) can reduce material use (agency benefit), but it may be difficult to assign a value (percent reduction, dollars, etc.) that this specific tool contributes when used in combination with other maintenance operations (e.g., plowing or anti-icing). This must be kept in mind when reviewing the information provided by the following text.

<u>Winter Maintenance Costs</u>

In addition to the need for safety, there is also a large economic benefit associated with good winter maintenance. In 1999 it was estimated that approximated $1.4 billion dollars would be lost in wages alone if all of the snowbelt states were immobilized for just one day due to a winter weather event. Since then that number has climbed closer to $2.6 billion according to IHS Global Insight (Booz Allen Hamilton, 1999; IHS Global Insight, 2014; while the one day loss of retail sales was found to be $870 million (IHS Global Insight, 2014). When looking into the number of dollars lost as a full economic impact at a federal, state, local and individual level the numbers are even more staggering at around $3.9 billion[1] (Booz Allen Hamilton, 1999). A study of economic forecasts for Kansas estimated that for an average February weekday, the Interstate and State highway system caries $175 million in goods and accounts for $30 million in daily wages (Kansas DOT, 2013).

Costs per storm are determined on a routine basis. Below are a few examples of states' calculated cost per storm:

- New Hampshire cost for 8-hour storm is $587,227 including two salt applications (includes state equipment, hired equipment, labor, fuel, salt and sand). New Hampshire spends $40 million per year on snow and ice removal (Wickham, 2012).
- Virginia: The average cost for a major statewide snow or ice storm affecting all nine VDOT districts and requiring a full mobilization is approximately $11 million per day (Virginia DOT, 2014).

[1] Based on impacts to the following snowbelt states if they were shut down due to winter weather: Illinois, Iowa, Indiana, Kentucky, Maryland, Michigan, Massachusetts, Minnesota, Missouri, New Jersey, Ohio, Pennsylvania, Virginia, Utah, and Wisconsin The greatest impact per day would be New York with $700.17 million, and the least would be Iowa at $70.4 million.

The economic impact of snow-related road closures far exceeds the cost of timely snow removal. Although states and localities may be hesitant to expend significant upfront resources in the short-term, the long-term payoff more than justifies the expense (Roadway Safety Foundation, Undated). Among all economic classes, snow- related shutdowns harm hourly workers the most, accounting for almost two- thirds of direct economic losses.

Costs of maintaining roadways vary greatly by state and region; these metrics rely greatly on the number of lane miles that the DOT maintains as well as the amount of snow received each season. Winter maintenance budgets for the Clear Roads member states range from $50 to $90 million dollars for one winter season. Staffing for the winter season is similarly location dependent and was found to be between approximately 650 to 3,300 employees. Due to the various reporting by each of the DOTs these numbers typically include the snow plow operators, dispatch personnel, mechanics, and all other winter maintenance staffing. The overall winter maintenance budget typically also funds the training operations held by each DOT normally performed during the off season. At a minimum, all facilities have new driver training, annual refresher courses and safety training. Examples of off-season training include Minnesota’s and California’s programs that include yearly summer training camps, as well as Iowa’s program which features a travelling plow training simulator.

Environmental Costs Assessment

There is very limited information in the published domain on the environmental costs of winter maintenance practices. This is in part because it is difficult to assign a dollar value to a tree, fish, or stream, for example. Some attempts to assign values to trees have used damaged fruit trees because it was easy to assess the loss of fruit and the financial loss to the farmer (Bacchus, 1986). Another study conducted in a state park surveyed visitors to determine how viewing trees and other damage by winter maintenance practices impacted their experience in nature and determined the total loss of revenue based on the survey responses (Vitaliano, 1992). These two methods are good approaches to quantifying the environmental impacts of winter maintenance practices, but this area of research needs more attention.

To determine the cost or benefit of using a product, such as salt brine, it is necessary to quantify what the financial impacts are once the product leaves the roadway and enters the environment. To understand the full cost of a product, you need to consider how much you are paying to buy and ship the product, apply the product, clean-up or manage the product in the environment, and costs of direct impacts to the environment. 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, further complicating the issue. Despite the potential damaging effects of road salts, 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 (Fay and Shi, 2012).

Information on the environmental costs and benefits of winter maintenance products and practices can be found in Environmental Costs and Benefits.

<u>Winter Maintenance Benefits</u>

While overall travel times (3 percent to 16 percent reduction) and lane capacity (3 percent to 30 percent reduction) decrease during and shortly after a snow event, the overall preparedness and efficiency of a DOT can ensure that the removal process goes as quickly and effectively as possible to minimize delay and get travelers safely to their destination. The Federal Highway Administration (FHWA) has determined that winter weather conditions are responsible for approximately 31 percent of weather related crashes over a ten year period, a metric that would be much higher if winter maintenance was not performed according to the Roadway Safety Foundation.

The FHWA has published the following 10-year average (2002-2012) weather-related crash statistics for road weather conditions (Table 2). For example, over the ten year period 211,188 crashes occurred, for which 4%, or 847, occurred during conditions classified as snow/sleet. Of 211,188 crashes which occurred during snow/sleet conditions 17%, or 35,902, were weather related.

Table 2 Weather-related crash statistics by road weather conditions (FHWA 2014).

Road Weather Condition	10 -Year Annual Average (2002-2012)	10 Year Percentage	
Snow/Sleet	211,188 crashes	4% of vehicle crashes	17% of weather-related crashes
	58,011 persons injured	3% of crash injuries	13% of weather-related injuries
	769 persons killed	2% of crash fatalities	13% of weather-related fatalities
Snow/Slushy Pavement	175,233 crashes	3% of vehicle crashes	14% of weather-related crashes
	43,503 persons injured	2% of crash injuries	10% of weather-related injuries
	572 persons killed	2% of crash fatalities	10% of weather-related fatalities

Winter weather has been shown to negatively affect winter driving. Reduced visibility and traction from snowfall can lead to reduced driving speeds, an increase in headway, and reduced acceleration. These in turn increase delay and crash frequency, while decreasing the effectiveness of traffic signal plans and roadway capacity. Average speed reductions on freeways have been determined for varying winter weather conditions (Table 3) (FHWA 2014).

Table 3 Traffic flow reduction on freeways caused by winter weather conditions (FHWA 2014).

Weather Conditions	Freeway Traffic Flow Reductions			
	Average Speed	Free Flow Speed	Volume	Capacity
Light Rain/ Snow	3%-13%	2%-13%	5%-10%	4%-11%
Heavy Snow	3%-16%	6%-17%	14%	10%-30%
Low Visibility	10%-12%	N/A	N/A	12%

Every winter, over 115,000 people are injured and over 1,000 are killed on America's highways due to snowy, slushy, or icy pavement (Roadway Safety Foundation, Undated). The common winter maintenance practice of deicing has been shown to reduce crash frequency by 88.3 percent, and to decrease the average cost of each crash by 10 percent.

Beyond the monetary value associated with the lack of closures and reduced number of crashes, these benefits can be hard to quantify. Many states employ a snow level of service (LOS) metric, which they strive to maintain throughout the winter season and use as a performance measure evaluation tool to improve the next season's maintenance planning.

Research Goals and Approach

The objectives of this research were to identify winter maintenance strategies which are sustainable in terms of cost, safety, and mobility; and assess and communicate the costs and benefits of commonly used winter maintenance strategies to better understand the safest and most cost-effective approaches based on desired level of service. To accomplish the objectives a comprehensive literature review was conducted to identify sustainable and commonly used winter maintenance strategies, associated benefit-cost, safety, and level-of-service data associated with each winter maintenance strategy, and to identify data gaps. A survey and follow-up interviews were used to capture additional data. Information gained in the literature review, survey, and interviews was used to create a summary matrix of winter maintenance strategies, associated level of service, costs, pros and cons, and a benefit-cost ratio for each winter maintenance strategy. The methodology used for each task is presented in Chapter 2 Methodology, and findings from each task are presented in this document.

Report Organization

This document is organized into four chapters. The first chapter has outlined the general problem examined by the project and provides background information on the different winter maintenance strategies of interest. Chapter 2 reviews the methodology used in each task of the research to develop the content of this report. Chapter 3 presents the information identified during a comprehensive literature review of the costs and benefits, both quantified and non-quantified, which are associated with the different components of each maintenance strategy of interest, as well as an overview of data and information gaps associated with each of the maintenance strategies being examined. Chapter 4 presents the developed matrix of information on the various winter maintenance strategies and the calculated benefit-cost ratios associated with each. Chapter 5 provides conclusions based on the work presented in this document and discusses information gaps and research needs to improve upon this work.

Chapter 2
Methodology

Literature Review

A comprehensive literature review was completed which focused on the use of the winter maintenance strategies and the related agency costs in achieving a level of service; economic impacts to users and society of winter maintenance; corrosion impacts to highway equipment, users, and infrastructure; abrasive wear impacts to highway equipment, users and infrastructure; safety impacts of strategies; and environmental impacts of strategies. The information on these different aspects of each strategy, including specific costs and benefits, have been summarized in a manner that documents financial values and other numerical metrics (e.g., percent reductions in crashes) and qualitative metrics (e.g., reduced cleanup following a storm) where possible for inclusion in the benefit-cost matrix. Information gained from the literature search was incorporated into all aspects of this report and was also employed in the development of the survey questionnaire.

Information was gathered from a review of several databases including: Transportation Research International Database (TRID), Google Scholar, ISI Web of Science, and the Montana State University library. Research conducted domestically and internationally was used whenever available, including work completed by DOTs, Clear Roads, Pacific Northwest Snowfighters (PNS) Association, University Transportation Centers (UTCs), Strategic Highway Research Program (SHRP), FHWA, National Cooperative Highway Research Program (NCHRP), Airport Cooperative Research Program (ACRP), American Public Works Association (APWA), and AASHTO. Ongoing research efforts that were complimentary or that produced information of interest to the project were incorporated into the report greatest extent possible.

Survey

A survey was developed to seek additional information on various winter maintenance strategies and fill in data gaps identified in the literature review. The developed survey was submitted to the project panel for review, was revised and posted using an online survey tool. A link to the online survey was sent out to Clear Roads member states, and posted on the Snow and Ice ListServ, and on the Winter Maintenance & Effects LinkedIn page. The audience for the survey was winter maintenance professionals from the United States and other international agencies. The initial survey received minimal complete responses, likely due to survey fatigue. A follow-up request for information was sent out to Clear Roads member states, and again posted on the Snow and Ice ListServ, and on the Winter Maintenance & Effects LinkedIn page. Respondents to the follow-up survey who indicated they were willing to be contacted for follow-up information were sent an online survey focused on the Advanced Activities. Limited responses were received from the follow-up survey.

Phone interviews were conducted as a follow up to the surveys, specifically targeting survey respondents who did not provide detailed information regarding winter maintenance practices and products used. A total of 19 winter maintenance practitioners from 12 states with varying climates were interviewed. The interview questionnaire aimed at collecting information regarding winter maintenance practices, materials, and associated costs and benefits particularly for product categories that received little feedback from the survey. Based on the interviewee's responses to the survey, specific questions were used for different types of products and corresponding costs and performance. Information gained from the surveys and follow-up interviews was used to populate the benefit-cost matrix. The survey interview questionnaires can be found in Appendix A, and the survey and follow-up survey results can be found in Appendix B.

Benefit-cost Matrix

Information gained from the literature, survey, and interviews was used to populate the summary matrix. The matrix presents information on the following winter maintenance activities: plowing and use of abrasives (Basic Activities), use of solid and liquid salt (sodium chloride) for anti-icing and deicing (Intermediate Activities), and use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, or blended products (Advanced Activities). For each activity information is reported on the cost, benefits, effectiveness in achieving LOS, positive and negative impacts, pros and cons, respective performance, environmental impacts, and the calculated benefit-cost ratio where possible. The benefit-cost matrices can be found in Chapter 4 along with a description of how the benefit-cost ratios were calculated.

Chapter 3
Literature Review

Costs and Benefits of Common Winter Maintenance Practices

Roughly 20% of the budgets of state DOTs are expended on winter maintenance activities, with a direct cost of $2.3 billion and an indirect (infrastructure and environmental) cost of $5 billion annually (FHWA, 2014). Typically, the strategies employed by agencies come with many tradeoffs, including costs to the agency, economic impacts to society, corrosion and abrasive wear, and potential environmental impacts, as well as the safety and mobility benefits to travelers. In light of these costs and benefits that result from winter maintenance, it is necessary to assess and communicate how different strategies can produce cost-effective approaches to providing the traveling public with safety and mobility.

Due to the tradeoffs associated with winter maintenance strategies, it is necessary to establish a better understanding of the respective costs and benefits associated with the materials and operations employed in the scenarios. This understanding will both identify the quantitative values associated with the various costs and benefits of these strategies, and identify those for which a value has not been quantified. Collectively, this information can serve as a starting point to identify and address any gaps in cost and benefit information and to support the analysis and organization of this information into a format to communicate to stakeholders.

Plowing

The types of plows generally used by DOTs are front plows, tow plows, underbelly (under body) plows, wing plows, and rotary plows. Front plows are typically the most common piece of equipment used for snow removal. DOTs reported having anywhere from 450 to 950 front end plows on the roads each season. Underbelly plows are equipped with a blade underneath the vehicle that assists in scraping the hard pack snow from the roadway. Underbody plows can be stand alone or be an additional plow blade added to a vehicle with a traditional front end plow. The wing plow is similar to the tow plow in many respects. Essentially, it is a 6 to 8 foot 'wing' that is attached to the side of the front end plow to clear a larger path than the traditional front plow alone. By using the wing plow, agencies can deploy fewer pieces of equipment and facilitate snow removal from areas such as roadway shoulders.

Tow plows are relatively new and add the capability to plow an additional 26 foot wide area as the plow is pulled behind the traditional plow allowing the one piece of equipment to clear two lanes of traffic in one pass. Tow plows cost between $70,000 and $93,000 and approximately 200 tow plows are being used nationwide. Rotary plows are much like today's snow blowers but on a much larger scale.

Tandem or gang plowing is not a type of plow but rather a plowing technique. Tandem plowing uses two or more plows driving in a staggered formation to clear an entire multi-lane roadway in one pass. DOTs use front end loaders and motor graders in the winter months for snow removal in places with heavy snow fall, such as the Donner Pass area of California.

Costs of Plowing

It is difficult to quantify the specific costs of plowing operations within a DOT's budget. Winter maintenance vehicles are used for year-round activities such as roadway maintenance, as well as other winter activities such as roadway salt and sand distribution. However, some DOTs have an hourly billing rate for equipment they can apply to winter operations. If they also have a plow up/plow down sensor, then an exact value for plowing operations can be derived. However, such information has not been available in literature to date. A few examples of state plowing costs follow.

In Maine, the DOT operates approximately 450 front end snow plow trucks. The cutting edge blades are used to clear 10,000 linear feet per season with a cost per linear foot of $48.32 (Maine DOT 2009).

For Michigan DOT, the cost of a new Tow Plow was $93,000 (Michigan DOT 2014). The cost of Tow Plows in New Hampshire ranged from $70,000 – $80,000 (Blechl 2012). In Iowa, the Tow Plow costs $70,000, which is about half the cost for a standard plow truck.

Benefits of Plowing and Plow Types

Front Plows

Front plows are the most common type of equipment in use; however, specific data on the costs and benefits of their use have not been discussed in literature. Rather, the literature related to front plows has in general focused on blade types and plow blade configurations. This information is summarized in the following subsections.

Plow Blade Inserts

Plow blade inserts are installed onto the plows to extend the life of the plow edge. Carbide flexible blade inserts have been found to be the most cost effective and longest lasting blade inserts available at $668.43 per inch or $0.71 per mile, although steel, rubber, or ceramic blade inserts can be used as well (Table 4) (Iowa DOT, 2010). Carbide is a metal alloy of tungsten, and these blades are tougher and more resistant to wear than steel (Maine DOT, 2004). However, the carbide can be more brittle than steel. The severe shock loads experienced by plows hitting rough broken pavement, rocks, curbs, or other objects can crack and break the carbide edges, leading to rapid wear on the edge. Maintenance crews say that once the carbide has worn away the blade must be replaced immediately because the remaining steel will not last for even one more storm, and it will damage the plow, resulting in costly repairs. Cracks can develop in the carbide, which spread to adjacent sections leading to increased breakage (Maine DOT, 2004). Additionally, an evaluation of carbide blades found that the chemical constituents of blades are very important, and that poor manufacturing processes result in inserts with voids and cracks that lead to more rapid wear (Braun Intertec Corp., 2010).

The JOMA 6000 plow blades are a combination of rubber, steel, and carbide blade inserts. These lightweight blades are flexible and adjust to the roadway. The blades lasted three times longer than the traditional carbide blades. In addition, after prices for carbide increased, the extra costs associated with the JOMA blades were deemed to be a cost effective investment with a cost per mile of less than half of a standard carbide blade (Iowa DOT, 2010). A re-testing/trial period in 2008 determined that the JOMA blades reduced noise and vibration in the cab, and were found to have three to four times longer wear, and “cleaned the roadway better than traditional blades” (Iowa DOT, 2009).

Table 4 Blade type, wearing rate, and cost (Iowa DOT, 2010).

Blade Type	Inches of Carbide Blade	Miles per Inch of Carbide	Cost of 11' Blade Set	Cost per inch of Carbide	Cost per Mile
JOMA 6000	1	4161.7	$1,226.89	$1,226.89	$0.35
Polar Flex	3/4	5911.9	$2,785.20	$3,713.60	$0.69
Std. Carbide	5/8	1295.95	$417.77	$668.43	$0.71
Milo FlexEdge (Iowa DOT design)	5/8	Not tested for wear			

North Dakota performed an evaluation of JOMA and Polar Flex blades compared to a traditional carbide blade and stacked (multiple) carbide blade (North Dakota DOT, 2011). The stacked blade was found to have no advantage and was discontinued. The carbide cost was $525.20 per complete plow setup, while the stacked blade was double this cost. The Joma blade cost was $1875.84 per complete plow setup, and the Polar Flex cost $2,310 per complete plow setup. The JOMA and Polar Flex blades lasted on average three to four times longer than the traditional carbide blades.

Extensive testing has been done with carbide blades as state DOTs spend between $500,000 to $1 million on carbide blade inserts annually, with many DOTs using more than 10,000 linear feet of plow cutting edges each season (Maine DOT, 2009; Braun Intertec Corp., 2010). Carbide blades have been found to be the most cost effective option to date (Iowa DOT, 2009). Both rubber encased steel blades and full rubber blades have been used by DOTs, but have not been deemed to be comparable alternatives based on poor performance and higher unit costs (Iowa DOT, 2009). Ceramic blade inserts showed promising results in a 2009 study as a viable alternative based on performance, and could be an option in the future if the costs decreased.

Iowa DOT conducted testing of ceramic blade inserts and other blade types because of the high cost of ceramic blades (Iowa DOT, 2009). These blades were reviewed in 2008-2009 and again in 2009-2010 as an alternative to the traditional carbide blade. The ceramic blades were determined to perform at a level comparable to the traditional carbide blades based on level of hardness, weight, and cutting edge wear. Ceramic blades prices may decrease in the future and a benefit-cost analysis should be considered if this occurs.

Plow Blade Configuration

The configuration of the plow blades can lead to more effective snow removal (Ohio DOT, 2011). Common blade configurations are stacked, articulated, multi-blade, and special in-house configurations. Stacked blades are not commonly used and were found to be ineffective. However multi-blade configurations commonly have two to three blades that all perform different functions in snow removal. The multi-blade system has separate blades to remove slush and scarify the snow/ice, as well as a more typical cutting edge blade which is used for snow removal (Figure 1). The benefit of this multi blade system is that road segments with variable snow and ice conditions can be treated in a single pass. Prototype testing of a multi blade configuration was shown to remove 20 percent to 25 percent more material than traditional blades and it was determined that the multi blade plows "may be an effective tool for improved snow removal operations and potentially could reduce deicing chemical use" (Ohio DOT, 2011).

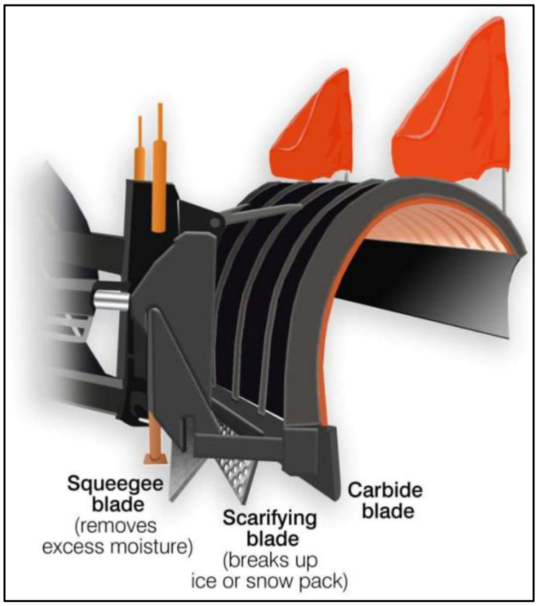

Figure 1 A picture of the multi-blade configuration (Iowa DOT 2010)

A two blade system, incorporating a snow blade in front and slush blade in the back, was tested in Northern Illinois. The trial was such a success, Illinois DOT now specifies that all new trucks have the two blade system (WTIC, 2012).

In-house blade modifications are typically unique to each DOT, but the results, if successful, may be shared within an organization. Maine DOT recently tested using a carbide blade on the under body plow instead of the traditional steel plow blade and found that the carbide underbody blade lasted much longer (Table 5) (Maine DOT, 2009). Additional testing was conducted the following season with the new blade configuration.

Table 5 Field testing of alternative carbide edge snow plow blades (Maine DOT 2009).

Snow Plow Blade Tests												
	Isolated Carbide Insert Blades (Test)						Regular Carbide Insert Blades (Control)					
		Miles	Hours	Ave. MPH	Ave. Cost (per lane-mile)	Ave. Cost (per hour)		Miles	Hours	Ave. MPH	Ave. Cost (per lane-mile)	Ave. Cost (per hour)
Amity		775.0	32.5	23.8	$0.38	$9.14		1014.0	53.8	18.9	$0.19	$3.63
Ellsworth		1161.0	63.5	18.3	$0.26	$4.68		1070.0	82.5	13.0	$0.18	$2.37
Baileyville		1036.0	95.0	10.9	$0.29	$3.13		1255.0	113.0	11.1	$0.16	$1.73
Richmond		1140.0	57.0	20.0	$0.26	$5.21						
South Paris		1280.0	63.7	20.1	$0.23	$4.66		1280.0	63.7	20.1	$0.15	$3.07
	Ave.	990.7	62.3	18.6	$0.28	$5.36	Ave.	1154.8	78.2	15.8	$0.17	$2.70
	Regular Carbide Insert Blades (Test, Alternative Brand)						Regular Carbide Insert Blade (Control, Stock Brand)					
		Miles	Hours	Ave. MPH	Ave. Cost (per lane-mile)	Ave. Cost (per hour)		Miles	Hours	Ave. MPH	Ave. Cost (per lane-mile)	Ave. Cost (per hour)
Gouldsboro		811.4	45.9	17.7	$0.37	$6.47		1786.0	62.8	28.5	$0.11	$3.11
Richmond		1360.0	68.0	20.0	$0.22	$4.37						
	Ave.	1085.7	57.0	18.8	$0.29	$5.42		1786.0	62.8	28.5	$0.11	$3.11

Assumptions:		
Costs (per foot)	Isolated Carbide Blades	$27.00
	Regular Carbide Blades (Alternative)	$17.76
	Regular Carbide Blades (Stock)	$17.76

Maine DOT conducted a 4 year evaluation of the Kuper-Tuca SX36, to determine if it would be comparable to the carbide blades the DOT was using (Maine DOT, 2004). The Tuca SX36 plow blade had a wear life of approximately 3,500 to 4,500 miles while the standard carbide blade lasted 1,500 to 2,000 miles. However, after comparing the $352.99 per set of carbide blades to the $1,782.00 cost for Tuca blades, the Maine DOT did not find the Tuca blades to be a cost effective investment for Maine DOT.

A synthesis on plow blades made the following conclusions:

- Rubber-encased steel blades, which have been more expensive than steel in the past, may be worthy of consideration as costs be have decreased. A benefit-cost analysis is recommended if an agency is considering this blade type.
- Solid rubber blades did not receive favorable results as compared to conventional blades.
- Alternative carbide edge snow plow blades did not receive favorable results as compared to conventional blades.

New products are continuously available but have not been evaluated; one of the recommendations called for working with vendors to test these products (EVS, 2011).

Plow Blades and Infrastructure Damage

Much of the past and current research on snow plow blades has focused on snow and ice removal performance and blade wear and has addressed the effects of hard cutting edges on various pavement types only in passing. With the advent and placement of thin overlays for pavement repair by many maintenance agencies, it is expected that hard cutting edges may adversely affect these thin overlays (EVS, 2011). A 2012 brainstorming session by Nebraska DOT highlighted the need for research to determine the best plow blade to roadway material configuration in an effort to extend the life of the roadway and reduce plow maintenance costs (Nebraska DOT, 2012). Finally, plow blades can damage pavement markings, leading to reduced retroreflectivity and lane guidance (Agent and Pigman, 2014).

Tow Plows

The Tow Plow has an expected service life of 30 years, while the average service life for a standard plow is 10-years (Michigan DOT, 2014). The cost of tow plows in Iowa, was $70,000 per plow vehicle which is about half the cost of a standard plow truck (Iowa DOT, 2014). The tow plow is 26-ft-wide, allowing two interstate travel lanes to be cleared and treated in a single pass (ITD, 2010; Ohio DOT, 2011). Because of the wider clearing path, Maine DOT was able to “free-up” or replace trucks to enable the department to improve its LOS (Maine DOT, 2009). The original design for the Tow Plow was the brainchild of a Missouri DOT (MoDOT) employee who applied his knowledge of farm equipment to snowplows. MoDOT worked with a snowplow contractor to design and build the version in use today. According to one vendor, the TowPlow can maintain speeds of 55 - 60 mph during the plowing process. According to MassDOT the TowPlow can take the place of three pieces of equipment, reduces emissions, and decreases manpower needs (MassDOT, 2012).

Underbody Plows

Iowa DOT conducted an investigation into using flame hardened under body plow blades ($170 per 8 foot blade) versus the typical baked steel under body blade ($94.13 per 8 foot blade) in the winter season of 2012-2013 (Rehbein, 2013). They found that on average the flame hardened blades lasted for 335 miles at a cost of $0.51/mile, while the standard blade lasted 273 miles at a cost of $0.34/mile. Despite the increased mileage from the flame hardened blade, the lack of cost savings did not facilitate procurement of the hardened blade for DOT use.

In 2006 Iowa DOT investigated the use of automation for underbody plows (Nixon, et al, 2006). Many variables influence the effectiveness of underbody plow: proper downward pressure where too little pressure can cause ineffective snow removal; too much pressure can result in damage to the plow blade and possible gouging to the road surface; and proper cutting edge angle. The automated underbelly plow system was designed to use a set of if-then system rules to determine the angle, and downward force needed to effectively remove snow from the road surface. The automated system was created and tested in a simulator, but has not yet been implemented on a plow due to funding constraints. However, this project did determine that a computer automated underbody plow would be a feasible option to improve plowing procedures and increase the life of the plow blades.

Wing Plows

Wing plow blades can clear an area up to 22-ft-wide (Caltrans, 1999). MassDOT found that using wing plows clears snow from a wider portion of the roadway than a traditional front end plow, which reduces the total pieces of equipment and personnel needed (MassDOT, 2011). Many of Iowa DOT's plows also have the 6-8 foot wing plow attached to the trucks in addition to the standard front plow. Due to decreased visibility of wing plows, a GL3000C guidance laser was mounted to the cab of the plow, projecting a beam indicating where the truck and wing plow projected clearing path lies (Iowa DOT, 2009). This addition to trucks using wing plows will reduce the number of collisions with mailboxes, bridges, and other roadside structures.

Rotary Plows

Caltrans uses rotary plows and have found it costs about $120/hour to operate them (Caltrans, 1999).

Tandem and Gang Plowing

Tandem and gang plowing operations involve multiple trucks plowing in a pattern in order to clear multiple lanes on a roadway during one pass. Some entities also utilize other vehicles, such as garbage trucks, to perform winter maintenance during the course of their primary activity. The city of Chicago has quick hitch plows for their garbage trucks that they use in tandem with snow plows that have salt spreading capabilities. The partnership allows for heavy equipment and labor to be available from other municipal departments for snow removal operations during and after storms.

New Hampshire has found that tandem plowing makes it possible to clear roads and shoulders with increased productivity (New Hampshire DOT, undated). They have also found that roads where tandem plowing was used require less anti-icing, and buildup of snow and ice is prevented. Tandem plowing allows them to avoid leaving windrows which can be dangerous to the driving public, avoids throwing snow on already cleared pavement, removes snow from narrow medians, and allows trucks to separate and clear blocked ramps, while also preventing unsafe driving maneuvers, including vehicles passing plows.

Motorgrader Use

Caltrans has about 44 motorgraders in one district alone, costing about $60/hour to operate in the late 1990s (Caltrans, 1999).

Sanding

Blackburn, et al. discussed various winter maintenance operations, including the use of sand/abrasives (Blackburn et al., 2004). These materials are not ice control chemicals nor do they support the objectives of anti-icing or deicing. In particular, when applied before a storm, sand can be blown off the pavement by passing traffic, rendering the application useless. Sand and other abrasives are typically used at pavement temperatures below 12° F and on roads with lower traffic and lower LOS (Blackburn et al., 2004). Sanding may also be used when an agency has run out of chemicals to use for treatment. When used individually (or in combination with plowing), this approach cannot be expected to produce a high LOS (although an estimated LOS is not provided by the authors). The benefit of abrasives is that they can provide traction when temperatures have fallen to the point that chemicals are rendered ineffective. Effective application rates for these materials range from 500 to 1,500 pounds per lane mile, which can be extrapolated to a general material cost for sand based on local costs for the material. However, aside from the general discussions of effectiveness, no specific values of costs or benefits were cited.

Recent surveys of state highway agencies (Fay, et al., 2008; CTC & Associates, 2011) indicated that abrasives are recognized to have their place at low temperatures, despite concerns. During heavy snowfall, sand and grit are often used to provide traction. Fay, et al. completed a survey of agencies in which 17 indicated the use of abrasives in their winter maintenance operations (Fay, et al., 2008). While responses indicated that sand had a moderate advantage compared to other materials such as chlorides, acetates/formates, and ag-based treatments in terms of a low cost per lane mile, it was viewed as the easiest material to apply. It was also found to have the lowest performance compared to these other materials, however, having essentially no ice melting capacity. Abrasives were indicated as creating a hazard when applied prior to a storm since they reduce skid resistance in dry conditions. Respondents indicated that abrasives do have a low impact in terms of corrosion and pavement/structure damage, but high impacts on water quality and the general environment. Aside from survey responses, however, no specific values were assigned to the costs or benefits of abrasives by this work.

A more recent (2011) review of agency practice by CTC & Associates found that sand was either applied dry or prewetted with calcium chloride, magnesium chloride agricultural by-products or salt brines (CTC & Associates, 2011). Sand use was being minimized by many agencies because of concerns with effectiveness and environmental impacts. Innovations such as hot water sand spreaders offered the potential to more effectively apply abrasives by facilitating the freezing of sand to the snow, ice or pavement of the road surface. This reduces the bounce and scatter of materials as they are applied to the pavement. The document also reported on observations from the Maine DOT during a 2011 storm using different materials on an interstate route. A delayed application of sand was found to be the most cost effective approach (although no numbers were reported), with the sand applied when pavement temperatures were 6 to 7° F and the road surface had begun to glaze over. The use of salting early in the storm followed by sanding as temperatures rose was ineffective, primarily because the salt component was ineffective. Sand was still observed to be effective in providing traction in this case. The summary did not provide any specific figures related to the costs or benefits of sanding.

An FHWA report determined the total costs of using abrasives per lane mile in different states. In California, this cost, which included labor, equipment and materials, was $37.93 (1995 dollars). Calculated to a present cost, this value becomes $58.43. Similar values were obtained for Nevada, including $13.21 per lane mile without clean up and $57.64 with clean up. In 2014 dollars, these values are $20.35 and $88.80, respectively. Consequently, it is evident that cleanup costs have considerable impact on the economics of sand use.

A literature review for the Wisconsin DOT highlighted the limited effectiveness on abrasives on roads with higher vehicle speeds (CTC & Associates, 2008). It also noted that the use of sand had decreased over time as the result of several factors, including overall effectiveness, environmental impacts, safety implications, and cost. Limitations to the effectiveness of sand included the propensity for it to blow off the road and disperse with passing traffic, the need to keep salt from freezing so it remains workable, lower friction values compared to bare and wet pavement, and the reduced capacity for salt to melt ice when mixed with sand. Among the environmental impacts cited was the tendency for 50 to 90 percent of sand to remain in the environment after clean up, the entry of sand into waterways and drains, the potential for fine particles to enter the air, and for salt leeching from storage piles. Finally, windshield damages were 365 percent higher in areas where abrasives were used compared to alternatives.

An early evaluation of the impacts of sanding came from work performed by Kuemmel and Hanbali (1992). On roads where sand and salt mixtures were applied, it was found that crash rates for all accident types (per million vehicle miles travelled) fell by 87 percent, while the average cost per crash fell by 10 percent. Travel time costs were reduced from $0.22 to $0.16 cents per vehicle mile travelled on routes using sand-salt mixtures. Finally, the direct road user benefits of using sand and salt mixes were $6.50 for every $1.00 spent on direct maintenance costs of operations.

In a follow-up to their previous work, Kuemmel and Bari (1996) evaluated the cost effectiveness of abrasives in winter maintenance. The authors found that the benefit-cost ratio associated with the use of abrasives was 0.8:1 on two lane roads and 2.8:1 on freeways. The costs taken into account were direct costs associated with maintenance operations for the routes, while the benefits included travel time savings, fuel savings, and crash reduction savings. As the results indicate, potential benefits for sanding appear to exist for higher-volume roads.

Nixon (2001), as part of a review of the use of abrasives for the Iowa DOT, developed a set of recommended practices for the use of the material. Recommended applications included rural gravel roads (low speed sections), rural intersection approaches, and low speed urban roads and urban intersection approaches when snow pack persists. The benefit cited for these locations was that traction would be provided while sand dispersion by vehicles would be minimized.

Parker (1997) compared the Oregon DOT's plow and sand strategies to chemical-based strategies (calcium magnesium acetate and magnesium chloride). The motivation for the comparison stemmed from concerns over airborne particulates and silting from the use of sanding and other abrasives in the state. Figures at the time (1997) indicated the cost of sanding was between $15 and $65 per lane mile ($21.94 - $95.08 in 2014). These figures included labor, material, equipment, and clean-up costs. Even after clean up, it was found that 50 percent to 90 percent of abrasives remained in the environment. Clean-up costs alone ranged from $2 to $20 per cubic yard ($2.93 - $29.26 in 2014) and varied depending on the type of roadway shoulder present at a site. Other costs associated with sanding included cracked windshields, with claims against the DOT totaling approximately $50,000 per year ($73,140 in 2014).

Fischel (2001) documented that sand and other abrasives can pose negative impacts to water quality and aquatic species, air quality, vegetation, and soil, and incur hidden costs such as cleanup. Specific to air quality, the use of sands in winter maintenance can contribute at least 45 percent of the small particulates present in the air. However, the low cost of abrasives makes their use economical. In Colorado, the cost of sand and other abrasives ranged from $6 to $16 per ton in 2001 ($7.95 - $21.21 in 2014).

Schlup and Ruess (2001) provided a balanced perspective on the use of abrasives and salt, based on their impact on security, economy, and the environment. Based on an analysis of test segments of roads in Switzerland, they found that the cost of applying abrasives was six times higher than those of salt during a normal winter. During a severe winter, the cost of using abrasives was ten times higher. Additionally, abrasives had only a short term effect on friction when applied.

Leppänen (1996), in examining the socioeconomic effects of winter maintenance and studded tires in Finland, discussed the results of tests using sand instead of salt on low volume roads (<6,000 vehicles per day). The work found that the use of sanding increased costs by an average of 20 percent over salting, and sanded roads were free of snow and ice only 59 to 68 percent of the time. However, the observed increase in costs was not attributed to a specific aspect of sanding, although one could conclude that clean-up costs were the most likely explanation.

Chang, et al. (2002) discussed the costs associated with the sanding operations of the Colorado DOT. The costs identified by the work included materials, labor (mechanical and manual sweeping, snow removal/sanding and ice control), and equipment. In general, it was observed that the cost of abrasive materials was low compared to alternatives such as rock salt. Costs for labor by district ranged from $1.35 to $2.50 per mile (2000 dollars, or $1.84 - $3.41 in 2014). Equipment costs for sanding ranged from $1.00 to $3.00 per mile ($1.36 - $4.09 in 2014).

Mokwa and Foster (2013), in discussing the potential for the Montana Department of Transportation (MDT) to recycle recovered sanding materials in subsequent winters, performed a cost analysis to determine if such a practice was economically viable. The total estimated cost per ton for using different mixes of recycled and virgin materials ranged from $10.50 to $21.00 (2013 dollars). Depending on the material mix, estimated cost savings from using recycled abrasives could range from $0.70 to $1.52 compared to the alternative of using virgin materials. In some cases however, negative savings were estimated, indicating that the cost of using recycled materials would exceed the use of virgin materials.

Chang, et al. investigated then-current (1994) practices for environmentally sensitive sanding practices for the Colorado DOT (Chang, et al., 1994). While specific values were not documented, the report did highlight the positives and negatives of sand and abrasive use in winter maintenance. Positive aspects included the ability to increase the coefficient of friction on snow and ice covered roads, the ease of application, and the generally low cost of materials. Negative aspects cited in the report included the need for post storm/season clean up, the addition of particulates into the air, and the potential to decrease the coefficient of friction on dry roads.

Fu, et al. (2006) evaluated the effects of winter maintenance treatments, including sanding, on highway safety in Ontario, Canada. Based on statistical modeling that considered crash frequency, weather, and maintenance operations, the authors determined that a 1 percent increase in sanding operations (in total kilometers treated) would reduce crashes by 0.245 percent.

O'Keefe and Shi (2005) synthesized information on anti-icing and prewetting operations for the Pacific Northwest Snowfighters (PNS) Association. The work touched upon sanding and abrasives, particularly their drawbacks. These included the need to apply up to seven times more material than alternatives to treat a segment of road, impacts on water quality, and the addition of particulates into the air. This figure of seven times more material being required came from www.saltinstitute.org.

Gertler, et al. (2006) examined the impacts of street sweeping of winter maintenance sand on dust entrainment. The use of street sweeping was found to increase dust emission rates, specifically PM10 emissions. Consequently, while cleaning sand at the end of the season reduces its overall environmental impacts in some respects, it increases air quality issues in doing so.

The Handbook of Road Safety Measures provided guidance, primarily obtained from studies in Europe, of the effectiveness of different winter maintenance measures on safety (Elvik, et al., 2009). The use of sanding within 24 hours of a storm event could reduce crashes (unspecified types) by as much as 85 percent.

Shi et al. (2014) evaluated different snow and ice control materials for comparison purposes, including sand. The work developed a composite index for this comparison, which considered the cost of the material per lane mile, its average performance in addressing snow and ice conditions, its impacts to vehicles and infrastructure, and its environmental impacts. Based on testing results, the composite index for sand was lowest among all materials, highlighting its poor performance aside from providing friction and its high environmental impacts.

A collaboration between Colorado DOT and the Colorado auto insurance industry provided data on windshield damage costs and the use of sand as a winter traction material (Chang et al., 2002). The total windshield damage cost includes both repair and replacement. For Colorado, the statewide industry total windshield damage costs were $6.19 million annually in 2002. Colorado DOT, specifically in the Denver Metro area, now limits its use of sand as a winter traction material because of air quality issues.

Prewetting

Prewetting is a winter maintenance practice that employs the addition of a liquid chemical to an abrasive or solid chemical before it is applied to the road. The pre-wetting of these solids is performed either at the stockpile or at the spreader. O'Keefe and Shi (2005) synthesized information obtained from a literature review and agency surveys on the advantages and disadvantages of pre-wetting for winter highway maintenance relative to traditional methods for snow and ice control. They found that pre-wetting led to decreased applications of chemical products, reduced use of abrasives, decreased maintenance costs, improved roadway friction, and lowered accident rates. Pre-wetting has been shown to increase the performance of solid chemicals or abrasives and their longevity on the roadway surface, thereby reducing the amount of materials required. Overall, maintenance agencies are confident that pre-wetting strategies significantly improve material retention and speed up the melting process. Pre-wet abrasives refreeze quickly to the road surface and create a sandpaper-type surface, which can cut abrasive use by 50 percent in cold temperatures (Williams, 2003). If warm, chemicals can accelerate break-up of snow pack while providing increased traction for the public (Williams, 2003).

For the City of Kamloops, British Columbia, switching to anti-icing and pre-wetting reduced the use of abrasives and resulted in an estimated cost savings of $11,933 per year just from costs associated with roadside cleanup of abrasives (McCormick Rankin Corp and Ecoplans Limited, 2004).

Prewet Sand

A review of agency practice by CTC & Associates found that sand was either applied dry or prewetted with calcium chloride, magnesium chloride, agricultural by-products, or salt brines (CTC & Associates, 2011). When pavement temperatures reached 10° F, prewetted salt (using a 70/30 blend of salt brine and magnesium chloride) was applied at a rate of 400 pounds per lane mile. Specific costs and benefits associated with prewetting were not cited.

Hot water-wetted sand or prewetting abrasives with liquid deicers or hot water can greatly reduce bounce and scatter and contribute to improved friction even with vehicular traffic (Dahlen and Vaa, 2001; Perchanok, 2008). Initial tests in Ontario by the Ministry of Transportation (MTO) indicated that the use of hot water sanding equipment could reduce sand use by traditional dry applications by 25 percent. Additionally, it was estimated that the traditional mixture of salt with the sand to keep it from freezing could be eliminated, producing cost savings for salt as well (a reduction of 74 tons was cited by the author) (Perchanok, 2008). Dahlen and Vaa discussed the results of work in Finland testing the application of wetted sand using water heated to between 90 - 95° C (Dahlen and Vaa, 2001). It was found that even after 2,000 vehicles had passed, friction levels were maintained above the existing standard of using dry sand for snow covered conditions. Additionally, it was concluded that hot water-wetted sand was likely to remain on the road surface 10 to 20 times as long as dry sand with the same traffic volume.

In a recent report, the Iowa DOT provided an estimate on cost savings when using salt brine as a prewetting chemical (Iowa DOT, 2014b) as shown in Table 6. The study considered using brine as a prewetting agent for two scenarios such as 50/50 salt/sand mix applied at 300 pounds per lane-mile on a 40-lane-mile route and straight salt applied at 200 pounds per lane-mile on a 40-lane-mile route. Further, Iowa assumed a reduction in 25 percent of dry materials usage due to prewetting. It can be noted from Table 6 that a total cost savings of $32.88 and $40.95 for 50/50 salt/sand mix and straight salt respectively can be achieved from prewetting on a 40 mile lane route. In addition, Iowa also estimated the cost savings to be more significant when prewetting is used for larger operations.

Table 6: Expected Cost savings by using brine as prewetting agent (Iowa DOT, 2014b)

Assumptions	
Salt	$45 per ton
50/50 salt/sand mix	$26 per ton
Brine	$0.09 per gallon
Prewet at 15 gallons per ton of dry material	
50/50 salt/sand mix applied at 300 pounds per lane-mile on a 40-lane-mile route	
Without prewetting	
6 tons of material at $26/ton	$156
With prewetting assuming application rate is reduced by 25 percent (225 pounds per lane-mile)	
4.5 tons of dry material at $26 per ton	$117.00
68 gallons of brine at $0.05 per gallon	$6.12
Total costs	$88.90
Total savings	$32.88
Straight salt applied at 200 pounds per lane-mile on a 40-lane-mile route	
Without prewetting	
4 tons of material used at $45 per ton	$180
With prewetting assuming application rate is reduced by 25 percent (150 pounds per lane-mile)	
3 tons of dry material at $45 per ton	$135.00
45 gallons of brine at $0.09 per gallon	$4.05
Total costs	$139.05
Total savings	$40.95

Prewet Salt

Prewetting can accelerate the dissolution of solid chemicals and enhance its melting action (TAC, 2013). The benefit of prewetting salt is that particle bounce can be minimized, however, care must be taken when applying prewetting agent from a vehicle to minimize the amount that is directly applied to the pavement. Prewetting can reduce salt usage (no figures cited) but can also require more complex equipment, storage tanks and brine making equipment.

In general, DOTs recommend using prewet salt for their winter maintenance operations. A New Hampshire report strongly recommended using 23 percent sodium chloride, 32 percent calcium chloride, Magic Minus Zero TM and other patented products as prewetting chemicals for winter maintenance activities. The report estimates a cost savings of up to one third over dry salt (NH Best Management practices, 2014). In addition, another report prepared by Cripps and Leeds (2013) to the town of Milton recommended prewetting dry salt with 23 percent salt brine for winter maintenance operations. In order to implement this prewetting technology, the study recommended conversion of the city's eleven winter plow trucks to accommodate salt brine dispensing equipment. The cost of truck conversion was estimated at about $106,205 with the expected payback period to be less than two years due to reduction in salt usage (Cripps and Leeds, 2013). Sooklall et al. (2006) evaluated the use of calcium chloride as a prewetting agent for rock salt in a study using highways in Ontario, Canada. It was found that prewetted salt outperformed dry salt, reducing snow cover on the roadway between 14.8 and 37.9 percent at a prewetting ratio of 7 percent by mass of dry salt.

Burtwell discussed the results of the use of prewetted salt on roads in England (Burtwell, 2004). Prewetting agents in use included sodium chloride, calcium chloride, and water. The work found that prewetted salt was retained on roads better with less waste through targeted spreading. Evidence suggested that a 25 to 33 percent savings in salt was possible through the use of prewetting. However, spreading equipment must be calibrated for the specific salt grade in use, and prewetting may not be applicable for all weather conditions.

A University of Wisconsin Transportation Bulletin indicated that prewetting could reduce salt loss on road surfaces by 30 percent while providing faster melting and penetration of snow and ice pack (University of Wisconsin, undated). Salt should be prewetted with 8 to 12 gallons of liquid per ton. Salt use could be reduced by 20 percent through the use of prewetting, although the exact source of this figure was not stated.

Perchanok (2001) examined the feasibility of applying salt at higher travel speeds in Ontario by using ground speed controllers and prewetting using magnesium chloride. The work found that at lower speeds (35 km/h) prewetting did not improve material placement over dry salting. However, at a higher speed (60 km/h), prewetting improved material placement. This improvement would translate into reduced loss of materials on the roadside that would impact the environment and improve maintenance operation efficiency by allowing them to be conducted at higher speeds.

Luker et al. (2004) examined the melting performance of rock salt with the use of prewetting agents in a laboratory environment. Different prewetting agents were tested, including distilled water, calcium chloride, IceBan, liquid corn salt, Caliber, and Mineral Melt Elite. Results from friction recovery times showed that prewetting salt slightly decreased its performance at temperatures of -1° C and -5° C, but was effective at -10° C. Melting was improved by increasing the ratio of liquid to rock salt. Overall, it was concluded that melting performance of salt improved by prewetting at colder temperatures. Benefits stemming from prewetting were cited as improved retention of particles on the roadway, improved melting capacity at certain temperatures, and a reduction in the amount of dry salt that would need to be applied. However, the work did not discuss the relative costs associated with the different prewetting agents tested.

Comparison of Prewetting with Liquid Sodium Chloride, Magnesium Chloride, or Calcium Chloride

Prewetting can be accomplished by brine or other liquid chemicals such as NaCl, $MgCl_2$ and $CaCl_2$. A recent report was published about the cost-effectiveness of prewetting chemicals (Salt Institute, Undated). The study demonstrated the cost savings due to the use of $CaCl_2$ as a prewetting chemical with dry salt. The study estimated about 30 percent reduction in salt usage and approximate net savings of $5,950 (per 1000 tons of dry salt) due to the use of $CaCl_2$ as a prewetting chemical. The cost savings was calculated based on the difference between dollars saved from reduced salt usage and dollars spent on $CaCl_2$ (prewetting chemical). Experiments conducted in 1993 and 1994 by the British Columbia Ministry of Transportation and highways found a significant reduction in salt usage due to prewetting salt with $MgCl_2$ and $CaCl_2$ (as much as 53 percent in one instance) (Bodnarchuck and Gooding, 1994). In the 1970s the Michigan DOT conducted a study that confirmed the effectiveness of pre-wetting in winter maintenance activities (Lemon, 1975). Over three winter seasons, the study found a reduction in salt usage due to more salt staying on the road. In particular, the salt usage was reduced by 12 percent in the 1974-1975 winter season compared to the 1973-1974 winter season even though snow accumulation and number of storms were higher for 1974-1975 winter season. The study used 30 percent $CaCl_2$ brine as a pre-wetting chemical with dry salt (10 gallons for every ton of dry salt). A cost analysis shows an annual savings in excess of $100,000 due to the reduction in application rates (reduced from 500 to 400 lbs. per mile) (Lemon, 1975).

Fu et al. performed a statistical analysis on observational data to identify the quantitative effects of weather and maintenance operations on snow melting trend (Fu, et al., 2006b). Chemicals included near-saturation solutions of NaCl (sodium chloride brine), $CaCl_2$ (calcium chloride brine with corrosion inhibiting additives), and $MgCl_2$ (magnesium chloride brine with corrosion inhibiting additives). $CaCl_2$ was found to be 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).

Prewetting Techniques

Prewetting can occur in the pile or at the spreader. Prewetting at the pile involves applying a quantity of prewetting agent to a granular storage pile in the yard before loading it on a truck. Prewetting at the spreader involves applying the prewetting agent as the solid material is about to be applied to the roadway by the spreader. Additionally the creation of material slurries by prewetting is a newer approach. Each approach offers advantages and disadvantages, as the following sections highlight.

At the Spinner

A more direct approach to prewetting is to perform the task at the material spreader on the plow vehicle. Prewetting at the spreader coats the deicer with liquid as it comes from the hopper via the conveyor/auger onto the spinner. The benefit of this approach is that liquid is only applied to the material when it is used.

Information from New Hampshire provided general information on prewetting best practices (Local Technical Assistance Center, undated). This included guidance on the use of 8 to 10 gallons of prewetting liquid per ton of deicer. The information provided indicated that the use of prewetting in general could reduce material application rates by 15 percent to 20 percent, producing material and cost savings for an agency. Similarly, NCHRP Project 20-07 (Task 117) provided guidance on liquid use in prewetting at the spreader, indicating 8 to 12 gallons per ton of material should be applied, with a solids application rate of 200 pounds per lane mile (Boselly, 2001).

Information from the Salt Institute indicated that prewetting could reduce salt application rates by 26 percent to 30 percent due to more material being retained on the roadway (Salt Institute, undated a). In a case where an agency used 1,000 tons of salt per winter, this could translate into thousands of dollars of savings, even when factoring in the cost of the prewetting brine (ex. $CaCl_2$).

Burtwell (2004) discussed the performance of prewetted salt spreading from trials in the United Kingdom. Prewetted salt that was wet at the spreader was found to be preferable to dry salt because most small salt grains dissolved before being blown off the pavement. It was reported that salt use reductions of 25 to 33 percent were possible using prewetting. However, it was noted that care must be taken when calculating prewetting cost savings because different salt types can be used for the base salt and wetting agent, as well as different proportions of dry salt to wetting agent, having direct impacts on the calculation of costs and benefits. Additionally, the life of prewetted salt vehicles is generally shorter than those vehicles applying dry salt.

Nixon (2009), as part of a field test study of abrasive delivery systems, discussed some of the advantages of prewetting. While prewetting at the different spreader systems were not part of the tests conducted, the advantages of such systems were cited from work completed by Lemon in Michigan (Lemon, 1975) and included material savings, as well as the potential to extend the patrol range of the snow plow itself. In the case of extending the plow range, this was the result of reduced material usage requiring fewer stops to reload, resulting in both time savings as well as increased maintenance coverage of the roadway system.

The Federal Highway Administration touches on general aspects of prewetting, including prewetting at the spreader, as part of a larger discussion on effective anti-icing programs (Ketcham, et al., 1996). Such systems were cited as reducing solid material quantities being used by 30 percent at speeds as high as 40 mph. Prewetting systems at the spreader were also cited as being relatively inexpensive, using electric or hydraulic pumps, in cab controls, nozzles, hoses, tanks and general fittings. However, no cost figures were provided by the report to quantify what was considered inexpensive at the time.

Perchanok (2001) examined the use of prewetting at the spreader in conjunction with high-speed salt spreading in Ontario. The work found that at lower speeds (35 km/h) prewetting at the spreader did not improve over traditional application approaches but worked equally as well. At a higher speed (60 km/h), prewetting at the spreader improved material placement, translating to reduced environmental impacts and more efficient salting operations.

In the Pile

Prewetting in the pile is another approach to prewetting. Since it does not require specialized equipment (ex. prewetting spreaders), it offers an initial, basic approach to prewetting. The common approach to this practice involves spreading the salt (or other granular material) on a flat, impermeable surface. Next, the prewetting agent is sprayed in the salt, with the salt being moved around to allow for adequate and consistent coverage. Once the salt has been covered, it is placed back into a pile for storage and later use. Alternatively, injections of the prewetting agent may be made into the upper section of the stockpile itself. Ketcham, et al. (1996) indicated that approximately 8 gallons of liquid prewetting agent should be applied per ton of granular material. Frequent reworking of the pile may be needed to keep the material manageable.

Most likely because of its basic nature, the costs and benefits of this approach to prewetting have not been discussed in literature. Despite the lack of documented information, the benefit of this approach can be identified as allowing for prewetting to be conducted without the purchase of extensive support equipment (ex. prewetting spreaders). This approach allows an entity to develop experience with prewetting and to make a determination of whether it is an approach worth implementing on a larger scale without making an extensive investment. The costs associated with this approach are primarily for prewetting agents from the manufacturer, although an entity could purchase brine making equipment and storage tanks in support of a longer-term commitment to prewetting at the pile. There is a potential for liquid runoff to occur at the bottom of the pile, particularly as temperatures rise above 70° F, which can present environmental issues as well (Ketcham, et al., 1996).

Slurries

Schnieder et al. (2013) discussed the results of an evaluation of the Epoke slurry spreader in Ohio, which was performed to determine its feasibility in wider use. The evaluation examined the impact of the spreader on level of service, material usage and equipment versatility. When compared to standard salting trucks, the use of the slurry spreader reduced salt use by 12 percent while treating the same segment of roadway. Level of service remained the same between slurry and salt applications, with the slurry spreader requiring 17 treatment passes versus 26 treatment passes for the salt spreader (all storms compared collectively). Using a slurry spreader and based on a 12 percent salt use reduction, the slurry spreader investment cost was estimated to be recovered within eight years.

An application of an unspecified model of Epoke unit in West Des Moines, Iowa was summarized in 2009. The unit prewets salt at rates of up to 90 gallons per mile, while reducing salt gradation to achieve faster melting action (Barbaccia, 2009). An informal evaluation found that a prewetting rate of 60 gallons per ton of salt was effective when using a liquid comprised of 80 percent salt brine, 10 percent Fusion or GeoMelt and 10 percent calcium chloride. The unit allowed for a 25 to 30 percent reduction in granular applications, lowering the amount of chloride entering the environment.

The Maine DOT evaluated a Monroe slurry maker that crushed salt to a smaller particle size and then combined it with salt brine at a rate of 50 gallons or more to produce slurry (Colson, 2009). The equipment required two days to install at a cost of $1,000. The evaluation, which was conducted over 10 storm events in 2008-2009, found that the unit did well in crushing salt to a more desirable size and applying it as a slurry. However, hydraulic issues with the salt crusher were encountered when the vehicle was operating its plow and wing. The key findings from the evaluation were that a larger crushed particle size (3/8 inch) was required for temperatures below 20°F to prevent refreezing, while a smaller particle size (1/4 inch) was acceptable during warmer temperatures.

The Epoke and Monroe units are very different. The Epoke unit requires a finer gradation of salt which may be more costly or require specialized crushing equipment, but the Epoke unit can spread salt in up to three lanes in a single pass, potentially offsetting these costs by saving time and money.

Deicing (with Rock Salt)

Kuemmel and Hanbali performed a simple before and after analysis on the effectiveness of salting on safety in New York, Minnesota and Wisconsin (Kuemmel and Hanbali, 1992; Hanbali, 1994). 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. This approach employed 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. 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 $0.073 cents to $0.061 cents per vehicle mile traveled on two-lane highways and $0.53 cents to $0.23 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 dollar spent on two-lane highways and $3.50 for every dollar 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.

Usman et al. (2012) developed disaggregate models for quantifying the safety effects of winter maintenance activities at an operational level. 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. 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 were quite low, steadily rising back to the expected mean had no maintenance been performed over a period of hours following the maintenance. 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.

Baroga (2004) evaluated different aspects of salt use with and without the use of corrosion inhibitors in Washington state. This work included cost comparisons, differences in road conditions following applications, corrosion impacts, and environmental impacts. The reported cost per lane mile for salting operations, including labor, equipment, and materials ranged from $113.98 to $683.10 (2004 dollars), depending on the region of the state. The cost of salting with the use of corrosion inhibitors ranged from $695.55 to $1652.93 for the same winter season. Road surface conditions with and without the use of corrosion inhibitors were found to be largely the same. Corrosion inhibitors reduced metal corrosion by 53 percent in the field (when measured using metal coupons on maintenance vehicles). However, steel coupons mounted on roadside guardrails experienced 17 percent more corrosion on routes where corrosion inhibitors were used. No differences in environmental impacts were found between the use of salt with and without corrosion inhibitors.

Fu et al. (2006b) performed a statistical analysis on observational data to identify the quantitative effects of weather and maintenance operations on snow melting trends. Chemicals included rock salt with and without pre-wetting liquid. The test site was a 50 kilometer route on Highway 21 in southwest Ontario, Canada. 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.

Norem (2009) discussed the selection of winter maintenance strategies based on climatic parameters in Sweden. Of interest was the discussion of the 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 -8°C.

Environment Canada (2006) summarized the different costs and benefits associated with road salt use in Canada. Among the benefits cited was a reduction in accidents of up to 88 percent, a figure obtained from the Salt Institute (Salt Institute, Undated b). Other specific benefits cited included:

- Fuel savings – 33 percent reduction, translating into savings of $1.88 (2006 Canadian dollars) per 62 miles traveled (100 kilometers traveled)[2]
- Travel time savings - $11.00 per hour for car, $9.73 per hour for bus
- Avoided fatalities, injuries and property damage- savings of $1,594,412 per fatality, $28,618 per injury and $5,724 per property damage crash eliminated

Indirect benefits included:

- Reduction in tort liability claims
- Maintained economic activity – estimated at $27.00 per hour per employee
- Maintained access to social activities

Qiu and Nixon (2008) examined performance measurements for winter maintenance operations. As part of this work, the effects of maintenance operations, including the use of sand-salt on vehicle speeds and volumes were investigated. In general, the winter maintenance operations (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). Chemical treatment had a small effect (below 1 mph higher speeds the following hour after treatment).

Miedema and Wright (1995) identified several direct and indirect benefits to winter maintenance when examining the impacts that different weather information sources might have on response

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[2] This is approximately equivalent to $1.65 in 2015 US dollars per 62 miles traveled, or $2.18 in 2015 Canadian dollars per 100 km traveled.

times (call outs) to storms. Direct benefits included decreased materials usage (salt), equipment costs, and labor costs. Indirect benefits identified included decreased accidents, travel time, and fuel consumption. While direct benefits varied by location (in this case, sub-districts), general values for indirect benefits were developed. The benefit of reduced accidents was valued as $0.0748 per vehicle kilometer of travel on two lane roads and $0.0357 for four lane roads. The benefit of improved weather information on travel time was $0.0383 per vehicle kilometer of travel on two lane roads and $0.0162 on four lane roads. Finally, the benefit of reduced fuel consumption was determined to be $0.0007 per vehicle kilometer of travel on two lane roads and $0.0003 for four lane roads. Note that the savings listed here are not entirely attributable to salt, but also include the overall benefits accrued by maintenance operations incorporating the use of salt.

Ye, et al. (2012) developed methods for estimating the benefits of winter maintenance operations using statewide data from Minnesota. The analysis included consideration of materials (primarily salt) to establish safety, operational (travel time) benefits, and fuel savings benefits from maintenance operations. It was determined that by performing winter maintenance, crashes were reduced by 4,600 over the do nothing alternative between 2001 and 2006. A travel time savings of $10,915,690 was produced by facilitating higher travel speeds and a fuel savings of $41,057,063 resulted from more efficient travel. When the value of all benefits was compared to the total costs over the 5 year time period, a benefit-cost ratio of 6.0 was computed.

Fortin Consulting (2014) estimated damages to infrastructure, automobiles, vegetation, human health and the environment from the use of road salt and provided a cost range from $803 - $3,341 per ton of salt used.

The Handbook of Road Safety Measures provided guidance, primarily obtained from studies in Europe, of the effectiveness of different winter maintenance measures on safety (Elvik, et al., 2009). The use of salting throughout a winter season was estimated to reduce injury crashes by 7 percent and 22 percent and property damage crashes by 19 percent and 39 percent.

Shi, et al. (2013a) discussed the use of chloride-based salts in winter maintenance, specifically the benefits they produce and their negative impacts. Specific benefits of salt include reduced crashes, improved mobility, and reduced travel costs. Crash reductions cited from previous literature ranged from 78 percent on freeways to 87 percent on two lane roads. Improvements to mobility cited from prior work are presented in Table 7. Finally, cost savings provided by salt cited from previous work ranged from $0.06 to $0.53 cents per mile on two lane roads and freeways. Negative aspects of salts included vehicle and infrastructure corrosion as well as impacts to water and soils.

Table 7 Mobility improvements achieved by salt use (Shi, et al., 2013a).

Volume to capacity ratio	Improvement observed
Low snowfall event	
0.35 - 0.60	6 - 7%
0.70 - 0.75	26 - 27%
0.90 - 1.0	10 - 11%
Heavy snowfall event	
0.35 - 0.60	11%
0.70 - 0.75	29 - 36%
0.90 - 1.0	5 - 12%

Rubin, et al. (2010) examined the use of salt on Maine roads, including its impacts on the environment and its costs. It was found that the use of salt on all roads in the state totaled 750 pounds per resident annually. Climatic conditions, methods of use, and application rates all contributed in influencing the extent of corrosion caused by salt use in winter maintenance. Environmentally, salts entered water and soil along roads in the state, with long-term impacts found along some routes (ex. well contamination). Recovery from the use of salt in the state was estimated to require years and possibly decades should salt use be stopped.

Fitch, et al. (2013) conducted an environmental life cycle assessment of winter maintenance treatments, including salt, using data from Virginia. Based on calculations of the costs associated with the energy used to produce the materials, greenhouse gas emissions, water use, chloride emissions, and biochemical oxygen demand, the environmental burden of salt on a per storm basis was calculated to be $3,149. This value was associated with a 100 lane mile segment of roadway.

Fu and Usman (2014) analyzed crash data between 2000 and 2006 from Ontario, Canada to determine the relationship between safety and the use of salt. The work found that a 10 percent improvement in road surface conditions from conducting some form of winter maintenance could produce a 20 percent reduction in the average number of crashes that occurred. The use of salt in winter maintenance reduced the average number of crashes over the study period by 20 to 85 percent and reduced crash rates by 51 percent.

The environmental impacts of road salts have been a subject of research since their usage became widespread during the 1960s for highway maintenance (Hawkins, 1971; Roth and Wall, 1976; Paschka, et al., 1999; Ramakrishna and Viraraghavan, 2005). The environmental costs of salt were estimated to be an average of $469 per ton of material used (in 2005 dollars) (Shi, 2005). Evidence demonstrates that chloride salts accumulate in aquatic systems (Mason, et al., 1999; Kaushall et. al, 2005), cause damage to terrestrial vegetation (Public Sector Consultants. 1993; Bryson and Barker, 2002), and alter the composition of plant communities (Miklovic and Galatowitsch, 2005). Environment Canada (2001) reported that many woody plant species sensitive to salt had vanished from Canadian roadsides. 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. Despite the potential damaging effects of road salts, 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 (Fay and Shi, 2012).

Anti-icing

Anti-icing is 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" (Ketcham et al., 1996). Anti-icing has proven to be a successful method of proactively maintaining roadways during the winter season.

In comparison with traditional deicing methods, anti-icing operations reduce the cost significantly for snow and ice control operations (Illinois Technology Transfer Center, 1998). Washington DOT conducted three case studies to determine the benefit-costs of anti-icing strategies compared to traditional deicing methods. The first case study was conducted on a 20 mile lane with average distance travelled (ADT) of 2,500 vehicles covered with heavy frost and ice. Repeated treatments of sand and chemicals were used for deicing, and liquid $MgCl_2$ at 30 gallons per lane mile were used for anti-icing operations. Overall, both methods were effective for snow and ice control operations. However, on cost comparison, the anti-icing cost was about $383 and the traditional deicing method was about $4,400 (11.5 times greater). In the second case study, calcium magnesium acetate (CMA) was used for an anti-icing operation on a 23 mile segment of interstate highway consisting of four travel lanes (including bridges and underpasses, ADT of 42,000 vehicles). Similarly, the cost of anti-icing was significantly less than the traditional deicing, estimated at $1360 for anti-icing and $4,179 for deicing (sand and granular chemicals). In the third case study, several bridges were used (ADT of 2,200 vehicles) to study the cost effectiveness of deicing and anti-icing (liquid $MgCl_2$) methods on controlling ice formation. Similar to the previous two case studies, the cost of anti-icing ($22 per bridge) was very less compared to traditional deicing ($257 per bridge). Further, the cost of deicing would go up by $302 by including sweeping charges resulting from sand usage (Illinois Technology Transfer Center, 1998).

In another report, Minnesota field trials show a savings of about 10 percent in costs due to the use of anti-icing methods. The cost reduction is further increased if the snow falls on a weekend, due to the increased labor cost during weekends. In addition to cost savings, the time required to treat the lane also significantly reduces (MnDOT, 2009).

Colorado evaluated the cost of sanding applications in terms of labor, equipment and materials. This helped the Colorado DOT evaluate best practices for winter maintenance and implement changes where necessary. In the last decade or so, Colorado has had one of the highest population growths in U.S. history, resulting in increased traffic, insurance claims, and insurance costs. The number of windshield replacement claims is cyclical with peaks occurring in the late spring and early summer. Yet, with the increase of liquid chemicals for anti-icing, the number of claims has been following a downward trend, resulting in cost savings to the public (Chang et al., 2002). While implementing anti-icing practices has allowed Colorado to meet air quality standards and reduce windshield replacement and repair claims, total costs for winter maintenance are still increasing due to the increasing population. Equipment and labor costs have remained relatively constant with the addition of anti-icing; however, the cost of chemical product per lane mile has increased nearly 400 percent (Chang et al., 2002).

Kahl (2002) completed work for the Michigan DOT 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. As part of this work, the impact of anti-icing was determined on one route (I-94, 123 miles). It was estimated that anti-icing activities reduced the number of expected crashes along the study route by 401 crashes 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 one study of the cost savings of anti-icing, Colorado, Kansas, Oregon, Washington and the Insurance Corporation of British Columbia (ICBC) were asked to state any cost savings from anti-icing. Specifically, Colorado saw an overall cost savings of 52 percent while Oregon saw a cost savings of 75 percent for freezing rain events. It was concluded that anti-icing could provide a 10 percent to 20 percent cost savings in snow and ice control budgets, and possibly result in a 50 percent reduction in cost per lane mile (Boselly, 2001).

On a highway in Idaho, implementing anti-icing reduced accidents by 83 percent and labor costs by 62 percent (Breen, 2001). Reducing accidents also translates into an economic savings to the traveling public in terms of vehicle repair, insurance costs, and injuries or fatalities, as well as litigation costs. A reduction of accidents by 8 percent in Canada resulted in savings of over $240,000 (McCormick Rankin Corp and Ecoplans Limited, 2004).

In a large study on the economic benefits of anti-icing, it was found that savings could range "from $1,266 to $30,152 per typical maintenance snowplow truck route per year," while user cost savings in terms of reduced accidents could be as high as $107,312 for 900 storm hours. Total cost savings were estimated to be $1.7 billion (Epps and Ardila-Coulson, 1997).

In Montana, the 4-year average (1997-2000) centerline mile cost (labor, equipment, materials) for winter maintenance was examined for two sections using different practices to achieve the same level-of-service. Anti-icing the Plains section of State Route 200 resulted in a 37 percent reduction in costs per lane mile compared with the Thompson Falls section where pre-wetting is used (Goodwin, 2003).

Brine

Brine Making and Storage

Benefits associated with brine-making equipment are accrued from the use of brine itself, which is discussed elsewhere in this document. However, there are costs associated with brine making that have been documented. Veneziano, et al. (2010b) discussed the use of a benefit-cost toolkit for winter maintenance operations, equipment, and materials. As part of this work, the costs associated with brine-making were identified. If an agency made brine itself, a cost for labor (per hour, per employee) as well as material inputs (ex. granular material such as salt) would be incurred. In addition, brine-making equipment would also need to be purchased. In 2010, the cost of such equipment varied widely, ranging from $1,940 to $21,500.

Using Recycled Water

Water from cleaning snow and ice control equipment may have a wide range of contaminants, including oil and other hydrocarbons, metals, detergents, road salts, and grit. It is important to collect, reuse, and properly manage vehicle wash water and salt-impacted site drainage to comply with local water quality regulations and protect surface and groundwater resources (Transportation Association of Canada, 2013).

Many state DOTs have implemented systems where water used to wash vehicles is recycled and then used to make brine on site. Reusing salt-laden truck wash water allows for material cost savings in making the brine solutions and conserves water use, while reducing the amount of runoff into the environment (Allenman, et al., 2004; Fay, et al., 2013). The city of Toronto recycles salt-laden runoff from its wash bays by collecting the water, removing the oil and grit using separators and settling, and then placing in holding tanks for brine making (Fay, et al., 2013).

Virginia DOT (VDOT) conducted a research project to look into the option of using recycled runoff for its onsite brine making operations, including a benefit-cost analysis comparing only the costs of using recycled runoff with the alternative of hauling away the runoff (Craver, et al., 2008). They determined that recycling was feasible, and that all capital costs would be recovered in 2 to 4 years depending on the severity of winters and the average amount of salt used. Based on these findings, VDOT is working to recycle all collectable runoff, an estimated 60 million gallons of water (Salt Institute, 2010). In an average year, the collected runoff should be sufficient to supply all water needed for brine production.

Indiana DOT (INDOT) conducted a field investigation of a proof-of-concept brine production system using recycled wash bay water (Alleman, et al., 2004). The cost estimate for the “do-it-yourself” system was $3,055, but they had a lot of necessary equipment already on hand. In 2000 to 2001, approximately 3,600 gallons of salt brine were produced from recycled wash water. By 2004, six of the 33 INDOT brine-making facilities were set up to use truck wash water to make brine.

Initial investment costs for a commercial vehicle washing facility were estimated to be $80,000 (1991 dollars), with an additional investment of $1,600 every 10 years and maintenance costs of about $4,000 per year (Kovac and Kocis, undated). The estimated investment recovery period was 1.3 years, while achieving an 80 percent recycling of runoff.

Magnesium Chloride

Little information specific to the costs and benefits of magnesium chloride ($MgCl_2$) has been documented to date. The work done with this material has largely focused on its effects on corrosion from a chemistry standpoint, as well as the performance of corrosion inhibitors. Corrosion is clearly one of the costs of the material itself.

Parker (1997) compared the use of alternative deicers, including $MgCl_2$, to sand use in Oregon. Results of a cost comparison found that $MgCl_2$ produced benefit-cost ratios ranging from 3.93 to 15.0 over sanding, depending on the specific type of storm event being addressed.

Lewis (1999) examined the environmental effects of $MgCl_2$ in Colorado in the late 1990s. The advantages of this material that were cited by the author included allowing a reduction in the use of sand and salt mixtures, as well as an improvement in road surface conditions versus these alternatives. Toxicity tests found that aquatic organisms differed in their sensitivity to $MgCl_2$. It was concluded that the use of $MgCl_2$ was unlikely to contribute to environmental damage at a distance greater than 20 yards from a roadway.

Fischel (2001) evaluated several deicer materials, including $MgCl_2$, based on information in existing literature. Reported cost information at the time (2001) showed $MgCl_2$ with corrosion inhibitors cost $0.25 to $0.78 per gallon or $46.00 to $124.00 per ton. This translated into a cost per lane mile for the material of $8.00 to $28.00, depending on application rates.

Shi, et al. (2009) evaluated alternative anti-icing and deicing compounds for the Colorado DOT. The reported costs of $MgCl_2$ ranged from $0.53 to $0.84 per gallon, including delivery, with a usage rate of 20 to 100 gallons per lane mile. The authors confirmed the negative effects of solid salt as well as liquid NaCl and $MgCl_2$, especially those on the durability of metals and Portland cement concrete. However, it was recommended to continue the use of chloride brines until better alternatives became available.

Shi, et al. (2014) evaluated the performance of different materials used in snow and ice control, including $MgCl_2$ (with corrosion inhibitors). The work developed a composite index for this comparison, which considered the cost of the material per lane mile, its average performance in addressing snow and ice conditions, its impacts to vehicles and infrastructure, and its environmental impacts. Based on testing results, the composite index for $MgCl_2$ was high (a rating of 59 out of 100) compared to other materials, indicating that the material should be considered a best practice when road conditions warrant its use. In particular, the authors recommended that $MgCl_2$ brine would be a better choice to use for cold pavements compared to other materials.

<u>Calcium Chloride</u>

Calcium chloride ($CaCl_2$) is a deicer that can also be employed in anti-icing operations when in a liquid form. Similar to magnesium chloride, the focus of published information for $CaCl_2$ has been on the testing of the material in lab settings, as opposed to quantifying its costs and benefits. Still, some quantified and non-quantified costs and benefits have been reported over time.

Fischel (2001) evaluated several deicer materials, including $CaCl_2$, based on information in existing literature. One benefit of $CaCl_2$ was that it does not attract animals to the roadside like other materials due to its lack of sodium. Inhibited $CaCl_2$ could deposit trace metals into the environment, with possible impacts to human health. The material could also increase soil and water salinity. Reported cost information at the time (2001) showed $CaCl_2$ with corrosion inhibitors cost $0.50 per gallon or $91.00 per ton. This translated into a cost per lane mile of $10.00 and $25.00.

Vestola, et al. (2006) examined the side-effects of $CaCl_2$ in Finland. Side effects were compared to those of sodium chloride, which was also being used in winter maintenance operations, including differences in extent and severity. $CaCl_2$ was found to contribute to vehicle corrosion, bridge and equipment corrosion, and impacts to asphalt pavements (reducing the sealing performance of bentonite layers). Vehicle and bridge corrosion were found to be more severe than that caused by NaCl. Additionally, $CaCl_2$ was found to reduce friction between vehicle brake discs and pads, impacting stopping performance. $CaCl_2$ was also harmful to vegetation and groundwater, although the impact was dependent on the quantity applied to the roadway.

Tuan and Gerbino-Bevins (2012) discussed findings from an investigation of different winter maintenance materials, including $CaCl_2$. Results from friction tests found $CaCl_2$ would not cause slippery roads when applied. $CaCl_2$ also showed longer refreeze times than other materials in a lab setting, translating to a benefit in achieving bare pavement during winter maintenance operations. However, the material was found to be corrosive to stainless steel through anecdotal observations during lab tests. Interestingly, the finding of longer refreeze times contradicts that of Nixon and Wei (2003), who found during lab tests that refreeze generally occurred quickly (within 30 minutes) of the initial application. This difference may be the result of the form of material tested; Nixon and Wei tested solid $CaCl_2$ samples as opposed to liquids.

Agriculturally Based Products

There is very limited information on agriculturally based (ag-based) products in the published domain. Information found on ag-based products includes the qualitative assessment that ag-based products remain on the road longer than chlorides, with limited lab and field data available to support this finding. Lab data from the ongoing Clear Roads project *Understanding the Effectiveness of Non-Chloride Liquid Agricultural By-Products and Solid Complex Chloride/Mineral Products Used in Snow and Ice Control* suggests that manufacturer developed chloride and ag-based blended products work at colder temperatures and can be applied at lower application rates to achieve the same or better LOS when compared to salt brine. All products tested with an ag-based component were found to reduce the bond strength between snow/ice and the pavement allowing for easier plowing. Additionally the ag-based products spread more evenly on the pavement surface and remained on the pavement longer than salt brine.by up to 250 to 750 vehicle passes varying by product type.

In another project, field testing showed that after 4 days 20 percent, 30 percent, and 50 percent of applied products (CCB, NaCl + GLT, and Freezeguard; respectively) remained on the road surface (Shi et al., 2011).

Corrosion and Corrosion Inhibitors

With the increased use of road salts, there is genuine concern from the general public, trucking industry, and DOTs about the corrosion damage that snow and ice control operations may cause to motor vehicles and transportation infrastructure (steel bridges, large span supported structures, parking garages, pavements, etc.), which can have significant safety and economic implications (Johnson, 2002; Shi, et al., 2009, Honarvarnazari et al., 2015). Chlorides are generally considered the most corrosive winter maintenance chemicals (Shi, et al., 2009). Often, commercially available, corrosion-inhibited versions of these chemicals are used to reduce their deleterious impacts on vehicles and infrastructure. It should be cautioned that deicer products noncorrosive to one metal might be corrosive to other metals (Fay, et al., 2008) and additives used to inhibit certain metallic corrosion may have little to no inhibition effect on other metals (Levelton Consultants, 2007).

Chloride based deicers sales topped 20.2 million tons in 2008 and continue to grow because they are the least expensive materials to use for deicing and anti-icing to date (www.saltinstitute.org). The upfront cost of purchasing products is an easy way to justify using specific products, but the secondary costs, or indirect costs, such as corrosion and environmental impacts, are often not considered in the initial purchase cost. DOTs and the trucking industry have observed directly the effects of corrosion to vehicles and infrastructure (Buckler and Granato, 1999; Koch et al., 2002, Johnson, 2002). Average costs of about $32 per vehicle was the estimate for corrosion to vehicles from deicers, with higher corrosion costs of about $140 per vehicle in seasonally cold maritime climates, such as Boston, Massachusetts and Bangor, Maine (Johnson, 2002).

Theoretically, a region could estimate the number of cars and estimate corrosion costs to vehicles and include this in the purchase cost of various products. This does not include corrosion impacts to infrastructure, such as reinforced or pre-stressed concrete structures and steel bridges (Koch et al., 2002). In fact, NCHRP 577 identified deicer corrosion to steel rebar as the primary concern, followed by impacts to vehicles, concrete in general, structural steel, and then roadside structures (Levelton Consults, 2007). The estimated cost to install corrosion protection on new bridges and repair old bridges in snowbelt states is between $250 million and $650 million annually (TRB, 1991). Indirect costs including corrosion to parking garages, pavements, roadside hardware, and non-highway objects are estimated be greater than ten times the cost of corrosion maintenance, repair, and rehabilitation (Yunovich et al., 2002).

Costs of Corrosion

Several studies have examined the costs of corrosion. Some of the findings from this work include:

- In 1978, Battelle estimated the cost of corrosion to the US at $70 billion, ~4.2% GNP (Battelle, 1978)
- Michigan DOT reported costs due to vehicle corrosion ranging from $715 - $8,558 per vehicle (Michigan DOT, undated).
- In 2002, NACE, FHWA, CC Technologies Laboratories, Inc., estimated the cost of corrosion using two methods, 1. Cost of corrosion control methods and services, and 2. Corrosion costs of specific industry sectors (explained below) (Koch, et al., 2002).
    1. Corrosion Control Methods and Services – this includes protective coatings ($108.6 billion), corrosion-resistant alloys ($7.7 billion), corrosion inhibitors ($1.1 billion), polymers ($1.8 billion), anodes and cathodic protection ($2.22 billion), and corrosion control and monitoring equipment ($1.2 billion). Other contributions to total annual direct cost considered include: contract services, corrosion research and development ($20 million), and education and training ($8 million) (Koch et al., 2002). Total cost of corrosion = $121 billion, ~ 1.4percent gross domestic product (GDP).
    2. Corrosion costs of specific industry sectors – Infrastructure, Utilities, Transportation, Production and Manufacturing, and Government Figure 2 shows corrosion costs for each category (Koch et al., 2002). Total cost of corrosion = $137.9 billion, ~1.6percent GDP.

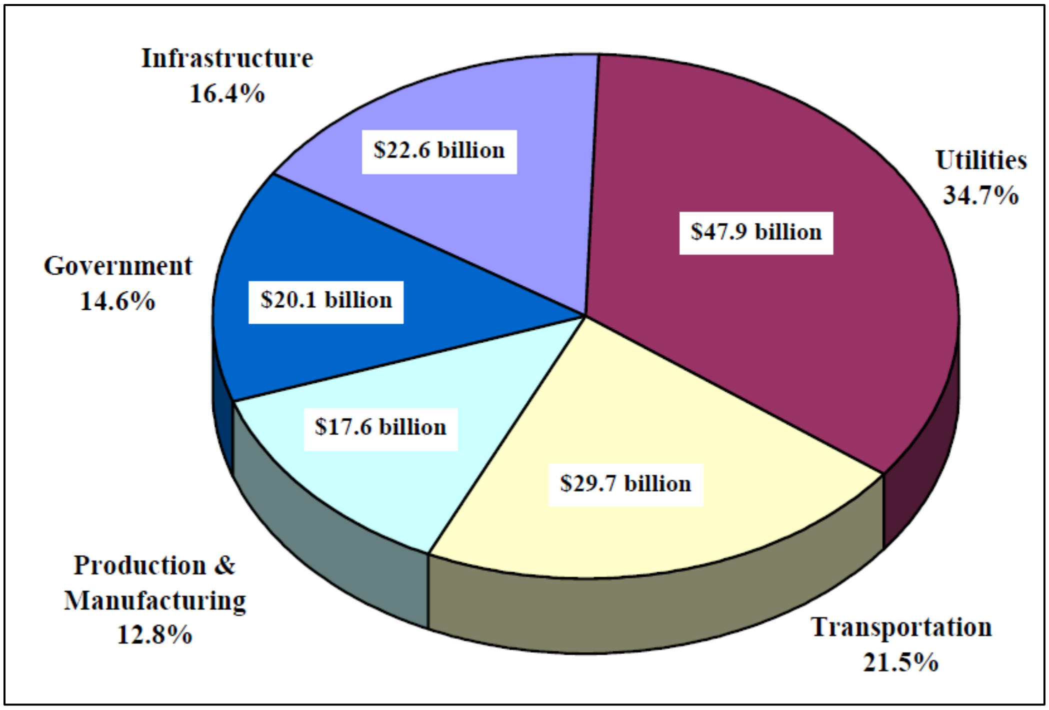

Figure 2 Cost of corrosion in sector categories analyzed by Koch, et al. based on total cost of corrosion at $137.9 billion per year (Koch, et al., 2002).

The costs of corrosion to the transportation sector was broken down into the following smaller categories - motor vehicles, ships, aircraft, rail cars, and hazardous materials transport (Koch, et al., 2002). Relevant to this project is the motor vehicles category, which considered increased manufacturing costs for corrosion engineering and resistant materials, corrosion related repairs and maintenance, and corrosion related depreciation of vehicles; for a total cost of corrosion estimated to be $23.4 billion. Motor vehicles were considered to have the greatest corrosion cost, accounting for approximately ~80percent of the transportation category.

A total cost of corrosion for all sectors of the US economy, including those not considered in the second benefit-cost approach by Koch, et al. (2002), was estimated to be $276 billion, ~3percent GDP, and indirect costs (lost productivity due to outages, delays, failures, and litigation; taxes and overhead on the cost of the corrosion portion of good and services; and indirect costs of non-owner/operator activities) of corrosion were estimated to be $552 billion, ~6percent GDP (Koch, et al., 2002).

It was estimated that 25 – 30percent of corrosion costs could be saved if optimum corrosion management practices were used. This document also stated the current per capita direct cost of corrosion for each US resident (as of 2001) is about $970 per year, and if indirect user costs are included this number would double (Koch, et al., 2002).

As part of a comprehensive study of the impacts of deicers in Michigan, estimates of the direct costs of corrosion to vehicles and bridge decks for various deicers were developed and are presented below (Public Sector Consulting, 1993).

- Road Salt – vehicle corrosion $119 - $265.5 million and bridge deck corrosion $11.2 – $25.5 million.

- Salt/Sand – vehicle corrosion $79.6 - $177 million and bridge deck corrosion $7.5 - $17 million.
- CMA – vehicle corrosion $8.6 – $32 million and bridge deck corrosion $1.3 – $3.1 million.
- CG-90 Surface Saver – vehicle corrosion $54.8 - $122 million and bridge deck corrosion $11.2 - $45.2 million.
- Calcium Chloride – vehicle corrosion $76.4 - $170 million and bridge deck corrosion $7.2 - $16.3 million.

Jones and Jeffery (1992) estimated annual vehicle corrosion cost associated with road salting at $11.7 billion nationwide. Kelting and Laxon (2010) estimated salt induced corrosion cost of $2.1 - $4.2 billion per year, based on TRB (1991) estimates of corrosion protection costs per vehicle of $125 - $250 multiplied by the 10.7 million cars sold in 2009. Kelting and Laxon (2010) pointed out that “it is difficult to estimate the specific cost associated with corrosion protection of vehicles. The value of even the most detailed calculation is questionable, and must be used with caution.”

A study of deicer impacts in Anchorage, Alaska estimated that corrosion damage to vehicles was $5.1 million per year, and repair costs for corrosion damage to bridge decks was estimated at $68,000 per year (Nottingham, et al., 1983). The goal of the study was to determine the actual costs of using salt in winter maintenance, not just the purchase cost, as a possible means of justifying using alternative products that may cost more than salt initially. The corrosion damage to vehicles was estimated to cost $3,000 to restore a 5-6 year old vehicle to near-new condition, and value loss to the vehicle was estimated to be 50 percent of repair costs. This study estimated that if Alaska DOT continued to use the same winter maintenance practices, by 1990 vehicle value loss would be $6.5 million per year, and by 2000 $8 million per year.

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 (Shi, et al., 2009). Over five billion dollars are spent each year by state and local agencies to repair infrastructure damage caused by snow and ice control operations (FHWA, 2014), which translates into $333 per ton of road salts. As of 1999, there were 583,000 bridges in the United States, with approximately 15 percent of all bridges structurally deficient and an annual corrosion cost of $8.3 billion. It is 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 (TRB, 1991). 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 ten times the direct cost of corrosion maintenance, repair, and rehabilitation (Yunovich, et al., 2002).

A recent publication by Shi et al. (2013a) determined total repair costs for Washington State DOT (WSDOT) equipment for 2008 through 2011. The relevant values are presented in Table 8.

Table 8 Total and Plow-related Corrosion Repair Costs in Washington (Shi, et al. 2013a).

Year	All corrosion related maintenance	Snowplows maintenance only
2008	$457,956	$327,529
2009	$712,969	$355,514
2010	$558,516	$268,816
2011	$736,362	$299,578

Figure 3 provides a visual description of corrosion costs seen on WSDOT vehicles, with the majority of corrosion costs resulting from damage to chassis, axles, brakes, frame, steering, suspension, and tire and wheels, accounting for 32 percent of corrosion costs.

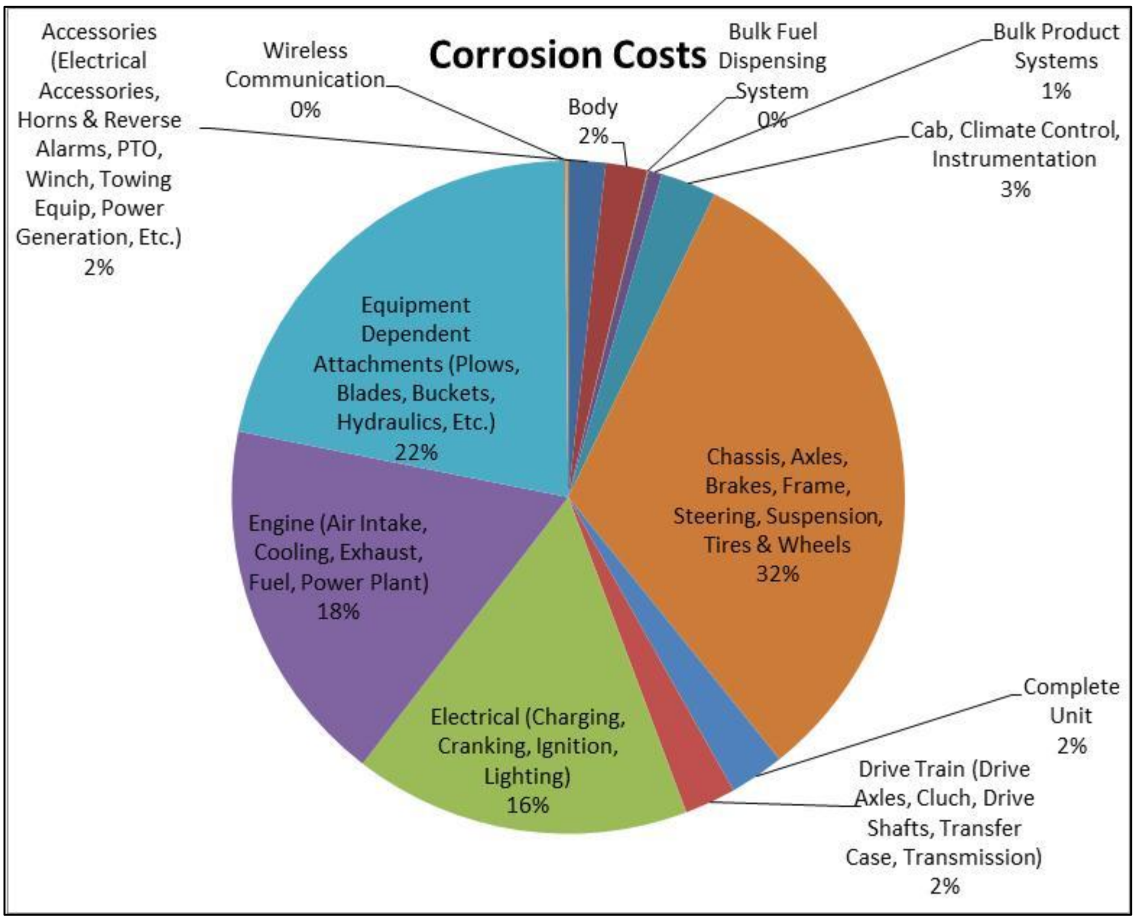

Figure 3 Allocation of corrosion-related repair costs among WSDOT equipment (Shi, et al., 2013a).

Based on the information gathered on equipment, and corrosion damage and repair costs, it was determined that corrosion related damage from deicers could be reduced by 20 percent if WSDOT increased its investment in proactive maintenance and corrosion prevention (Shi et al., 2013a). A benefit-cost ratio of 8.0 was calculated for proactive maintenance and corrosion prevention, which was found to be a conservative value because indirect costs of equipment corrosion (estimated to be at least 20 percent) were not taken into account. Estimated corrosion costs to DOT equipment fleet related to deicer exposure is $14,050,368 per year (Shi et al., 2013a), with the benefit-cost of 13.2 calculated by Honarvarnazari et al. (2015) for corrosion prevention and mitigation by DOTs.

Corrosion Inhibitors and Prevention

Shi et al. (2009) suggested that the most effective way to address concrete durability is at the design and material selection phase. It is important to maintain adequate concrete cover and to use high-quality concrete. Additionally, increasing the concrete thickness over steel rebar to act as a barrier to chloride migration improves durability (Newton and Sykes, 1987). Other options to mitigate the corrosive impacts of chlorides on concrete are the addition of corrosion-inhibiting admixtures to fresh concrete, surface treatment of steel rebar, or using alternative reinforcement materials (Shi, et al., 2009). Other options include a hydrophobic surface treatment of concrete to reduce the ingress of chloride, cathodic protection (CP), electrochemical extraction (ECE), injecting beneficial species into concrete or migrating corrosion inhibitors (MCIs), or electrochemical injection of corrosion inhibitors (EICI). While cost values were not provided for any of these techniques, Shi et al. (2009) suggested that EICI has not taken off as a treatment method due to high costs. Another option to reduce corrosion is to seek out non-corrosive deicer alternatives and optimize application rates using all available technology.

Work by Glass and Buenfield (2000) estimated that replacing all rebar with epoxy coated rebar in transportation infrastructure would cost over $5 billion. Vitaliano (1992) estimated the cost to repair or rehabilitate interstate and arterial bridges in 14 snow-belt states at $2.5 billion per year. Another estimate for rehabilitation of bridge decks damaged by salt estimated it would cost $50 to $200 million per year for 10 years (TRB, 1991).

Work by Monty et al. (2014) found that salt neutralizers used to wash vehicles to reduce corrosion from chloride based deicer products can cost from $567 - $1,810 for a 350 gallon wash per truck. Using salt neutralizers was estimated to increase service life by 6 months to 1 year for vehicles, when washed five to 18 times per year (varies based on facility and vehicle replacement lifecycle). Monty et al. (2014) found the least expensive salt neutralizer to be cost-effective. Potential additional savings may appear as more data becomes available, such as reduced maintenance of wiring.

Environmental Costs and Benefits

There is very limited information in the published domain on the environmental costs of winter maintenance practices. This is in part because it is very difficult to assign dollar values to natural items such as trees, fish, or streams. To further complicate this issue, questions arise about who assigns these values and how this is done. For example, if a stream has an endangered species in it is it worth more than a stream without an endangered species? If only trees in the right-of-way are impacted are they worth less than if trees were impacted that are beyond the right-of-way?

To determine the cost or benefit of using a product, like salt brine, it is necessary to quantify what the financial impacts are once the product leaves the roadway and enters the environment. To understand the full cost of a product, it is necessary to consider the cost of the product,

product transportation costs, application costs, clean-up costs, costs to manage the product in the environment, and costs of direct impacts to the environment.

There is substantial research that shows that application of sanding materials, and deicing and anti-icing products like salt, salt brine, and magnesium chloride and calcium chloride (liquid and solid) can impact soil, plants, waterways, and animals (Fay et al., 2014). Salt use has been shown to disrupt the natural ecological balance in specific areas. Assigning a dollar value to these losses is challenging, but several methods have been used to quantify the environmental costs associated with winter maintenance practices.

Murray and Ernst (1976) used available data to determine the costs of highway deicing and snow removal practices to water supplies (lakes and rivers), trees and other vegetation, bridges, vehicles, underground power transmission lines, and on public health. Estimated minimum annual cost associated with salt use in snowbelt states was $2.9 billion. The environmental costs were further broken down as:

- Surface and groundwater supplies with the potential for irreversible public health damage to the hypertension-sensitive segment of the population = $150 million
- Vegetation = $50 million
- Highways and Bridges = $500 million
- Vehicles = $2000 million
- Underground power transmission lines = $10 million
- Salt purchase and application = $200 million

Murray and Ernst (1976) found that the damage associated with road salt use cost almost 15 times the annual national purchasing budget, and almost six times as much as the annual national budget for snow and ice removal. Applying these values to recalculate the environmental costs of road salt based on more recent salt volumes used and current snow and ice budgets, environmental costs associated with road salt use can be estimated as follows:

- 15 x (annual national budget for salt purchases) = 15 x (20.2 million tons[3] x $70 per ton[4]) = $21.2 billion (2013 dollars)
- 6 x (annual national snow and ice removal budget) = 6 x $2.3 billion[5]= $13.8 billion (2013 dollars)

Work by Bacchus (1986) utilized an expert panel to investigate financial implications of switching from salt to CMA throughout Ontario, Canada. The expert panel identified the following costs – material costs, storage and spreading costs, vehicle corrosion costs, bridge deterioration costs, parking garage deterioration costs, groundwater contamination costs, and damage to vegetation and other private property. Indirect costs associated with impacts to groundwater contamination and damage to vegetation and other private property due to salt

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[3] Salt Institute, amount of salt purchased for winter maintenance in 2007.
[4] Average cost of salt per ton delivered based on the 2012-2013 DOT salt price comparison and 5 year average completed for the National Peer Exchange, n=43 states.
[5] FHWA, Road Weather Management Program, http://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm, last modified July 2, 2013.

damage were not included. The costs that were considered were based on damage observed to fruit trees and nursery shrubs (see Figure 4).

Bacchus (1986) concluded that the relatively high costs of CMA as compared to salt were too high to offset the costs of damages to the identified parameters. For CMA to break-even, costs need to be around $343 to $481 per ton. The calculated saving from vehicle corrosion if they switched to CMA was $650 million per year, a savings of $135 per car per year. At the time this document was written, costs of CMA were still above the breakeven range of $343 - $481 per ton suggested by Bacchus (1986).

Acetates are known to cause elevated biological oxygen demand (BOD) in water bodies, and have been shown to have much higher environmental footprint than chlorides when you consider the process used to make CMA (Fitch et al., 2013). While the degree of impacts to the environment for varying products may be debatable, it is important to remember that all available deicing products have impacts and it is important to be aware of them.

Claims Against MTO

Fruit	Highway(1) Frontage km	Affected(2) Area km^2	Full (3) Value $/km²/yr (000)	% Damage(4)	$ Loss/Yr (000)
Apple	119	3.57	357	30%	382
Peach	17	0.51	513	60%	157
Mixed (apple and other or peach and other)	49	1.47	369 For want of precise proportions a simple arithmetic average is taken	45%	244
Nursery (shrubs)	3	0.09	?	45%	---
Other (grapes or plums or pears)	17	0.51	325 (av. - 349) (257) (and 370)	60%	99
TOTAL					882

NOTE: It is realized that damage occurs, in a salt world, to lawns, gardens, aluminum siding, boats, etc., but data on these items are not readily available.

Present Value of these savings, in 1985 dollars
Discounted at 5% over 20 years = $11 x 10^6
Discounted at 10% over 20 years = $ 8 x 10^6

Claims Against Municipalities

Applying ratio of 1:2.225 (see Section on Groundwater), we get:
Present Value of Savings, in 1985 Dollars
Discounted at 5% over 20 years = $24 x 10^6
Discounted at 10% over 20 years = $17 x 10^6

Figure 4: Damage to vegetation and other private property from Bacchus (1986).

Work by Vitaliano (1992) also looked at the economic feasibility of using CMA as a deicing alternative to salt. This feasibility assessment was based on an estimate of salt damage values to bridges and for bridge repairs and highway maintenance which totaled $615 per ton of salt used This estimate included accelerated vehicle corrosion costs of $113 per ton of salt used, and salt damage to trees described as lost aesthetic value in Adirondack Park at $75 per ton of salt used. In 1992 the estimated cost of CMA was $615 per ton, which seemed high compared to the estimated cost of rock salt at $50 per ton, but based on the completed economic analysis, CMA was shown to be a potentially cost-effective option.

Damage to Trees

To assign a value to the damage to trees reported as the environmental cost of salt by Vitaliano (1992), a Hotelling-Clawson travel cost model and loss of consumer surplus from degraded recreational experience were calculated based on visits to Adirondack campsites. This method estimates a low value for the social cost of damage to the environment from using road salt on campers in the Adirondacks, a limited set of individuals, but ones that may be highly sensitive to this issue. A $1.55 per capita cost was determined, and when multiplied by the 2 million non-winter visits total damage costs of $3.1 million were related to tree damage from road salt. Based on local salting practices and an average of 43,000 tons of salt estimated to be used in the area of the study, the damage per ton was calculated by dividing $3.1 million by 43,000 tons of salt, yielding an aesthetic damage cost of $73 per ton (which was rounded up to $75 per ton).

Estimated damage to trees and shrubs estimated by MTO totaled $882,000 per year (Bacchus, 1986).

Road salt can contribute sodium cations to drinking water sources. For this reason Vitaliano (1992) investigated the potential link between road salting practices, excess sodium cations in drinking water, and deaths from hypertension. A cross-sectional regression of hypertensive deaths from 106 communities in New York State was completed. A positive but statistically insignificant relationship between sodium levels in public drinking water supplies and hypertensive related deaths was found. This study reinforces the finding that road salting contributes sodium cations to drinking water supplies, such that for every one-ton increase in lane mile salting, the sodium levels in drinking water supplies increase by 6.4 percent. Based on these numbers, there is potential for road salting to increase sodium cations in drinking water beyond the 20 mg/L threshold for human health effects.

Newbery (1987) looked at the costs of transportation on British roads. Environmental costs were defined as noise and exhaust emissions pollution, and assigned a cost of 4 percent to 6 percent for trucks in urban areas (not considering other vehicles and non-urban areas). Newbery (1987) looked at road damage costs, congestion costs, the value of time (commute), capital and recurrent costs of the road network, costs of accidents, the value of life, and accident external factors.

Shi et al. (2014) assessed the relative risk of deicers used by the Idaho Transportation Department (ITD) on the environment and considered the following parameters: average aquatic toxicity (as average lethal concentration (ALC), chemical oxygen demand (COD), biological oxygen demand (BOD), risk to air quality (as average aggregate emissions), and chloride anion emission (ClE). Shi et al. (2014) utilized data from multiple disciplines and published work. The data shown in Table 9 is an overall risk assessment of deicers commonly used by ITD. The higher the *ALC*, 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 a significant reduction in the concentration of dissolved oxygen in the surrounding environment such as receiving soil and water bodies. Finally, the *EF* (air quality emission factor) and *ClE* (chloride emissions) indicate the air quality risk and the amount of chloride emission into the environment, respectively, and lower values are desirable. Among the ITD deicers examined, salt brines featured the lowest *COD*, *BOD*, *EF* and *ClE* values as well as the highest *ALC* values.

Table 9. Risk of ITD deicers and sand on the natural environment (from Shi, et al. 2014).

	ALC (g/L)	COD (mg/L)	BOD (mg/L)	Air Quality (Emission Factor (EF), mg/km)	Cl^- emissions (ClE) (Kg, per lane mile)
All Salts, including IceSlicer	3.04	6209	1085	26.4	204
All 23% Salt Brines	13.22	3725	651	6.1	130
30% $MgCl_2$ Boise	2.58	27800	4860	7.9	208

Shi et al. (2014) performed an analysis of the data, normalizing the results based on four dimensions and a composite indices of factors identified as important by ITD district and maintenance sheds winter maintenance practitioners, including economics, performance (safety and mobility), infrastructure preservation, and environmental stewardship. The analysis design is flexible and allows for varying factors to be used to run "what if" scenarios to compare for impacts for varying products and factors. Based on this analysis, AF salt, a solar salt, featured the highest composite index of 65 and thus should be considered a best practice where the road weather scenario allows its effective use. Some salt brines also featured relatively high composite indices. The inhibited $MgCl_2$ liquid deicer featured the lowest composite index of 41 among the investigated chemicals. One caveat is that in the absence of sensitivity analysis, it is unclear how the error in the raw data would propagate through the calculation of composite index. In other words, it is uncertain whether the differences in rankings are statistically significant or not.

While there has been some effort to assign a cost value to environmental impacts from deicers, another approach to consider is ranking the products based on their relative impacts compared to one another. Work completed by Fitch et al. (2013) and Pilgrim (2013) can be used to assign a relative value based on product type, so that products other than just rock salt can be considered.

Figure 5 shows the relative ranking of corrosion inhibited deicer toxicity, or the Deicer Toxicity and Impact Scale based on work by Fitch et al. (2013) and Pilgrim (2013).

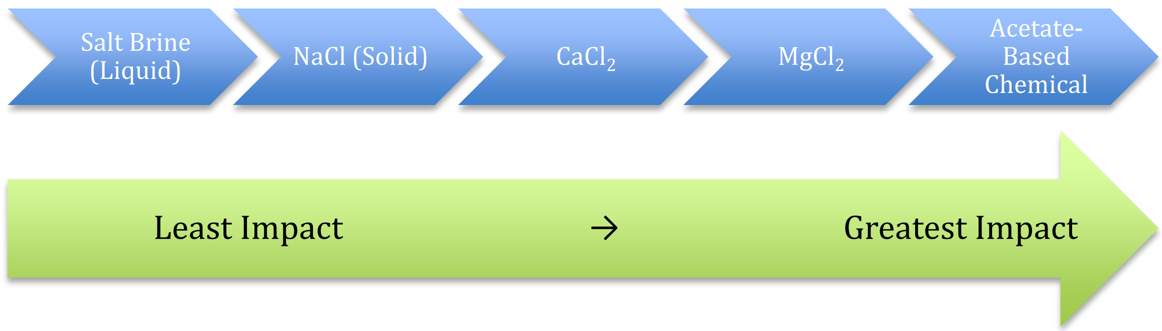

Figure 5. Relative ranking of toxicity of corrosion inhibited products used during snow and ice control operations.

Fitch et al. (2013) also identified the following DOT-controlled steps as having the greatest potential for improvement: reducing energy consumed for the salt application process and implementing practices that reduce total storm water runoff to reduce chloride loading.

Chapter 4
Benefit-cost Matrix

The summary benefit-cost matrix was developed using information gained from the literature review, surveys, and interviews. The matrix is broken down into three sub-matrices;

- Basic Activities which include plowing and the use of abrasives,
- Intermediate Activities which include the use of solid and liquid salt (NaCl) for anti-icing and deicing,
- Advanced Activities which include the use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, or blended products.

Within each sub-matrix, information is reported on the cost, benefits, effectiveness in achieving LOS, positive and negative impacts, pros and cons, respective performance, environmental impacts, and the calculated benefit-cost ratio where possible. The effectiveness in achieving LOS used the following LOS definitions:

- A - Bare pavement - wet, extensive chemical use and plowing to achieve this condition and maintain normal travel speeds.
- B – Bare wheel paths - some slush, plowing, and chemical applications being made, maintenance performed to maintain roadway being open to near-normal travel.
- C – Fair condition – Wheel paths may or may not be visible, some snowpack remaining, chemical use and plowing performed but travel ability is reduced.
- D – Poor condition – Maintenance is being performed, but snowpack across the roadway. Travel ability is diminished or reaching the point where it is not advisable.

The process of calculating the benefit-cost values reported in the matrices is presented below. Note that the benefit-cost values were calculated based on available data and may vary in the costs and benefits for winter maintenance strategy based on local conditions and pricing.

<u>Benefit-Cost Calculations</u>

When a financial value can be assigned to most of the costs and benefits of a piece of equipment, a practice, or an operation, a benefit-cost ratio can be calculated. Benefit-cost ratios greater than 1.0 are generally desired. In some cases, winter maintenance items can entail long lives such as Road Weather Information Systems (RWIS) that incorporate present and future (e.g., recurring maintenance) costs and benefits. In such cases there is a need to bring the values of all future costs and benefits accrued to a present value. A discount rate is employed to normalize costs to a present value where necessary (non 2014-2015 data). In cases where older values were used (such as values reported in past research), these were brought up to a present (2015) value by using applying the Consumer Price Index (CPI, 2015).

Benefit-cost values were calculated by dividing present value benefits by present value costs, each which had been reported or provided by survey participants on a per lane mile basis. Total costs and benefits include those accrued by the agency (e.g. material costs, labor costs, etc.) and the benefits accrued by the agency and road users (e.g. reduced material application savings, improved safety, etc.). The benefit-cost figures were developed using information from the matrices, specifically reported and estimated values that were reported on a per lane mile basis. For example, using the cases of abrasive and salt applications, the specific cost data employed in the calculation were $3,173 and $4,784, as shown in the Basic and Intermediate matrices. The respective benefits of abrasive and salt use were $696 and $11,357, respectively. Dividing these figures (in some cases updated to 2015 dollar values when necessary) produced the respective benefit-cost ratios. Using the example figures provided, the ratio for abrasives was calculated as 696/3,173 = 0.20. Similarly, the figure for salt was calculated as 11,357/4,784 = 2.37. For the remaining ratios presented, the same approach was applied.

The majority of materials and plowing produce positive benefit-cost ratios. Abrasives did not produce a benefit-cost ratio exceeding 1.0, due in large part to the clean-up costs associated with the material combined with spot applications that do not produce as significant of safety benefits compared to other materials applied on a wider scale. These ratios are based primarily on the values reported in literature and by survey respondents. Some values, specifically benefits such as the value of reduced corrosion are not readily available, as they have often not been quantified in any manner. Still, the ratios presented in the matrix provide a general indication of the cost effectiveness of each material and a baseline with which different materials can be compared to one another.

Maintenance operation	Basic Activities	
	Plowing	**Abrasives**
Value of Costs	**Annual average cost / lane mile - $1,335** ● State DOTs - $1,353 ● Counties - $882* ● Municipalities - $251*	**Average cost / ton of abrasives** - $9.32 (range - $4.00 - $16.00) **Average cost / ton of abrasive-salt mixtures** - $20.86 (range - $15.00 to $35.00) **Average clean up cost/mile** - $85.66 (range - $62.95 - $120.00)
Value of Benefits	**From research (Hanbali and (Kuemmel, 1993) direct road user benefits amounted to $6.50 for every $1.00 spent on maintenance for two-lane highways and $3.50 for every $1.00 spent on freeways. Determined for salt use but could be extrapolated to plowing.** *Ye, et. al 2012 found lane mile benefit of plowing and combined salt/abrasive use to be $6960*	**Reduced/targeted abrasive use** - produce savings of $185 to $277 per lane mile **Estimated abrasive annual cost/lane mile** - $3,173 *Ye, et. al 2012 found lane mile benefit of plowing and abrasive use to be **$696***
Effectiveness in Achieving LOS‡	**LOS of C or D** produced using this approach alone or combined with abrasives	**LOS of C or D** produced using this approach alone or combined with plowing
Positive Impacts	● Directly remove snow and ice from road surface ● Provides for mobility ● Helps reduce treatment material usage	● More effective than chemicals at low temperatures and for spot traction - hills, curves, intersections, shaded areas ● Provides for mobility ● Useful alternative in environmental sensitive locations (no salt roads)
Negative Impacts	● Degraded LOS versus targeted levels when used alone or in combination with only abrasives ● Reduced mobility, slower traffic speeds when used alone	● Degraded LOS versus targeted levels when used alone or in combination with only plowing ● Recovery from storms slower when used alone or in combination with only plowing ● More passes and applications required than if chemicals used ● Does not ensure safety and the mobility as well as alternative materials
Pros and Cons	**Pros** ● Improved safety (less crashes) ● Combination blades provide reduced noise, vibration, driver fatigue and longer life **Cons** ● Recovery from storms slower when used alone or in combination with only abrasives	**Pros** ● Ability to provide traction ● Improved safety (less crashes) ● Materials from clean up can be reused or employed elsewhere (ex. shoulders) **Cons** ● Cannot achieve deicing ● Not recommended for use on high traffic volume or high speed roads. ● Impacts on PM10 attainment ● Damage to vehicles and increased claims ● Require clean up after winter season ● Recovery from storms slower when used alone or in combination with only plowing
Respective Performance	**Blade life - miles** ● Carbide blades -809 to 3,600+ *(Iowa DOT, 2010)* ● Steel blades - 1,200 to 1,500 ● Combination blades - 300 to 4,430+ *(Iowa DOT, 2010)* ● Ceramic blades - ● Rubber blades - **Labor hours to complete replacement** ● Avg - 1 - 2 hrs ● Carbide blades - 1 - 2 hrs ● Steel blades - 1/2 - 2 hrs ● Combination blades - 4 - 5 hrs ● Ceramic blades - 1 - 2 hrs ● Rubber blades - 1 - 2 hrs	● Application rates per lane mile - 500 - 1500 lbs *(from survey response)* (Typical 400 - 1000 lbs/l-m) ● Abrasive-salt mix ratio range - 7% salt - 93% abrasive to 50% salt - 50% abrasive ● Gradations/sizes - 3/8 in. most common, range 1/4 - 1/2 in.
Environmental Impacts	● Minimal, only clear the roadway surface and at most move materials (abrasives, chemicals) to the roadside	● Abrasives can enter the water ways and clog streams and clog drains, can impact water quality and aquatic species. Can impact air quality. ● Can be left on gravel roads without clean up after season ● Straight abrasive use does not pose corrosion issues, but abrasive-salt mixes can
B/C ratio	5.32	0.22

Maintenance operation	Intermediate Activities	
	Solid salt (NaCl) for anti-icing and deicing	Salt Brine for anti-icing and deicing
Value of Costs	**Average cost/ton** - $71.04 (range - $48.63 - $120.00) **Average cost of anti-icing / lane mile** - $68.41 (range - $39.47 - $100.00)	**Average cost of brine (per gallon)** - $0.16 (range $0.05 - $0.35) **Average costs of brine production and application / lane mile** - $37.92 (range - $5.91 - $78.94) **Average cost of anti-icing / lane mile - $68.41** (range - $39.47 - $100.00) **Average brine-making equipment cost** - $89,273 (range - $7,000 - $250,000)
Value of Benefits	**1/3 reduction in material applications versus abrasives** **Estimated granular salt annual cost/lane mile** - $4,784 **Estimated granular salt annual benefit/lane mile** - $11,357	**Estimated salt brine annual cost/lane mile** - $2,964 **Estimated salt brine annual benefit/lane mile** - $11,290 **Brine use reduces granular salt use by up to 30%**
Effectiveness in Achieving LOS‡	**LOS of B** produced using this approach combined with plowing	**LOS of B** produced using this approach combined with plowing
Positive Impacts	● Increased LOS over Basic practices ● Improved public safety and mobility ● Prevent snow and ice from bonding to pavement ● Improved melting capacity	● Increased LOS over Basic practices ● 28% - 83% crash reduction versus untreated roads ● Prevents snow and ice from bonding to pavement (anti-icing) ● Improved melting capacity ● 62% labor cost reduction (anti-icing) ● Reduced granular scatter (prewetting)
Negative Impacts	● Corrosion ● Impacts on roadside and waterways ● Potential animal attractant ● Pavement deterioration	● Corrosion ● Impacts on roadside and waterways ● Potential animal attractant ● Difficulty in handling and application ● Pavement deterioration
Pros and Cons	**Pros** ● Faster recovery time ● Improved safety versus Basic practices ● Melting capacity ● Low cost of material ● Ease of application **Cons** ● Environmental impacts ● Corrosion ● Public feedback	**Pros** ● Low cost of material ● Improved safety and mobility ● Reduced pavement marking wear **Cons** ● Corrosion ● Environmental impacts ● Special storage and handling may be needed if storing over summer or if longer storage is required
Respective Performance	● Application rates -25 - 600 pounds/lane mile *(from survey response)* (Typical 100 - 800 lbs/l-m)	● Application rates (on road) -11 - 100 gallons/lane mile (from survey response) (Typical 10 - 40 gal/l-m) ● Application rates (prewet solids) - 5 - 17.8 gals/ton (or 10% to 23%) (from survey response) (Typical 8 - 20 gal/l-m) ● Up to 10% - 20% cost savings in total winter maintenance budget (anti-icing) ● 400% increase in chemical cost /lane mile (anti-icing) ● Cost savings of $1,266 to $30,152 / typical maintenance snowplow truck route / year (anti-icing)
Environmental Impacts	● Entry into waterways ● Impact to roadside soil, vegetation ● Corrosion to vehicles and infrastructure	● Entry into waterways ● Impact to roadside soil, vegetation ● Corrosion to vehicles and infrastructure
B/C ratio	2.37	3.8

‡ Level of service (LOS) defined as:
A – Bare pavement: wet, extensive chemical use and plowing to achieve this condition and maintain normal travel speeds.
B – Bare wheel paths: some slush, plowing and chemical applications being made, maintenance performed to maintain roadway being open to near normal travel.
C – Fair condition: wheel paths may or may not be visible, some snowpack remaining, chemical use and plowing performed but travel ability is reduced.
D – Poor condition: maintenance is being performed, but snowpack across the roadway. Travel ability is diminished or reaching the point where it is not advisable.

Maintenance operation	Advanced Activities		
	Corrosion inhibitors	Inhibited salt brine	Magnesium Chloride
Value of Costs	**Average cost per gallon** - $1.18 (range $0.78 to $1.50) **Cost per ton** - $650.00 **Cost per lane mile** - $695.55 to $1652.93 **Liquid storage (tank, pump, hose and nozzle) setup for stockpile prewetting** - $3,000.00	**Average cost per gallon** - $0.31 (range - $0.12 - $0.50)	**Inhibited solid cost / ton** - $150.00 **Inhibited liquid cost / gallon** - $1.00 - $1.50 **Uninhibited liquid cost / gallon** - $1.20
Value of Benefits	**See specific materials below**	**50% and 70% less corrosive than salt brine**	**Estimated Magnesium Chloride annual cost/lane mile** - $3,408 **Estimated Magnesium Chloride annual benefit/lane mile** - $12,165 **Corrosion inhibited Magnesium Chloride at least 75% less corrosive than granular salt**
Effectiveness in Achieving LOS‡	**Dependent on the specific treatment material being used**	**LOS of B** produced using this approach combined with plowing	**Comparable LOS to salt and salt brine at 1/2 the application rate**
Positive Impacts	● Better cold temperature performance ● Improved safety and mobility ● Prevents snow and ice from bonding to pavement ● Public vehicle protection ● Increased service life of agency vehicles	● Reduced salt and abrasive use ● Better cold temperature performance ● Improved safety ● Cost savings	● Prevents snow and ice from bonding to pavement (anti-icing) ● Reduced salt and abrasive use ● Better cold temperature performance ● Improved safety and mobility ● Reduced amount of product used ● Cost savings ● Reduced corrosion (inhibited materials) ● Reduced number of application vehicles needed
Negative Impacts	● High cost of products	● Impacts on roadside and waterways ● Material cost ● Difficulty in handling and application ● Pavement deterioration	● Pavement deterioration ● Increased corrosion (uninhibited materials) ● Environmental impacts ● Difficulty in handling and application ● Material cost
Pros and Cons	**Pros** ● Improved LOS at lower temperatures ● Reduced corrosion to vehicles and infrastructure ● More rapid melt ● Improved roadway condition in less time **Cons** ● Cost of materials ● Politics of using inhibitors	**Pros** ● Improved LOS at lower temperatures ● Better performance **Cons** ● Cost of materials ● Requires more frequent applications (2x more than MgCl) ● Special storage and handling may be needed if storing over summer or if longer storage is required	**Pros** ● Persists on the road surface, aiding in longer black ice prevention ● Reduced applications needed ● Reduced scatter with solid materials (prewet) ● Achieve LOS faster than with other products **Cons** ● Can cause slick conditions when anti-icing if over applied in certain conditions ● Cost of materials ● Special storage and handling may be needed if storing over summer or if longer storage is required
Respective Performance	● Inhibited salt (NaCl) brine 50% and 70% less corrosive than salt brine ● Corrosion inhibited Magnesium Chloride at least 75% less corrosive than granular salt (NaCl)	● Average application rate gals/lane mile - 36 (or 20 - 100 gals/lane mile)	Application rates: ● Inhibited solid - 180 - 220 lbs/lane mile ● Uninhibited solid - 100 - 300 lbs/lane mile, up to 500 lbs/l-m ● Inhibited liquid - 15 - 150 gals/lane mile or 6-10 gals/ton ● Uninhibited liquid - 5 -15 gals/lane mile (typical 10 - 40 gal/l-m) ● Used when temperatures were below 22°F ● Blended with salt brine for temperatures below 20°F ● Mixed with stockpiles to prevent freezing
Environmental Impacts	● Potential impact to waterways ● Potential impact to roadside	● Less public complaints about vehicle corrosion after switching from corrosion inhibited magnesium chloride ● Entry into waterways ● Impact to roadside	● More public complaints with vehicle corrosion versus inhibited salt brine ● Entry into waterways ● Impact to roadside ● Impact to bridge infrastructure ● Leaching/run-off from stockpiles ● Products are not animal attractants
B/C ratio	Not able to be calculated at this time	3.8	3.57

Maintenance operation	Advanced Activities	
	Calcium Chloride	Blended products
Value of Costs	**Inhibited liquid cost / gallon** - $1.00 - $2.80 **Uninhibited liquid cost / gallon** - $0.40 - $1.09 **Uninhibited solid cost / ton** - $340.00-$450.00 **Inhibited solid cost / ton** - $963.50	**Inhibited liquid cost / gallon** - $0.50 - $2.80
Value of Benefits	**Estimated Calcium Chloride annual cost/lane mile** - $3,048 **Estimated Calcium Chloride annual benefit/lane mile** - $11,672	**Estimated ag by-product annual cost/lane mile** - $3,241 - $3,328 **Estimated ag by-product annual benefit/lane mile** - $12,675 - $12,921
Effectiveness in Achieving LOS‡	**Comparable LOS to salt and salt brine at 1/2 the application rate**	**Comparable LOS to salt and salt brine at 1/2 the application rate**
Positive Impacts	● Prevent snow and ice from bonding to pavement (anti-icing) ● Better cold temperature performance ● Improved safety and mobility ● Cost savings ● Reduced amount of product used ● Reduced salt and abrasive use ● Reduced number of application vehicles needed	● Better cold temperature performance ● Reduced need for salt and abrasives ● Improved safety and mobility ● Cost savings ● Reduced amount of product used ● Longer lasting applications
Negative Impacts	● Pavement deterioration ● Increased corrosion ● Environmental impacts ● Material cost ● Difficulty in handling and application	● Environmental impacts ● Material cost ● Pavement deterioration ● Increased corrosion ● Difficulty in handling and application
Pros and Cons	**Pros** ● Reduced product used ● Better performance at low temperatures ● Public feedback ● Liquids easier to handle than solids ● Mixes well with salt brine **Cons** ● Cost of materials ● Special storage and handling may be needed if storing over summer or if longer storage is required	**Pros** ● Reduced product used ● Longer lasting applications ● More effective than salt and abrasives **Cons** ● Cost of materials ● A high level of accuracy required for mixing correct ratio ● Special storage and handling may be needed if storing over summer or if longer storage is required
Respective Performance	Application rates ● Inhibited liquid - 8-30 gals/lane mile to pretreat, 1.5-5 gals/ton for "hot loads" ● Inhibited solid - 300-500 lbs/lane mil ● Uninhibited liquid - 6-8 gals/ton to pre-wet, 13 gals/lane mile ● Uninhibited solid - spot treatment ● Mixed with salt for temperatures below 25°F ● Mixed with salt brine and beet juice for temperatures below 25°F ● Used when temperatures were below 10°F ● Mixed with stockpiles to prevent freezing	Application rates ● Inhibited liquid - 9-150 gals/lane mile, 2.5-35 gals/ton for pre-wetting ● High ice melting capacity ● Low effective temperature ● Mixed with salt brine
Environmental Impacts	● Entry into waterways ● Impact to roadside ● Products are not animal attractants	● Entry into waterways ● Impact to roadside ● Products are not animal attractants ● Leaching/run-off from stockpiles ● Complaints from mechanics about aluminum corrosion
B/C ratio	3.83	3.81 - 3.99

Chapter 5
Conclusions and Recommendations

Various costs and benefits are incurred while performing winter maintenance operations. However, a summary of these costs and benefits for different maintenance scenarios has not been compiled to date. The information contained in this report provides all levels of decision-makers with information on which to base sound decisions. In doing so, agencies could better maximize the LOS relative to the maintenance strategy's cost and have a mechanism to explain the available options, their costs, benefits, and consequences to various stakeholders, including DOT personnel, legislators, and the general public.

In order to facilitate the summary of cost and benefit information, it was first necessary to identify past work that identified the quantified and non-quantified costs and benefits of the three different winter maintenance strategies of interest to this project. The first strategy included was basic and consisted of actions performed to maintain traveler mobility and safety, including plowing and the use of abrasives (sanding). A second, intermediate strategy reflected an improvement over the basic approach. It consisted of plowing and the use of some abrasives in spot locations, but also relied on salt in solid or liquid forms for anti-icing and deicing. The third strategy uses magnesium chloride, calcium chloride, and blended products such as corrosion-inhibiting liquids and/ or treated or chemically enhanced solid chemicals in anti-icing and deicing to address the corrosion risks associated with untreated materials. This strategy allows for the selection of specific chemicals that will work best in a specific climatic region or temperature range, avoiding the overuse of salt or salt brine at colder temperatures as may be the case in the second strategy. Collectively, these three approaches employ various equipment and materials. Literature related to these various components was identified and summarized during the course of a literature review, the results of which have been presented in this document.

Some components of the various strategies of interest have better cost and benefit information available than others. This is particularly true of sanding/abrasives and use of road salt (sodium chloride). This may stem from their historical use over time, because they have been the most common treatments used by maintenance agencies. Historically, salting approaches have been recorded to provide benefits that generally exceed the costs associated with them. For example, they have been shown to reduce crashes and improve or maintain mobility (travel time and speeds).

The costs and benefits of snow plows, which represent the other common approach employed historically by agencies, have not been as well defined. It is possible that agencies have difficulty separating the contribution of plowing versus material usage. As more automated recording technologies are employed by agencies in winter maintenance, comparing the contributions of various activities occurring simultaneously or individually should become more feasible. For example, sensors recording information such as plow status (up versus down) and material applications on the same vehicle can address this shortcoming.

Other, more recently developed and employed approaches and materials (e.g. prewetting and materials such as magnesium chloride and calcium chloride), have more limited cost and benefit information published. While the cost of the equipment and materials are available from agency records (although it did not appear in literature), benefit information is generally lacking outside of generalized terms. Such information gaps were determined through an agency survey conducted for this project. The intent of such a survey is to develop a reasonable value range for costs and benefits that do not have quantified values available in literature. The survey would also seek to obtain any quantified information that an agency may have that has not appeared in literature.

As one would expect, there are a number of different environmental impacts associated with different components of each maintenance strategy. This is particularly true of materials, each of which had positive and negative impacts on the environment. In some cases, equipment or practices can be employed to reduce this impact. For example, the use of prewetting can facilitate adhesion and enhance melting action of granular chemicals, such as salt and magnesium chlorides. Similarly, wetting abrasives with hot water can enhance adhesion to ice and snow covered pavements, reducing bounce and scatter into the roadside environment. Research has shown prewetting of sand to provide up to 25 percent material savings, and prewetting rock salt to provide 20 to 33 percent material savings. Additionally, one researcher found $CaCl_2$ to be 9.5 to 71.4 percent more effective as a prewetting agent and outperformed $MgCl_2$.

The results of the survey and interviews have been incorporated into the benefit-cost matrices. In general, the survey and interviews identified Basic and Intermediate Activities as the most commonly used winter maintenance strategies. This includes plowing, use of abrasives, use of solid and liquid salt (sodium chloride) for deicing and anti-icing. Less commonly reported was the use of the Advanced Activities including the use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, or blended products. This may be indicative of these winter maintenance strategies being less commonly employed, a result of who responded to the survey and interviews, or the result of survey fatigue. Gathering information on costs associated with the various winter maintenance strategies from the individuals surveyed and interviewed was a challenge. This highlights the need for easy to use cost-tracking tools for use by winter maintenance professionals.

The information gathered in the literature review, surveys, and interviews was used to populate the developed benefit-cost matrix. The matrix is presented as three sub-matrices Basic Activities, Intermediate Activities, and Advanced Activities. Within each sub-matrix information is reported on the cost, benefits, effectiveness in achieving LOS, positive and negative impacts, pros and cons, respective performance, environmental impacts, and the calculated benefit-cost ratio where possible.

Table 10 Summary of winter maintenance strategies and the calculated benefit-cost ratios.

Activities	Winter Maintenance Strategy	Benefit/Cost Ratio
Basic	Plowing	5.3
	Abrasives	0.2
Intermediate	Rock salt (solid NaCl)	2.4
	Salt brine (liquid NaCl)	3.8
Advanced	Corrosion inhibitors	8.0-13.2*
	Inhibited salt brine	3.8
	Magnesium Chloride ($MgCl_2$)	3.6
	Calcium Chloride ($CaCl_2$)	3.8
	Blended products	3.8 - 4.0

*The B/C ratios represent the use of proactive maintenance and corrosion prevention. Calculated by Shi et al., 2013a; Honarvarnazari et al., 2015.

The benefit-cost ratio was calculated based on cost data per lane mile. Benefit-cost ratios were able to be calculated for all winter maintenance strategies with the exception of the use of corrosion inhibitors, where not enough information was available to successfully calculate a benefit-cost ratio. Table 10 shows the calculated benefit-cost ratio for the various winter maintenance strategies.

Knowledge Gaps and Recommendations

Based on the literature review presented in this document, survey and follow-up interviews specific knowledge gaps associated with the components for each maintenance strategy of interest could be identified. In reviewing the information presented in this report, it is clear that some components of the different maintenance strategies have better defined information than others. This is particularly true of sanding and salt use. It stands to reason that these aspects have more detailed information available, because they represent the approaches that have been in use for decades at agencies. Newer materials and equipment often lack detailed information on costs and benefits. In some cases, cost information can vary significantly due to the quantities being purchased by an agency, the location of the agency versus the procurement source, and so forth. As a result, such information does not necessarily get discussed in existing literature. This highlights the need for detailed cost data in general, but specifically a cost analysis of corrosion inhibitors and agriculturally derived products. This could be aided by the development of an easy to use cost tracking tool.

References

Agent, Kenneth and Jerry Pigman. Time for Recessed: Study Explores Ways to Plow Snow. Roads & Bridges, 2014. pp. 46-49.

Allenman, James, Barry Partridge and Lee Yeung. Innovative Environmental Management of Winter Salt Runoff Problems at INDOT Yards. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, 2004, Report FHWA/IN/JTRP-2001/27, 156 p.

Bacchus, A. Financial Implications of salt vs. CMA as a deicing agent: costs and benefits estimates by an MTO expert group. Ministry of Transportation of Ontario, Downsview, Ontario, 1986, Report ME-87-20, 37 p.

Barbaccia, Tina. Salt Slurry Spreader: Smaller and Wetter is Better. Public Roads, June 2009, p.34.

Baroga, Enrico. Washington State Department of Transportation 2002-03 Salt Pilot Project. Proceedings: 6th International Symposium on Snow Removal and Ice Control Technology, Spokane, Washington, June 2004.

Battelle Memorial Institute. Economic Effects of Metallic Corrosion in the United States. National Bureau of Standards Special Publication 511-1, National Bureau of Standards, Gaithersburg, Maryland, 1978.

Blackburn, Robert, Karin Bauer, Duane Amsler, S. Edward Boselly and A. Dean McElroy. Snow and Ice Control: Guidelines for Materials and Methods. National Research Council, Transportation Research Board, Washington, D.C., 2004, NCHRP Report 526, 50 p.

Blechl, Robert. Plow Makes Test Run In Franconia," Littleton (New Hampshire) Record, January 24, 2012. http://littletonrecord.com/main.asp?SectionID=22&SubSectionID=121&ArticleID=18885

Bodnarchuck, A.J. and D. Gooding. 1994 Field trials of prewetting salt and sand with magnesium chloride brines – efficiency and effects. Highway Environmental Branch, BC Ministry of Transportation Highways.

Booz Allen Hamilton Inc. Evaluation of Minnesota Department of Transportation's Intelligent Vehicle Initiative Snowplow Demonstration Project on Trunk Highway 19 Winter 1998-1999. Minnesota Department of Transportation, St. Paul, 1999, 55 p. http://www.dot.state.mn.us/guidestar/1996_2000/snowplow_ivi_hwy_101/iviphase1report.pdf

Boselly, S. Edward. Benefit-cost Study of RWIS and Anti-icing Technologies. National Research Council, Transportation Research Board, Washington, D.C., 2001, NCHRP Report 20-7(117), 37 p.

Braun Intertec Corporation. Development of Standardized Test Procedures for Carbide Insert Snowplow Blade Wear. Clear Roads Pooled Fund and Minnesota Department of Transportation, St. Paul, 2010, Project 0092-08-31/CR07-11, 63 p. http://www.clearroads.org/research-projectsdownloads/Carbide%20Insert%20Blade%20Final%20Report.pdf

Breen, Bryon. Anti Icing Success Fuels Expansion of the Program in Idaho. Idaho Transportation Department, Boise, 2001, 7 p. http://www2.state.id.us/ida-road/WinterMaint-AntiIcing.htm.

Bryson Gretchen and Allen Barker. Sodium Accumulation in Soils and Plants Along Massachusetts Roadsides. Communications in Soil Science & Plant Analysis, 2002, Vol. 33, No. 1–2, pp. 67–78.

Buckler, Denny and Gregory Granato. Assessing Biological Effects from Highway Runoff Constituents. U.S. Department of the Interior and U.S. Geological Survey, Washington D.C., 1999, Open-File Report 99-240, 53 p. http://webdmamrl.er.usgs.gov/g1/FHWA/products/ofr99-240.pdf

Burtwell, Marilyn. Deicing Trials on U.K. Roads: Performance of Prewetted Salt Spreading and Dry Salt Spreading. Sixth International Symposium on Snow Removal and Ice Control Technology. Spokane, Washington, June 2004.

California Department of Transportation. Snow & Ice Control Operations. California Department of Transportation, Sacramento, 1999, 20 p. http://www.dot.ca.gov/hq/roadinfo/snwicecontrol.pdf

Chang, Nien-Yin, Walter Pearson, James Chang, A.I. Gross, Mark Meyer, Marva Jolly, Barbara Yang and Hellen Samour. Environmentally Sensitive Sanding and Deicing Practices. Colorado Department of Transportation, Denver, 1994, Report No. CDOT-CTI-95-5, 208 p.

Chang, Nien-Yin, Brian Brady, Faith Oncul, Troy Gottschalk, Erin Gleason, Dan Oravez, Kevin Lee and Murugan Palani. Costs of Sanding. Colorado Department of Transportation, Denver, 2002, Report No. CDOT-DTD-R-2002-5, 175 p.

Colson, Stephen. Evaluation of the Monroe Slurry Maker. Maine Department of Transportation, Augusta, 2009, Technical Brief 09-5, 4 p.

CPI Inflation Calculator. Bureau of Labor Statistics. http://www.bls.gov/data/inflation_calculator.htm. Accessed on June 13, 2015.

Craver, Vinka, G. Michael Fitch and Andres Smith. Recycling of Salt-Contaminated Storm Water Runoff for Brine Production at Virginia Department of Transportation Road-Salt Storage Facilities. Transportation Research Record: Journal of the Transportation Research Board, No. 2055, 2008, pp. 99 – 105.

Cripps, M.P., L. Leeds. Winter Control – Pre-wetting of Salt. Town of Milton, Ontario, Canada, 2013, Report ENG-026-13, 5 p. http://www.milton.ca/MeetingDocuments/Council/agendas2013/rpts2013/ENG-026-13%20Winter%20Control%20Pre-wetting%20proposal%20FINAL.pdf

CTC & Associates, Limitation of the Use of Abrasives in Winter Maintenance Operations. Wisconsin Department of Transportation. 2008

CTC & Associates. Snow and Ice Control at Extreme Temperatures. Wisconsin Department of Transportation, Bureau of Highway Operations, Madison, 2011, 8 p.

Dahlen, Jon and Torgeir Vaa. Winter Friction Project in Norway. Transportation Research Record No. 1741, 2001, pp. 34-41.

Elvik, Rune, Truls Vaa, Alena Erke and Michael Sorensen, eds. The Handbook of Road Safety Measures. Emerald Group Publishing, Bingley, United Kingdom, 2009, 255 p.

Environment Canada. Priority Substances List Assessment Report: Road Salts. Environment Canada, Gatineau, Quebec, 2001, 180 p. http://www.hc-sc.gc.ca/ewh-semt/alt_formats/hecs-sesc/pdf/pubs/contaminants/psl2-lsp2/road_salt_sels_voirie/road_salt_sels_voirie-eng.pdf

Environment Canada. Winter Road Maintenance Activities and the Use of Road Salts in Canada: A Compendium of Costs and Benefits Indicators. Environment Canada, Gatineau, Quebec, 2006.

Epps, Jon and Maria Ardila-Coulson. Summary of SHRP Research and Economic Benefits of Snow and Ice Control. Nevada Transportation Technology Transfer Center, Reno, Report No. FHWA-SA-98-0151997, 1997, 28 p.

EVS. Snow Plow Cutting Edges for Improved Plowing Performance, Reduced Blade Wear, and Reduced Surface Impacts. Minnesota Department of Transportation, St. Paul, 2011, 12 p. http://www.lrrb.org/media/reports/TRS1101.pdf

Fay, Laura, Kevin Volkening, Chase Gallaway and Xianming Shi. Performance and Impacts of Current Deicing and Anti-icing Products: User Perspective versus Experimental Data. Compendium of Papers, 87th Annual Transportation Research Board Meeting, Washington D.C., 2008, 23 p.

Fay, Laura and Xianming Shi. Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge. Water, Air & Soil Pollution, Vol. 223, 2012, pp. 2751 - 2770. http://www.springerlink.com/content/n1451658mky72964/.

Fay, Laura, Xianming Shi, Marie Venner and Eric Strecker. Toxicological Effects of Chloride-Based Deicers in the Natural Environment. American Association of State Highway and Transportation Officials, Washington, D.C., NCHRP Project 25-25, Task 86. 2014, 104 p. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25%2886%29_FR.pdf

Fay, Laura, Xianming Shi and Jiang Huang. NCHRP Synthesis 449, Strategies to Mitigate the Impacts of Chloride Roadway Deicers on the Natural Environment. National Research Council, Transportation Research Board, Washington, D.C., 2013, Washington, D.C., http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_449.pdf

Federal Highway Administration. How Do Weather Events Impact Roads. United States Department of Transportation, Washington, D.C., 2014. http://ops.fhwa.dot.gov/Weather/q1_roadimpact.htm.

Fischel, Marion. Evaluation of Selected Deicers Based on a Review of the Literature. Colorado Department of Transportation, Denver, Publication No. CDOT-DTD-R-2001-15, 2001, 169 p.

Fitch, G. Michael, James Smith and Andres Clarens. Environmental Life-Cycle Assessment of Winter Maintenance Treatments for Roadways. Journal of Transportation Engineering, Vol. 139, No. 2, 2013, pp. 138-146.

Fortin Consulting, Inc. The Real Cost of Salt Use for Winter Maintenance in the Twin Cities Metropolitan Area. Minnesota Pollution Control Agency. 2014.

Fu, Liping, Max Perchanok, Luis Miranda-Moreno and Quador Shah. Effects of Winter Weather and Maintenance Treatments on Highway Safety. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006a.

Fu, Liping, Rudolph Sooklall and Max Perchanok. Effectiveness of Alternative Chemicals for Snow Removal on Highways. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1948, 2006b, pp. 125-134.

Fu, Liping and Taimur Usman. Safety Impacts of Using Deicing Salt. University of Waterloo, 2014, 54 p.

Gertler, Alan, Hampden Kuhns, Mahmoud Abu-Allaban, Christopher Damm, John Gillies, Vicken Etyemezian, Russ Clayton and David Proffitt. A Case Study of the Impact of Winter Road Sand/Salt and Street Sweeping on Road Dust Re-entrainment. Atmospheric Environment, Vol. 40, No. 31, 2006, pp. 5976-5985.

Glass, G.K. and N.R. Buenfield. Chloride-induced Corrosion of Steel in Concrete. Progress in Structural Engineering Materials, Vol. 2, No. 4, 2000, pp. 448-458.

Goodwin, Lynette. Best Practices for Road Weather Management. Road Weather Management Program, Office of Transportation Operations, Federal Highway Administration, United States Department of Transportation, Washington, D.C., Report No. FHWA-OP-03-081, 2003, 131 p.

Hanbali, Rashad. Economic Impact of Winter Road Maintenance on Road Users. Transportation Research Record: Journal of the Transportation Research Board, No. 1442, 1994, pp. 151–161.

Hawkins R. Proceedings: Street Salting, Urban Water Quality Workshop. State University College of Forestry, Syracuse University, Syracuse, NY, 1971.

Honarvarnazari, Mehdi, Bergner, Dave, Shi, Xianming. Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control. Clear Roads and Minnesota Department of Transportation. 2015.

IHS Global Insight, The economic costs of disruption from a snowstorm, American Highway Users Alliance, 2013.

Idaho Transportation Department. States Approach Winter Roads with Variety of Techniques. Idaho Transportation Department, Boise, 2010. http://itd.idaho.gov/transporter/2010/121010_Trans/121010_AASHTOwinter.html

Illinois Technology Transfer Center. Anti-icing Technology. Illinois Department of Transportation, Springfield, 1998. https://www.dot.il.gov/blr/FTB-3%20Anti-Icing%20Technology.pdf

Iowa Department of Transportation. Iowa's Winter Maintenance Technologies Research. Research News, Iowa Department of Transportation, Ames, 2009, 12 p. http://www.iowadot.gov/research/pdf/Research%20News%20August%202009.pdf

Iowa Department of Transportation. ILLOWA Peer Exchange. Iowa Department of Transportation, Ames, 2010. http://www.iowadot.gov/maintenance/pdf/1WelcomePlows.pdf

Iowa Department of Transportation. TowPlows. Iowa Department of Transportation, Ames, 2014. http://www.iowadot.gov/maintenance/TowPlows.html

Iowa Department of Transportation. Materials. 2014b. http://www.iowadot.gov/maintenance/materials.html

Johnson, Joshua. Corrosion Costs of Motor Vehicles. DNV GL, Houston, Texas, 2002, 27 p. http://www.dnvusa.com/Binaries/motorvehicles_tcm153-378419.pdf

Jones, P.H., and B.A. Jeffrey. Environmental Impact of Road De-icing. In D'Itri, F.H. (Eds), Chemical Deicers and the Environment, Lewis Publishing, Boca Raton, Florida, 1992, pp. 1-107.

Kahl, Stephen. Agricultural By-Products for Anti-Icing and Deicing Use in Michigan. Michigan Department of Transportation Research, Lansing, 2002, Report R 1418, 63 p.

Kansas Department of Transportation. Kansas DOT Managing Snow and Ice. Kansas Department of Transportation, Topeka, 2013. https://www.ksdot.org/PDF_Files/SnowandIce Efforts.pdf

Kaushall Sujay, Peter Groffman, Gene Likens, Kenneth Belt, William Stack, Victoria Kelly, Lawrence Band and Gary Fisher. Increased Salinization of Freshwater in the Northeastern United States. Proceedings of the National Academy of Sciences, Vol. 102, No. 38, 2005, pp. 13517–13520.

Kelting, Daniel and Corey Laxon. Review of Effects and Costs of Road Deicing with Recommendations for Winter Road Management in the Adirondack Park. Adirondack Watershed Institute, Pauls Smith, New York, 2010, Report AW1210-01, 82 p. http://www.adkaction.org/files/public/Full_Study_Salt.pdf

Ketcham, Stephen, L. David Minsk, Robert Blackburn and Edward Fleege. Manual of Practice for an Effective Anti-icing Program. Federal Highway Administration, United States Department of Transportation, Washington, D.C., 1996, Report FHWA-DRD-95-202, 70 p.

Koch, Gerhardus, Michael Brongers, Neal Thompson, Y. Paul Virmani and J. Payer. Corrosion Cost and Preventative Strategies in the United States. Federal Highway Administration, United States Department of Transportation, Washington, D.C., 2002, Report FHWA-RD-01-156, 12p. https://www.nace.org/uploadedFiles/Publications/ccsupp.pdf

Kovac, Peter and Kornelia Kocsis. Source Book for Alternative Technologies for Freshwater Augmentation in East and Central Europe: Section 3.15 Recycling of Wastewater in the Transportation Industry. United Nations Environmental Programme, New York, 1998. http://www.unep.or.jp/ietc/publications/techpublications/techpub-8b/recycling.asp

Kuemmel, David and Rashad Hanbali. Accident Analysis of Ice Control Operations. Final Report, The Salt Institute, Alexandria, Virginia, 1992, 26 p.

Kuemmel, David and Quazi Bari. Benefit-Cost Comparison of Salt-Only Versus Salt-Abrasive Mixtures Used in Winter Highway Maintenance in the United States. Fourth International Symposium, Snow Removal and Ice Control Technology, Reno, Nevada, 1996.

Lemon, Harold. 1974-1975 Prewetted Salt Report. Michigan Department of Transportation, Lansing, 1975.

Leppänen, Anne. Final Results of Road Traffic in Winter Project: Socioeconomic Effects of Winter Maintenance and Studded Tires. Transportation Research Record: Journal of the Transportation Research Board, No. 1533, 1996, pp. 27-31.

Levelton Consultants Ltd. Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts. National Cooperative Highway Research Program, National Research Council, Washington, D.C., 2007, Report 577, 50 p.

Lewis, William. Studies of Environmental Effects of Magnesium Chloride Deicer in Colorado. Colorado Department of Transportation, Denver, 1999, Report No. CDOT-DTD-R-99-10, 113 p.

Local Technical Assistance Center. New Hampshire Best Management Practices: Prewetting. Local Technical Assistance Program, University of New Hampshire, Durham, Undated, 1p.

Luker, Craig, Barry Rokosh, and Timothy Leggett. Laboratory Melting Performance Comparison, Rock Salt with and without Pre-wetting. Sixth International Symposium on Snow Removal and Ice Control Technology. Spokane, Washington, 2004.

Maine Department of Transportation. Field Testing of Alternative Carbide Edge Snow Plow Blades. Maine Department of Transportation, Augusta, 2004, Technical Memorandum 03-11, 10 p. www.maine.gov/mdot/tr/documents/pdf/report0311t.pdf

Maine Department of Transportation. Evaluation of Alternative Snow Plow Cutting Edges. Maine Department of Transportation, Augusta, 2009, Technical Brief (09-3), 8 p. http://www.maine.gov/mdot/tr/reports/wintermaintenance.htm

Mason Charles, Stephen Norton, Ivan Fernandez and Lynn Katz. Deconstruction of the Chemical Effects of Road Salt on Stream Water Chemistry. Journal of Environmental Quality, Vol. 28, No. 1, 1999, pp. 82–91.

Massachusetts Department of Transportation. MassDOT Winter Prep: Cost Savings, New Equipment. Massachusetts Department of Transportation, Boston, 2011, Road to Reform Newsletter. http://www.massdot.state.ma.us/InformationCenter/WeeklyNewsletters/RoadtoReformNewsletter11182011.aspx

Massachusetts Department of Transportation. New "Mega Plows" Part of MassDOT's Snow Fighting Fleet. Massachusetts Department of Transportation, Boston, 2012. http://www.massdot.state.ma.us/desktopmodules/advancedarticles/articledetail.aspx?itemid=236&moduleid=1030&tabid=367&portalid=0

McCormick Rankin Corporation and Ecoplans Limited. Case Study #6: Winter Maintenance Innovations Reduce Accidents and Costs – City of Kamloops. Insurance Corporation of British Columbia and Environment Canada, British Columbia, 2004, 6 p.

Michigan Department of Transportation. Chapter 4 Costs and Specific Impacts on Michigan of Selected Deicing Materials. Undated.

Michigan Department of Transportation. Tow Plow. Michigan Department of Transportation, Lansing, 2014. http://www.michigan.gov/mdot/0,4616,7-151-9621_11008-291327--,00.html

Miedema, Hjalmar and J. Wright. A Decision Support System for Real-Time Snow and Ice Control. Joint Highway Research Project, Indiana Department of Transportation, Indianapolis, 1995, Report FHWA/IN/JHRP-95/04, 106 pp.

Miklovic Stefanie and Susan Galatowitsch. Effect of NaCl and Typha Angustifolia L. on Marsh Community Establishment: A Greenhouse Study. Wetlands, Vol. 24, No. 2, 2005, pp. 420–429.

Minnesota Department of Transportation. Anti-icing in Winter Maintenance Operations: Examination of Research and Survey of State Practice. Minnesota Department of Transportation, St. Paul, 2009, 519 p. ftp://ftp2.dot.state.mn.us/pub/outbound/researchservices/TRS0902_5.29.09.pdf

Mokwa, Robert and Andrew Foster. Testing and Evaluation of Recovered Traction Sanding Material. Montana Department of Transportation, Helena, 2013, Report FHWA-MT/13-003/8213, 72 p.

Monty, Chelsea, Alvaro Rodriguez, Christopher Miller and William Schneider. Evaluation of the Effectiveness of Salt Neutralizers for Washing Snow and Ice Equipment. Ohio Department of Transportation, Columbus, 2014, Report FHWA/OH-2013/18, 153 p.

Murray, Donald and Ulrich Ernst. An Economic Analysis of the Environmental Impact of Highway Deicing. Environmental Protection Agency, Washington, D.C., 1976, Report EPA-600/2-76-105, 138 p.

Nebraska Department of Roads. Brainstorming, Research Conference (Presentation). Nebraska Department of Roads, Lincoln, 2012. http://www.transportation.nebraska.gov/mat-n-tests/Presentations/2012_Research_Conf/Brainstorming_FINAL.pdf

Newbery, David. Road User Charges in Britain. The Economic Journal, Vol. 98, 1987, pp. 161-176.

Newton, C.J. and J.M. Sykes. The Effect of Salt Additions on the Alkalinity of Ca(OH)2 Solutions. Cement and Concrete Research, Vol. 17, No. 5, 1987, pp. 765-776.

New Hampshire Department of Transportation. Snow Removal in New Hampshire, Q & A. New Hampshire Department of Transportation, Concord, Undated. http://www.nh.gov/dot/org/operations/highwaymaintenance/documents/WinterSnowRemoval_inNH_doublewide.pdf

New Hampshire. Pre-wetting. Best Management Practices, New Hampshire Department of Transportation, Concord, 2014, 1p. http://des.nh.gov/organization/divisions/water/wmb/was/salt-reduction-initiative/documents/bmp-pre-wet.pdf

Nixon, Wilfrid. The Use of Abrasives in Winter Maintenance. Iowa Highway Research Board, Ames, 2001, IIHR Report 416, 28 p.

Nixon, Wilfrid and Yingchang Wei. Optimal Usage of De-icing Chemicals when Scraping Ice. Iowa Highway Research Board, Ames, 2003, IIHR Report 434, 132 p.

Nixon, Wilfrid, George Kochumman, Carrie Novotny and Anton Kruger. Development of a Computer Controlled Underbody Plow. Iowa Highway Research Board, Ames, 2006, Report TR-412, 50 p. http://www.iowadot.gov/research/reports/Year/2006/fullreports/tr412.pdf

Nixon, Wilfrid. Field Testing of Abrasive Delivery Systems in Winter Maintenance. Iowa Highway Research Board, Ames, 2009, Report 471, 61 p.

Norem, Harald. Selection of Strategies for Winter Maintenance of Roads Based on Climatic Parameters. Journal of Cold Regions Engineering. Vol. 23, No. 4, 2009, pp. 113-135.

North Dakota Department of Transportation. Evaluation of Snow Plow Blade Systems. North Dakota Department of Transportation, Bismarck, 2011. Report MR 2010-03, 72 p. http://www.dot.nd.gov/divisions/materials/research_project/mr201003final.pdf

Nottingham, Dennis, Susan Schoettle and William Gunderson. Costs to the Public Due to the Use of Corrosive Deicing Chemicals and a Comparison to Alternative Winter Road Maintenance Procedures. Alaska Department of Transportation and Public Facilities, Juneau, 1883, 35 p.

Ohio Department of Transportation. Snow and Ice Practices. Ohio Department of Transportation, Columbus, 2011, 36 p. https://www.dot.state.oh.us/Divisions/Operations/Maintenance/SnowandIce/Snow%20and%20Ice%20Best%20Practices/ODOT%20Snow%20and%20Ice%20Practices%20March%202011.pdf

O'Keefe, Katie and Xianming Shi. Synthesis of Information on Anti-icing and Pre-wetting for Winter Highway Maintenance Practices in North America. Pacific Northwest Snowfighters Association, 2005, 97p.

Parker Richard. Alternative Snow and Ice Control Methods: Field Evaluation. Oregon Department of Transportation, Salem, 1997, Report No. FHWA-OR-RD-98-03, 65 p.

Paschka Michael, Rajat Ghosh and David Dzombak. Potential Water-quality Effects from Iron Cyanide Anticaking Agents in Road Salt. Water Environment Research, Vol. 71, No. 6, 1999, pp. 1235-1239.

Perchanok, Max. Evaluation of Methods for High-Speed Application of Road Salt. Transportation Research Record: Journal of the Transportation Research Board, No. 1741, 2001, pp. 193-198.

Pilgrim, Keith. Determining the Aquatic Toxicity of Deicing Materials, Clear Roads Pooled Fund and Minnesota Department of Transportation, St. Paul, 2013, Project 99083/CR11-02, 64 p. http://www.clearroads.org/research-projects/11-02toxicity-of-deicing-materials.html

Public Sector Consultants. The Use of Selected De-icing Materials on Michigan Roads: Environmental and Economic Impacts. Michigan Department of Transportation. Lansing, 1993, 6 p.

Qiu, Lin, and Wilfrid Nixon. Modeling the Causal Relationships Between Winter Highway Maintenance, Adverse Weather and Mobility. Proceedings: 87th Annual Meeting of the Transportation Research Board, Washington D.C., 2008.

Qiu, Lin and Wilfrid Nixon. Performance Measurement for Highway Winter Maintenance Operations. Iowa Highway Research Board, Ames, 2009, Report 474, 128 p.

Ramakrishna Devikarani and Thiruvenkatachari Viraraghavan. Environmental Impact of Chemical Deicers- A Review. Water, Air & Soil Pollution, Vol. 166, No. 1-4, 2005, pp. 49-63.

Rehbein, Jennifer. Flame Hardened Underbody Plow Blades. Iowa Department of Transportation, Ames, 2013, Report No. RB13-012, 4 p.

Roadway Safety Foundation. Clear Winter Roads Protect Lives and Commerce. Roadway Safety Foundation, Washington, D.C., Undated. http://www.roadwaysafety.org/wp-content/uploads/clear-winter-roads-brochure.pdf

Roth D. and G. Wall G. Environmental Effects of Highway Deicing Salts. Ground Water, Vol. 14, No. 5, 1976, pp. 286-289.

Rubin, Jonathan, Per Gårder, Charles Morris, Kenneth Nichols, John Peckenham, Peggy McKee and Adam Stern. Maine Winter Roads: Salt, Safety, Environment and Cost. Margaret Chase Smith Policy Center, University of Maine, Orono, 2010, 156 p.

Salt Institute. Highway Salt and Our Environment. Salt Institute, Fairfax, Virginia, 2004. http://www.safewinterroads.org/wp-content/uploads/2011/08/Highway-Salt-and-Our-Environment.pdf

Salt Institute. Virginia DOT Sets Pace in Recycling Salty Runoff at Storage Facilities. Salt and Highway Deicing Newsletter, Vol. 47, No. 1, 2010.

Salt Institute. Prewetting Salt: Another Cost Effective Tool for Your Winter Maintenance Toolbox. Salt Institute, Fairfax, Virginia, Undated a.

Salt Institute. Winter Road Safety. Salt Institute, Arlington, Virginia, Undated b.

Schlup, Ulrich and Beatrice Ruess. Abrasives and Salt: New Research on Their Impact on Security, Economy, and the Environment. Transportation Research Record, No. 1741, 2001, pp. 47-53.

Schneider, William, Christopher Miller, William Holik and Mallory Crow. Evaluation of Epoke Bulk Spreader for Winter Maintenance. Ohio Department of Transportation, Columbus, 2013, Report No. FHWA/OH-2012/24, 214 p.

Shi, Xianming. The Use of Road Salts for Highway Winter Maintenance: An Asset Management Perspective. Proceedings: Institute of Transportation Engineers District 6 Annual Meeting, Kalispell, Montana, 2005.

Shi, Xianming, Laura Fay, Zhengxian Yang, Tuan Anh Nguyen and Yajun Liu. Corrosion of Deicers to Metals in Transportation Infrastructure: Introduction and Recent Developments. Corrosion Reviews, Vol. 27, No. 1-2, 2009, pp. 23-52.

Shi, Xianming, Fay, Laura, Fortune, Keith, Smithlin, Rob, Peterson, Jeanie, Creighton, Andrew, Yang, Zhang, Cross, Doug. Investigating Longevity of Corrosion Inhibitors and Performance of Deicer Products under Storage or after Pavement Application. Washington State DOT and PNS. 2011.

Shi, Xianming, Yongxin Li, Scott Jungwirth, Yida Fang, Nicholas Seeley. and Emily Jackson. Identification and Laboratory Assessment of Best Practices to Protect DOT Equipment from the Corrosive Effect of Chemical Deicers. Washington State Department of Transportation, Olympia, 2013a, Report No. WA-RD 796.1, 217 p. http://www.wsdot.wa.gov/research/reports/fullreports/796.1.pdf

Shi, Xianming, David Veneziano, Ning Xie and Jing Gong. Use of Chloride-Based Ice Control Products for Sustainable Winter Maintenance: A Balanced Perspective. Cold Regions Science and Technology. Vol. 86, 2013b, pp. 104-112.

Shi, Xianming, Scott Jungwirth, Michelle Akin, Ron Wright, Laura Fay, David Veneziano, Yan Zhang, Jiang Huang and Zhirui Ye. Evaluation of Snow and Ice Control Materials for Highway Maintenance Operations: A Renewed, Data-Driven Perspective. Proceedings: 93rd Annual Meeting of the Transportation Research Board, Washington D.C., 2014.

Sooklall, Rudolph, Liping Fu and Max Perchanok. Effectiveness of Pre-Wetting Strategy for Snow and Ice Control on Highways. Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island, 2006.

Transportation Association of Canada. Synthesis of Best Practices: Road Salt Management. Chapter 9. Winter Maintenance Equipment and Technologies. Ottawa, Ontario, Canada, 2013.

Transportation Research Board. Highway De-icing: Comparing Salt and Calcium Magnesium Acetate. National Research Council, Washington, D.C., 1991, TRB Special Report 235, 20 p.

Tuan, Christopher and Barbara Gerbino-Bevins. Improving the Freight Transportation Roadway System during Snow Events: A Performance Evaluation of Deicing Chemicals. Mid-America Transportation Center, Lincoln, Nebraska, 2012, Report No. 25-1121-0001-423, 139 p.

Usman, Taimur, Liping Fu and Luis Miranda-Moreno. A Disaggregate Model for Quantifying the Safety Effects of Winter Road Maintenance Activities at an Operational Level. Accident Analysis and Prevention, Vo. 48, No. 1, 2012, pp. 368-378.

Veneziano, David, Laura Fay, Zhirui Ye, Xianming Shi and Lisa Ballard. Development of a Toolkit for Benefit-cost Analysis of Specific Winter Maintenance Practices, Equipment and Operations: Final Report. ClearRoads and Wisconsin Department of Transportation, Madison, 2010, Project 0092-09-08/CR08-02. 2010a, 74 p.

Veneziano, David, Xianming Shi and Lisa Ballard. Development of a Toolkit for Benefit-cost Analysis of Specific Winter Maintenance Practices, Equipment and Operations: User Manual. Project 0092-09-08/CR08-02, ClearRoads Pooled Fund and Wisconsin Department of Transportation, 2010b, 153 p.

Veneziano, David, Laura Fay, Xianming Shi, and Lisa Ballard. Development of a Toolkit for Benefit-cost Analysis of Specific Winter Maintenance Practices, Equipment and Operations Phase 2: Final Report. ClearRoads Pooled Fund and Minnesota Department of Transportation, St. Paul, 2013, 70 p.

Vestola, Elina, Pekka Pohjanne, Leena Carpén, Tuija Kaunisto and Tina Ahlroos. Side Effects of Calcium Chloride. Finnish Road Administration (Finnra), Helsinki, 2006, Report No. 38/2006, 72 p.

Viking-Cives Group. Viking Cives Data Sheet. Viking-Cives Group, Harrisville, New York, 2014. www.vikingcives.com

Virginia Department of Transportation. VDOT Equipment and Supplies 2013-2014 Winter Season. Virginia Department of Transportation, Richmond, 2014. http://www.virginiadot.org/VDOT/Travel/asset_upload_file254_61762.pdf

Vitaliano, Donald. An Economic Assessment of the Social Costs of Highway Salting and the Efficiency of Substituting a New Deicing Material. Journal of Policy Analysis and Management, Vol. 11, No. 3,1992, pp. 397-418.

Wickham, S.K. DOT Officials Urge Patience Behind Plows this Winter. New Hampshire Union Leader, November 17, 2012 http://www.unionleader.com/article/20121118/NEWS07/121119189/0/NEWS05

Williams, Dan. Past and Current Practices of Winter Maintenance at the Montana Department of Transportation. Montana Department of Transportation, Helena, 2003 White Paper.

Wisconsin Transportation Information Center. Plow Blade Innovations Show Potential. Wisconsin Transportation Information Center, Madison, 2012, Crossroads Newsletter. http://epdfiles.engr.wisc.edu/pdf_web_files/tic/crossroads/xrds_2012_4.pdf

Ye, Zhirui, Xianming Shi and Christopher Strong. Cost–Benefit Analysis of the Pooled-Fund Maintenance Decision Support System - Case Studies. Paper # MMC09-020. 12th AASHTO-TRB Maintenance Management Conference. Annapolis, Maryland, 2009.

Ye, Zhirui, David Veneziano, Xianming Shi and Laura Fay. Methods for Estimating the Benefits of Winter Maintenance Operations. National Research Council, Washington, D.C., 2012, NCHRP Project 20-07(300), 56 p.

Yunovich Mark, Neal Thompson, Tunde Balvanyos and Lester Lave. Corrosion Costs of Highway Bridges. Concrete International Vol. 25, No. 1, 2003.

Appendix A
Survey Questionnaire

Overview

This survey is being undertaken by the Western Transportation Institute, Montana State University, and is sponsored by the Clear Roads Pooled Fund, to obtain information about the costs and benefits associated with different winter maintenance operations and materials. The specific operations and materials of interest to this work consist of three tiers:

I. Basic activities including plowing and the use of abrasives.

II. Intermediate activities including plowing, spot abrasive use, and the use of salt and/or salt brine (NaCl) for anti-icing and deicing.

III. Advanced activities including the selection and use of alternative chemicals, corrosion-inhibited liquids and/ or treated or chemically enhanced solid chemicals to match performance with environmental conditions for anti-icing and deicing, with plowing and possible spot use of abrasives.

The objective of this survey is to better understand the dollar values that may be associated with the components of these different tiers based on practical experience and to identify the Level of Service (LOS) achieved by each. Note that certain practices may not yield the LOS that an agency is looking for, and this may require the use of different practices in combination or on specific routes, and the participant should bear this in mind when completing the survey. In addition, this survey also seeks any other information you may have regarding the winter maintenance operations and materials that may be of interest to this work. In terms of dollar values, estimated values based on professional experience are sufficient; it is understood that the time required to look up records of specific values is prohibitive for a participant, but greatly appreciated.

If you would like to participate in this survey, please begin by answering the questions that follow. The survey may take up to 60 minutes of your time, depending on the approaches used by your agency and their complexity. You may provide this survey to others in your agency / organization as well. Participation is voluntary, and you can choose to not answer any question that you do not want to answer, and you can stop at any time.

Important: To save your answers and finish later, **click "Next" to save what you've entered on the current page**, even if you're not finished with that page. When you reopen the survey **on the same computer**, the survey will open to the last page you were working on. Use the "Prev" and "Next" buttons to navigate to unfinished pages. If you're unable to retrieve your responses, please contact David Veneziano at 406-994-6320 or david.veneziano@coe.montana.edu.

Your contact information will only be used by the researchers for the purposes of this study. The researchers will not contact you for any other reason and your contact information will not be released or shared for any other reason. For questions about the research project, contact David Veneziano at 406-994-6320 or david.veneziano@coe.montana.edu. For questions regarding your rights as a human subject, contact Mark Quinn, IRB Chair, 406-994-4707 or mquinn@montana.edu.

Background Information

Important: To save your answers and finish later, **click "Next" to save what you've entered on the current page**, even if you're not finished with that page. When you reopen the survey **on the same computer**, the survey will open to the last page you were working on. Use the "Prev" and "Next" buttons to navigate to unfinished pages. If you're unable to retrieve your responses, please contact David Veneziano at 406-994-6320 or david.veneziano@coe.montana.edu.

1. Contact Information

Name:

Agency (Region)/Title:

Mailing Address:

City:

State:

Zip Code:

Email address:

Phone Number:

2. Please provide some basic background on your agency and operations:

Number of plow vehicles

Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)

Number of lane miles maintained

Number of winter storm events per season

Average annual accumulative snow depth (inches)

*3. Does your agency employ basic activities for winter maintenance, including plowing and/or the use of abrasives?

- Yes
- No

Basic Practices

Basic Practices – includes plowing and/or the use of abrasives.

4. What is your agency's Level of Service using mainly the practices already in place and what would it be using only plowing and/or abrasives (please describe)?

5. What has the impact of this practice been on the mobility of the public (please describe)?

6. Has your agency observed a reduction in crashes using these practices compared to other winter maintenance practices? Reports or figures may be submitted via [this upload link].

7. Do you have any information on the number of passes or applications needed to achieve an LOS for a given condition for this approach versus another practice?

Basic Practices

***8. Does your agency use plowing as part of its maintenance operations?**

- ◯ Yes
- ◯ No

Basic Practices

9. What types of plows does your agency employ? (Select all that apply)

- ☐ Front plows
- ☐ Tow Plows
- ☐ Underbody Plows
- ☐ Wing Plows
- ☐ Rotary Plows or snowblowers
- ☐ Tandem/Gang Plowing
- ☐ Motor Graders

Other (please explain)

10. Please provide an estimate of the annual average cost per lane mile of responsibility to plow at your agency.

11. How important are the following plowing capabilities to you? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Removes snow and ice from the road	○	○	○
Reduced number of vehicle passes	○	○	○
Reduced treatment material usage	○	○	○
Reduced personnel hours	○	○	○

Other (please specify)

12. What type of blade inserts do you use? (Select all that apply)

- ☐ Standard steel
- ☐ Carbide steel
- ☐ Combination blades (rubber, steel and carbide, such as JOMA 6000)
- ☐ Full rubber or rubber encased steel
- ☐ Ceramic

Other (please specify)

13. How many plow miles does your agency achieve per blade set?

14. Approximately how many man hours are required to replace blade inserts for one truck?

15. What is the average hourly loaded labor rate for your personnel?

16. Please list or discuss any specific costs or benefits (ex. effective for snow and ice removal, expensive to replace inserts, etc.) you would like to share regarding plowing, plow types, and blade inserts.

Abrasives

***17. Does your agency use abrasives as part of its maintenance operations?**

- ◯ Yes
- ◯ No

Abrasives

18. When/how are they used?

- ☐ System-wide (all routes)
- ☐ Intersection approaches
- ☐ Curves
- ☐ Bridges
- ☐ Hills
- ☐ Shaded areas
- ☐ Windblown areas
- ☐ Low temperature events

Other (please specify)

19. What abrasive materials are used? (Select all that apply)

- ☐ Abrasives
- ☐ Abrasive-salt mix (Please indicate what percent mix is used in the "Other" text box.)

Other (please specify)

20. What abrasive gradation(s) are used by your agency? Note, if you have gradation information in a table, please submit it via this upload link. Otherwise, provide gradation examples that most closely represent those your agency uses.

21. What is the approximate cost per ton of each specific abrasive material being used?

22. How many tons of abrasives (straight and/or salt-mixed) are applied annually by your agency?

23. How important are the following benefits of using abrasives? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Low cost of material	◯	◯	◯
Ease of application	◯	◯	◯
Provide traction	◯	◯	◯

Other (please specify)

24. Do you have any specific values or information on any of these benefits (please list)?

***25. Does your agency have an abrasive clean-up program in place?**

◯ Yes

◯ No

Abrasive clean-up

26. Is cleanup performed by (select all that apply):

☐ Agency personnel

☐ Contracted out

27. What is the approximate cost to clean up abrasives per mile?

28. What is the approximate cost to dispose of spent abrasives?

29. Does your agency recycle abrasives? (If yes please explain)

Abrasives

30. How important are the following negative aspects of using abrasives? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Entry of abrasives into waterways	☐	☐	☐
Increased dust/air pollution	☐	☐	☐
Vehicle damage (ex. chipped windshields)	☐	☐	☐
Does not provide deicing capacity	☐	☐	☐

Other (please specify)

31. Do you have any specific cost information for any of the negative aspects of abrasives mentioned above (please list)?

Intermediate Practices

***32. Does your agency employ Intermediate activities, such as the use of solid salt (NaCl) or salt brine for anti-icing and deicing (in addition to Basic activities such as plowing and spot abrasive use)?**

◯ Yes

◯ No

Intermediate Practices

Intermediate activities include the use of salt and/or salt brine (NaCl) for anti-icing and deicing (with possible use of plowing and spot abrasive use).

33. What is your agency's Level of Service using mainly the practices already in place and what would it be using only Intermediate practices (please describe)?

34. What has the impact of Intermediate practices been on the mobility of the public (please describe)?

35. Has your agency observed a reduction in crashes using these Intermediate practices compared to other winter maintenance practices? Reports or figures may be submitted via this upload link.

36. Do you have any information on the number of applications needed to achieve an LOS for a given condition using Intermediate versus another practice?

***37. Does your agency use solid salt?**

- Yes
- No

Solid Salt

38. Approximately how many tons per year are used?

39. What is the approximate cost per ton delivered?

40. Please provide your table of application rates, either in the text box provided or via this upload link.

41. How important are the following aspects associated with the use of salt? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

42. How important are the following benefits associated with the use of salt? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Melting capacity	◯	◯	◯
Clear roads of snow and ice	◯	◯	◯
Ease of use/application	◯	◯	◯
Low cost of material	◯	◯	◯

Other (please specify)

Salt-abrasive mix

***43. Does your agency use a salt-abrasive mix?**

◯ Yes

◯ No

Salt-abrasive mix

44. What ratio of solid salt to abrasive material is used?

45. Please provide your table of application rates, either in the text box provided or via this upload link.

Salt Brine

***46. Does your agency use salt brine?**

- ◯ Yes
- ◯ No

Salt Brine

47. Approximately how many gallons per year are used?

48. Do you manufacture your salt brine or purchase it? (Select all that apply)

- ☐ Manufacture
- ☐ Purchase

49. What is the approximate cost per gallon delivered?

50. Please provide your table of application rates, either in the text box provided or via this upload link.

51. How important are the following aspects associated with the use of salt brine? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

52. How important are the following benefits associated with the use of salt brine? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Melting capacity	◯	◯	◯
Clear roads of snow and ice	◯	◯	◯
Ease of use/application	◯	◯	◯
Low cost of material	◯	◯	◯

Other (please specify)

Prewetting

*53. Does your agency prewet or pretreat (before material is loaded) with salt brine?

◯ Yes

◯ No

Prewetting

54. What does your agency prewet? (Select all that apply)

☐ Abrasives

☐ Solid Salt

Other (please specify)

55. How does your agency perform prewetting? (Select all that apply)

- [ ] At the pile
- [ ] At the spreader
- [ ] Use of slurry spreading
- [ ] Shower wetting of a truckload

Other (please specify)

56. What percentage of brine is used for prewetting solid material?

57. If your agency is using a slurry spreader, has it been able to reduce application rates, and if so by how much?

58. What percentage of brine is used for direct application?

59. Please provide an estimate of the annual cost associated with producing and applying salt brine at your agency (equipment, materials, labor, etc.).

60. How important are the following benefits of prewetting and/or pre-treating? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Reduced granular product used	◯	◯	◯
Reduce the amount of product lost into the environment (bounce and scatter)	◯	◯	◯
Achieve faster melt	◯	◯	◯
Increased range of maintenance vehicles between reloads	◯	◯	◯
Reduced vehicle patrol hours	◯	◯	◯
Reduced personnel hours	◯	◯	◯

Other (please specify)

Anti-icing with salt or salt brine

***61. Do you perform anti-icing using salt or salt brine?**

- Yes
- No

Anti-icing with salt or salt brine

62. What equipment do you use to apply anti-icers?

63. Please provide an estimate of the annual cost associated salt/salt brine anti-icing operations at your agency (equipment, materials, labor, etc.).

64. How important are the following benefits of salt/salt brine anti-icing? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Reduced amount of product used			
Reduced number of application vehicles needed			
Cost savings			
Improved safety			
Reduced impacts to the environment			
Reduced impacts to vehicles and infrastructure			

Other (please specify)

Brine making

***65. Does your agency make salt brine?**

- Yes
- No

Brine Making

66. What are the approximate annual costs ($) associated with the following:

Equipment

Transport (if product shipped to other locations)

Input materials

Fuel cost

Transport truck maintenance

Labor

Other costs? (please specify)

67. How important are the following benefits of brine making? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Can make as needed	☐	☐	☐
Quality Control	☐	☐	☐
Can control amount produced	☐	☐	☐
Cost savings (please provide an approximate estimate in the "Other" text box)	☐	☐	☐

Other (please specify)

Advanced Practices

*68. Does your agency use Advanced Practices? These include the selection and use of alternative chemicals, corrosion-inhibited liquids and/or treated or chemically enhanced solid chemicals to match performance with environmental conditions for anti-icing and deicing (in addition to Basic and Intermediate activities such as plowing and use of salt, salt brine and/or abrasives).

- ◯ Yes
- ◯ No

Advanced Practices

Advanced Practices include the selection and use of alternative chemicals, corrosion-inhibited liquids and/or treated or chemically enhanced solid chemicals to match performance with environmental conditions for anti-icing and deicing (in addition to possible use of Basic and Intermediate activities such as plowing and use of salt, salt brine and/or abrasives).

69. How much did advanced practices impact your organization's Level of Service? (please describe)?

70. What has the impact of Advanced practices been on the mobility of the public (please describe)?

71. Has your agency observed a reduction in crashes using Advanced practices compared to other winter maintenance practices? Reports or figures may be submitted via this upload link.

***72. Does your agency use corrosion inhibitors with your winter maintenance products?**

- Yes
- Yes, in some areas
- No

Corrosion Inhibitors - Materials come in different forms or fashions includ...

73. What corrosion inhibiting product(s) does your agency use? (Name/Brand)

74. What is the approximate cost of the material used? (per gallon or per ton)

75. Please provide and describe any additional costs associated with the use of the corrosion inhibitor(s) not included in the purchase price (storage, handling, etc.):

76. How important are the following benefits of the corrosion inhibitor(s)? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Public vehicle protection	◯	◯	◯
Increased service life of agency's vehicles	◯	◯	◯
Reduced corrosion to equipment (if so please explain below)	◯	◯	◯
Reduced corrosion to infrastructure (if so please explain below)	◯	◯	◯

Other (please specify)

Inhibited Salt Brine

*77. Does your agency use inhibited salt brine?

◯ Yes

◯ Yes, in some areas

◯ No

Inhibited Salt Brine

78. What application rate is used when applying this material? (per lane mile)

79. How much do you pay for this material (per gallon or ton)?

80. What equipment do you use to apply this material?

81. How do you use your inhibited salt brine and where do you use it?

82. Have you applied this material in combination with other products (like pre-wetting) ?

- ◯ Yes
- ◯ No

83. Do you have any information on the number of applications needed to achieve an LOS for a given condition versus another product?

84. Please provide an estimate of the annual cost associated inhibited salt brine operations at your agency (equipment, materials, labor, etc.):

85. How important are the following aspects associated with using inhibited salt brine? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

86. How important are the following benefits you have observed or experienced from using inhibited salt brine? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost savings	◯	◯	◯
Improved safety	◯	◯	◯
Reduced amount of product used	◯	◯	◯
Reduced number of application vehicles needed	◯	◯	◯
Better performance at cold temperatures	◯	◯	◯
Reduces need for salt and/or sand	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

Magnesium Chloride

***87. Does your agency use Magnesium chloride?**

◯ Yes

◯ No

Magnesium Chloride

88. In what form do you use magnesium chloride? (Select all that apply)

☐ Inhibited Liquid

☐ Uninhibited Liquid

☐ Inhibited Solid

☐ Uninhibited Solid

Other (please specify)

89. What application rate is used when applying this material? (per lane mile)

90. How much do you pay for this material (per gallon or ton)?

91. What equipment do you use to apply this material?

92. How do you use magnesium chloride and where do you use it?

93. Have you applied this material in combination with other products (like pre-wetting) ?

- Yes
- No

94. Do you have any information on the number of applications needed to achieve an LOS for a given condition versus another product?

95. Please provide an estimate of the annual cost associated magnesium chloride operations at your agency (equipment, materials, labor, etc.):

96. How important are the following aspects associated with using magnesium chloride? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

97. How important are the following benefits you have observed or experienced from using magnesium chloride? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost savings	◯	◯	◯
Improved safety	◯	◯	◯
Reduced amount of product used	◯	◯	◯
Reduced number of application vehicles needed	◯	◯	◯
Better performance at cold temperatures	◯	◯	◯
Not an animal attractant	◯	◯	◯
Reduces need for salt and/or sand	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

98. Using a magnesium chloride, do you see a savings versus a straight salt brine of:

- ☐ Reduction in vehicle refresh rates
- ☐ Reduction in applications
- ☐ Longer timeframe for black ice prevention

Other (please specify)

Calcium Chloride

*99. Does your agency use calcium chloride?

- ◯ Yes
- ◯ No

Calcium Chloride

100. In what form do you use calcium chloride? (Select all that apply)

- [ ] Inhibited Liquid
- [ ] Uninhibited Liquid
- [ ] Inhibited Solid
- [ ] Uninhibited Solid

Other (please specify)

101. What application rate is used when applying this material? (per lane mile)

102. How much do you pay for this material (per gallon or ton)?

103. What equipment do you use to apply this material?

104. How do you use calcium chloride and where do you use it?

105. Have you applied this material in combination with other products (like pre-wetting) ?

- ( ) Yes
- ( ) No

106. Do you have any information on the number of applications needed to achieve an LOS for a given condition versus another product?

107. How important are the following aspects associated with using calcium chloride? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

108. How important are the following benefits you have observed or experienced from using calcium chloride? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost savings	☐	☐	☐
Improved safety	☐	☐	☐
Reduced amount of product used	☐	☐	☐
Reduced number of application vehicles needed	☐	☐	☐
Better performance at cold temperatures	☐	☐	☐
Not an animal attractant	☐	☐	☐
Reduces need for salt and/or sand	☐	☐	☐
Public feedback	☐	☐	☐

Other (please specify)

Blended Products - agricultural byproducts blended with de-icing and anti-i...

*** 109. Does your agency use blended products?**

◯ Yes

◯ No

Blended Products

Blended Products - agricultural byproducts blended with de-icing and anti-icing chemicals.

110. What type(s) of blended product do you use?

111. Is the product inhibited or uninhibited?

- [ ] Inhibited
- [ ] Uninhibited

112. What application rate is used when applying this material? (per lane mile)

113. How much do you pay for this material (per gallon or ton)?

114. What equipment do you use to apply this material?

115. How do you use blended products and where do you use them?

116. Have you applied this material in combination with other products (like pre-wetting) ?

- ◯ Yes
- ◯ No

117. Do you have any information on the number of applications needed to achieve an LOS for a given condition versus another product?

118. Please provide an estimate of the annual cost associated blended product operations at your agency (equipment, materials, labor, etc.):

119. How important are the following aspects associated with using blended products? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost of material itself	◯	◯	◯
More difficult to handle and/or apply	◯	◯	◯
Environmental impacts to the roadside	◯	◯	◯
Increased corrosion	◯	◯	◯
Pavement deterioration	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

120. How important are the following benefits you have observed or experienced from using blended products? (Select all that apply)

	Very Important	Somewhat Important	Not Important
Cost savings	◯	◯	◯
Improved safety	◯	◯	◯
Reduced amount of product used	◯	◯	◯
Longer lasting applications	◯	◯	◯
Reduced number of application vehicles needed	◯	◯	◯
Better performance at cold temperatures	◯	◯	◯
Not an animal attractant	◯	◯	◯
Reduces need for salt and/or sand	◯	◯	◯
Public feedback	◯	◯	◯

Other (please specify)

Chemical Selection to Achieve LOS

Chemical selection to achieve LOS using deicing/anti-icing agents such as salt, brine or alternative chemicals.

121. What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- [ ] Cost
- [ ] Ease of use
- [ ] Effectiveness
- [ ] Availability
- [ ] Reduced impacts (environment, corrosion, etc.)
- [ ] Meets Level of Service objective
- [ ] Public feedback

Other (please specify)

122. Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

- ○ Yes
- ○ No

123. Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

124. Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., rock salt, brine, mag, calcium, blended products, pre-wet/pre-treated, or corrosion inhibited)?

Conclusion

If your organization has conducted any in-house research on the costs, benefits, or cost-benefit studies of any of the winter maintenance operations or materials discussed in this survey and has not published this work in the public domain but is willing to share this information, please upload it **here** or send to this study's Principal Investigator David Veneziano (406-994-6320, david.veneziano@coe.montana.edu) and we will follow-up with you.

Thank you for your time and participation in this survey!

Advanced Materials Survey Questionnaire

Interview Questionnaires

Corrosion Inhibitors

Contact Information

- Name:
- Agency (Region)/Title:
- Phone Number:

Please provide some basic background on your agency and operations:

- Number of plow vehicles
- Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)
- Number of lane miles maintained
- Number of winter storm events per season
- Average annual accumulative snow depth (inches)

What corrosion inhibiting product(s) does your agency use? (Name/Brand)

What is the approximate cost of each product used? (per gallon or per ton)

Please provide and describe any additional costs associated with the use of the corrosion inhibitor(s) not included in the purchase price (storage, handling, etc.):

What Level of Service is achieved by products using corrosion inhibitors in your operations? (please describe)?

Has your agency observed a reduction in crashes while using products with inhibitors? Do you have any reports or figures that document this?

How important are the following benefits of the corrosion inhibitor(s)? (Very, somewhat or not important)

- Public vehicle protection
- Increased service life of agency's vehicles
- Reduced corrosion to equipment (if so please explain)
- Reduced corrosion to infrastructure (if so please explain)
- Other (please specify)

What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- Cost
- Ease of use
- Effectiveness
- Availability
- Reduced impacts (environment, corrosion, etc.)
- Meets Level of Service objective

- Public feedback
- Other (please specify)

Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., salt brine, mag, calcium, blended products, prewet/ pretreated, or corrosion inhibited)?

If this is the only material that information is being sought for from the contact, be sure to thank them for their time and assistance.

<u>Corrosion Inhibited Salt Brine</u>

Contact Information

- Name:
- Agency (Region)/Title:
- Phone Number:

Please provide some basic background on your agency and operations:

- Number of plow vehicles
- Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)
- Number of lane miles maintained
- Number of winter storm events per season
- Average annual accumulative snow depth (inches)

What corrosion inhibiting product(s) does your agency use? (Name/Brand)

What application rate is used when applying corrosion inhibited salt brine? (per lane mile)

How much do you pay for corrosion inhibited salt brine (total cost per gallon)?

What equipment do you use to apply this material?

How do you use your corrosion inhibited salt brine and where do you use it?

Have you applied corrosion inhibited salt brine in combination with other products (like prewetting)?

What Level of Service is achieved by corrosion inhibited salt brine in your operations? (please describe)?

Please provide an estimate of the annual cost associated with corrosion inhibited salt brine operations at your agency (equipment, materials, labor, etc.):

How important are the following aspects associated with using inhibited salt brine? (very, somewhat or not important)

- Cost of material itself

- More difficult to handle and/or apply
- Environmental impacts to the roadside
- Pavement deterioration
- Public feedback
- Other (please specify)

How important are the following benefits you have observed or experienced from using inhibited salt brine? (very, somewhat or not important)

- Cost savings
- Improved safety
- Reduced amount of product used
- Reduced number of application vehicles needed
- Better performance at cold temperatures
- Reduces need for salt and/or sand
- Public feedback
- Other (please specify)

Do you have any additional information or thoughts on corrosion inhibited salt brine that you would like to share?

What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- Cost
- Ease of use
- Effectiveness
- Availability
- Reduced impacts (environment, corrosion, etc.)
- Meets Level of Service objective
- Public feedback
- Other (please specify)

Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., salt brine, mag, calcium, blended products, prewet/ pretreated, or corrosion inhibited)?

If this is the only material that information is being sought for from the contact, be sure to thank them for their time and assistance.

<u>Magnesium Chloride</u>

Contact Information

- Name:

- Agency (Region)/Title:
- Phone Number:

Please provide some basic background on your agency and operations:

- Number of plow vehicles
- Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)
- Number of lane miles maintained
- Number of winter storm events per season
- Average annual accumulative snow depth (inches)

Which of the following Magnesium Chloride forms do you use?

- Magnesium Chloride Solid
- Magnesium Chloride Liquid
- Magnesium Chloride Corrosion Inhibited Solid
- Magnesium Chloride Corrosion Inhibited Liquid

What application rate is used when applying Magnesium Chlorides (per lane mile)? Please specify application rates for all forms of Magnesium Chloride used (ex. solids, inhibited liquids, etc.).

How much do you pay for the form(s) of Magnesium Chloride used (total cost per gallon or ton)? Please specify costs for all forms of Magnesium Chloride used (ex. solids, inhibited liquids, etc.).

What equipment do you use to apply the form(s) of Magnesium Chloride being used? Please specify the specific equipment for all forms of Magnesium Chloride used (ex. solids, inhibited liquids, etc.).

How do you use Magnesium Chloride and where do you use it? Please specify the uses for all forms of Magnesium Chloride being employed (ex. solids, inhibited liquids, etc.).

Have you applied Magnesium Chloride in combination with other products (like prewetting)? Please consider the different applications for all forms of Magnesium Chloride used (ex. solids, inhibited liquids, etc.).

What Level of Service is achieved by the form(s) of Magnesium Chloride being used in your operations? (please describe)? Please specify the LOS achieved for all forms of Magnesium Chloride used separately (ex. solids, inhibited liquids, etc.).

Do you have any information on the number of applications needed for the form(s) of Magnesium Chloride used to achieve an LOS for a given condition versus another product?

Please provide an estimate of the annual cost associated with Magnesium Chloride operations at your agency (equipment, materials, labor, etc.):

Which of the following aspects associated with using Magnesium Chloride present concerns? (very, somewhat or not important)

- Cost of material itself

- More difficult to handle and/or apply
- Environmental impacts to the roadside
- Pavement deterioration
- Public feedback
- Corrosion (uninhibited materials only)
- Other (please specify)

Which of the following benefits you have observed or experienced from using Magnesium Chloride? (very, somewhat or not important)

- Cost savings
- Improved safety
- Reduced amount of product used
- Reduced corrosion (inhibited materials only)
- Reduced number of application vehicles needed
- Better performance at cold temperatures
- Not an animal attractant
- Reduces need for salt and/or sand
- Public feedback
- Other (please specify)

Do you have any additional information, cost or benefit values or thoughts on Magnesium Chloride that you would like to share?

What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- Cost
- Ease of use
- Effectiveness
- Availability
- Reduced impacts (environment, corrosion, etc.)
- Meets Level of Service objective
- Public feedback
- Other (please specify)

Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., salt brine, mag, calcium, blended products, prewet/ pretreated, or corrosion inhibited)?

If this is the only material that information is being sought for from the contact, be sure to thank them for their time and assistance.

Calcium Chloride

Contact Information

- Name:
- Agency (Region)/Title:
- Phone Number:

Please provide some basic background on your agency and operations:

- Number of plow vehicles
- Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)
- Number of lane miles maintained
- Number of winter storm events per season
- Average annual accumulative snow depth (inches)

Which of the following Calcium Chloride forms do you use?

- Calcium Chloride Solid
- Calcium Chloride Liquid
- Calcium Chloride Corrosion Inhibited Solid
- Calcium Chloride Corrosion Inhibited Liquid

What application rate is used when applying Calcium Chlorides (per lane mile)? Please specify application rates for all forms of Calcium Chloride used (ex. solids, inhibited liquids, etc.).

How much do you pay for the form(s) of Calcium Chloride used (total cost per gallon or ton)? Please specify costs for all forms of Calcium Chloride used (ex. solids, inhibited liquids, etc.).

What equipment do you use to apply the form(s) of Calcium Chloride being used? Please specify the specific equipment for all forms of Calcium Chloride used (ex. solids, inhibited liquids, etc.).

How do you use Calcium Chloride and where do you use it? Please specify the uses for all forms of Calcium Chloride being employed (ex. solids, inhibited liquids, etc.).

Have you applied Calcium Chloride in combination with other products (like prewetting)? Please consider the different applications for all forms of Calcium Chloride used (ex. solids, inhibited liquids, etc.).

What Level of Service is achieved by the form(s) of Calcium Chloride being used in your operations? (please describe)? Please specify the LOS achieved for all forms of Calcium Chloride used separately (ex. solids, inhibited liquids, etc.).

Do you have any information on the number of applications needed for the form(s) of Calcium Chloride used to achieve an LOS for a given condition versus another product?

Please provide an estimate of the annual cost associated with Calcium Chloride operations at your agency (equipment, materials, labor, etc.):

Which of the following aspects associated with using Calcium Chloride present concerns? (very, somewhat or not important)

- Cost of material itself
- More difficult to handle and/or apply
- Environmental impacts to the roadside
- Pavement deterioration
- Public feedback
- Corrosion (uninhibited materials only)
- Other (please specify)

Which of the following benefits you have observed or experienced from using Calcium Chloride? (very, somewhat or not important)

- Cost savings
- Improved safety
- Reduced amount of product used
- Reduced corrosion (inhibited materials only)
- Reduced number of application vehicles needed
- Better performance at cold temperatures
- Not an animal attractant
- Reduces need for salt and/or sand
- Public feedback
- Other (please specify)

Do you have any additional information, cost or benefit values or thoughts on Calcium Chloride that you would like to share?

What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- Cost
- Ease of use
- Effectiveness
- Availability
- Reduced impacts (environment, corrosion, etc.)
- Meets Level of Service objective
- Public feedback
- Other (please specify)

Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., salt brine, mag, calcium, blended products, prewet/ pretreated, or corrosion inhibited)?

If this is the only material that information is being sought for from the contact, be sure to thank them for their time and assistance.

<u>Blended Products</u>

Contact Information

- Name:
- Agency (Region)/Title:
- Phone Number:

Please provide some basic background on your agency and operations:

- Number of plow vehicles
- Number of winter maintenance practitioners/employees (incl. full and part time winter maintenance employees)
- Number of lane miles maintained
- Number of winter storm events per season
- Average annual accumulative snow depth (inches)

What types of blended products (in any form) do you use in your operations?

Are the blended products you use uninhibited or inhibited?

What application rate(s) is used when applying blended products (per lane mile)? Please list rates for each product used separately.

How much do you pay for the blended product(s) being used (per gallon or ton)? Please list the price of each product used separately.

What equipment do you use to apply blended products? Please list the equipment used for each product separately.

How do you use blended products and where do you use them? Please list the uses of different products separately.

Have you applied blended products in combination with other products (like prewetting)? Please consider the different applications for all forms of blended products used.

What Level of Service is achieved by the form(s) of blended product being used in your operations? (please describe)? Please specify the LOS achieved for all forms of blended product used separately.

Do you have any information on the number of applications needed for the form(s) of blended products used to achieve an LOS for a given condition versus another product?

Please provide an estimate of the annual cost associated blended product operations at your agency (equipment, materials, labor, etc.):

Which of the following aspects associated with using blended products are of concern? (very, somewhat or not important)

- Cost of material itself
- More difficult to handle and/or apply
- Environmental impacts to the roadside
- Pavement deterioration

- Public feedback
- Increased corrosion
- Other (please specify)

Which of the following benefits have you observed or experienced from using blended products? (very, somewhat or not important)

- Cost savings
- Improved safety
- Reduced amount of product used
- Longer lasting applications
- Reduced number of application vehicles needed
- Better performance at cold temperatures
- Not an animal attractant
- Reduces need for salt and/or sand
- Public feedback
- Other (please specify)

Do you have any additional information, cost or benefit values or thoughts on blended products that you would like to share?

What factors aid in the decision of what snow and ice control products are used? (Select all that apply)

- Cost
- Ease of use
- Effectiveness
- Availability
- Reduced impacts (environment, corrosion, etc.)
- Meets Level of Service objective
- Public feedback
- Other (please specify)

Has your agency modified its snow and ice control products selection to better meet the prescribed level of service?

Please explain what products were used, what product you switched to, why, and if the switch has proven to be more effective.

Has your agency received any feedback (positive, negative, constructive) on any of the products used (e.g., salt brine, mag, calcium, blended products, prewet/ pretreated, or corrosion inhibited)?

If this is the only material that information is being sought for from the contact, be sure to thank them for their time and assistance.

Appendix B
Survey and Follow-up Survey Results

Preliminary Survey Results

A total of 34 responses were obtained from various agencies throughout the United States. This included 18 state agencies (DOTs, some providing multiple responses), 7 counties and 3 towns/cities/public works entities. State DOTs responding to the survey included Colorado (1 response), Idaho (2 responses), Illinois (1 response), Iowa (1 response), Kansas (1 response), Kentucky (1 response), Missouri (1 response), Montana (1 response), Nebraska (1 response), New Hampshire (1 response), New York (1 response), North Dakota (2 responses), Ohio (1 response), Oregon (1 response), Vermont (2 responses), Virginia (1 response), Washington (3 responses) and Wyoming (2 responses). All of these states, with the exception of Kentucky, are Clear Roads member states, representing 59 percent participation from the overall group. All 7 of the respondent counties were from Wisconsin and included Fond du Lac, Green, Iowa, Oconto, Oneida, Ozaukee and Waukesha counties. Finally, municipalities responding to the survey included the Town of Heath, Massachusetts/Massachusetts Local Technical Assistance Program (LTAP), the City of West Des Moines, Iowa and the City of Cedar Rapids, Iowa.

Agency Background

The initial information provided by respondents pertained to the background of their agency's winter maintenance operation. General information including number of plow vehicles, number of employees, lane miles maintained, average number of storms per winter and average snow depth per winter were obtained. The number of plow vehicles operated varied by entity and ranged between 6 (Town of Heath, Massachusetts) and 11,993 (Virginia DOT). In one case (New Hampshire DOT), the number of vehicles reported included contractors. All responses taken together produced an average of 821 plows in use per entity. On average, state DOTs employed 1,162 plow vehicles, although this number was influenced by the overall responses coming in some cases from the statewide level and in other cases, the district or garage/shed/depot level. Vehicle numbers reported by county-level respondents were more consistent, with an average of 35 plows employed. Finally, respondents from municipalities reported an average of 40 plow vehicles in use, although this number was heavily influenced by the 95 plows in use by the City of Cedar Rapids, Iowa versus the 6 in use in Heath, Massachusetts.

Respondents were also asked for information on the number of personnel assigned to winter maintenance operations, including both full and part time employees. The number of personnel assigned to winter maintenance operations varied, depending on the size of the entity. Personnel ranged from 6 (Town of Heath, Massachusetts) to 15,000 (Virginia DOT). The average number of state DOT personnel reported was 1,965, while the county average was 43 and the city/municipal average 53. In the case of the New Hampshire DOT, the figure reported also included contractor/hired drivers, and these were not broken out separately.

The amount of lane miles maintained by an entity plays a significant role in the extent and costs of winter maintenance. In light of this, information was sought from respondents regarding the lane miles maintained by their entity. At the state level, the total lane miles maintained ranged from 730 to 76,000. Bear in mind that these figures reflect the position of the respondent, which in some cases was the statewide level and in other cases, the district or garage/shed/depot level. The average lane miles maintained by state DOTs was 22,432. As one would expect, the average lane miles for counties and cities/ municipalities was lower, being 1,334 and 501 miles, respectively.

Another items of interest to the work was the average number of storm events per winter season (i.e. October through March) faced by each responding agency. A total of 21 agencies provided feedback on the number of storms that occurred, with remaining agencies not providing any information and others indicating they had not tracked this data element. On average, all responding agencies experienced an average of approximately 31 storms per season. State DOTs indicated an average of 32 storms per season, while counties reported 31 storms and cities/municipalities reported 30 storms.

In line with information on the number of storms that occurred, the average total depth of snowfall for an entire winter season was also of interest. As one would expect, the range of values for snow depth varied, ranging from 10 to 12 inches up to 300 inches (on mountain passes). A total of 26 agencies provided feedback on snow depth, with remaining agencies not providing any information. State DOT's reported an average snowfall depth of 56 inches, while counties reported an average of 71 inches and cities/municipalities reported 46 inches.

Basic Practices

Basic winter maintenance practices were those that centered on the use of plowing and abrasives to address storm events. In developing the survey, it was expected that all responding agencies would incorporate these practices to some extent, and this was confirmed by the responses received. A total of 33 respondents indicated that their agency used plowing and/or abrasives in winter maintenance operations, while 1 respondent indicated that their agency did not use plowing or abrasives (incidentally no further survey responses were provided by this particular agency).

Given that plowing and abrasive use are basic procedures, the Level of Service (LOS) achieved through their use was of interest. To this end, respondents were asked what their agency's LOS was using practices already in place (which may include chemical use) versus what it would be if only plowing and/or abrasives were used. Summaries of the relevant information provided that was pertinent to answering this questions included:

- High level, moderate at best without chemical treatment.
- Plowing and abrasives only would not permit us to recover roads as quickly.
- Our LOS is dependent on AADT. If we were to only utilize plowing and abrasive treatments our LOS would be reduced.
- Abrasives are almost exclusively used at low temperature.
- Level of service varies by roadway type, however the only roads that currently are only plowed and treated with abrasives are type 5 roads that are no salt roads and is restricted to roads with less than 1,000 vehicles daily, with concurrence of the local public officials.
- Current LOS: A. Sand & Plow LOS: C.
- It is expected to have certain roads bare pavement after a storm in a certain time frame, the use of abrasives only would make that impossible. If we went strictly to abrasives it would be difficult and costly to still deliver this LOS.

- The Transportation Commission has demanded LOS B for the past several years. Using only plowing and abrasives, we would not be able to attain this LOS. Our LOS would be in the D area, snow-packed, icy in spots.
- Only plowing and/or abrasives would not ensure the safety and the mobility of the public as well.
- Would not be able to achieve our LOS using only plowing or abrasives.
- Current level of service for snow and ice control is to maintain reasonably safe and passible highways, preventing hard pack and keeping snow plowable. Using abrasives tends to promote hard pack conditions. Therefore LOS would not be maintained to our standards.
- Our level of service would degrade significantly, particularly on the continuous operations routes, if we employed only plowing and abrasive use.

As these responses indicate, the use of only plowing and abrasives in winter maintenance operations would lead to a deteriorated LOS compared to the established guidelines of agencies. In two cases, respondents indicated that LOS would be C or D (Washington State and Colorado, respectively) if only plowing and abrasives were used. Still, one respondent indicated that abrasives are almost exclusively used at low temperatures, while another certain "no salt roads" those with less than 1,000 vehicles per day. In light of this, the use of plowing and abrasives does occur, but LOS should be expected to be low and other considerations, such as low traffic volumes and/or environmental concerns can lead to the use of these approaches separate from chemicals.

Next, respondents were asked what the impact of using plowing and abrasives has been on the mobility of the public. Summaries of the relevant information provided that was pertinent to answering this questions included:

- Slower.
- Decreased LOS negatively impacts traveler mobility during and after winter storm events.
- If we are only using abrasives and not using chlorides, mobility would be impacted.
- Drive slower on pack.
- Lowered.
- Using abrasives tends to promote hard pack conditions that need to be avoided. This negatively impacts mobility. However during extremely cold weather, abrasives can be a benefit when salt is ineffective, by providing some traction on problem areas such as hills and intersections.
- If we used only plowing and abrasives there would a much longer time to meet this objective, resulting in reduced mobility.

As these responses indicate, the impacts on public mobility would be significant based on the experience or assumptions of the respondents. Vehicles would be expected to travel slower, and bare pavement would not be achieved. Instead, snow pack would persist and it would take longer to achieve a higher LOS than if chemicals were employed. However, one respondent did point out that abrasives have a benefit over salt in extremely cold weather, providing traction in problem areas such as hills and intersections. Consequently, there is some acknowledgement that abrasives (used with plowing) have their place in winter maintenance, but that use should be limited to spot treatments or extremely low temperatures.

With respect to plowing and abrasives, respondents were next asked whether their agency had observed a reduction in crashes using these practices compared to other winter maintenance practices. Those who responded to this question (19 agencies) were unsure whether plowing and abrasives had an impact on reducing crashes or indicated that they made some difference, but not as much as chemicals do. A common indication from respondents was that crashes during winter weather were not tracked, and so the impacts of different approaches were not immediately clear.

Next, respondents were asked whether they had any information to share regarding the number of passes or applications needed to achieve an LOS for a given condition using plowing and abrasives versus another practice. Most respondents indicated that they did not have such information available. However, those that did provide feedback indicated that more passes and applications would be required when using plowing and abrasives than if salt or other chemicals were used.

Plowing

With background on the operation itself provided, respondents were asked for information specific to plow and abrasive use. First, respondents were asked if their agency employed plowing in their winter maintenance operations. All agencies responding to the survey indicated that plowing was in use. Next, respondents were asked what types of plows were used by their agency. As the results of Figure 6 illustrate, front plows, wing plows and motor graders were the most commonly used pieces of plowing equipment. Underbody and tow plows saw lower use, but were still employed by a fair number of agencies. Items listed as “Other” included front end loaders, snow cats, tractors with plows, and sidewalk plows.

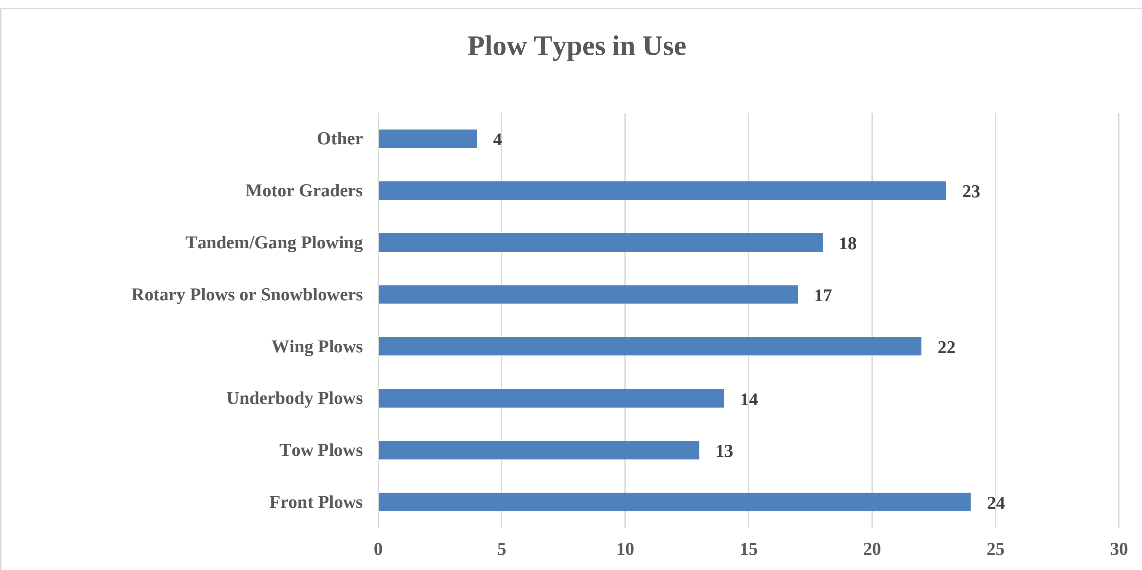

Figure 6: Types of plows in use by agencies

The costs associated with plowing were also of interest. Respondents were asked to provide an estimate of the annual average cost per lane mile of responsibility to plow at their agency. A total of 11 agencies provided feedback on this cost, with the annual average cost per lane mile for plowing being $1,335. For state DOTs, the average was $1,353 (8 agencies), while counties had an average of cost of $882 (2 agencies) and cities and average of $251 (1 agency). It is believed that the higher response rate from state DOTs is the result of better data collection and recording procedures being in place compared to smaller municipal entities. Still, the feedback to this question provides a useful element in better understanding the costs of plowing.

The importance of different aspects of plowing were next rated by respondents. The ability to remove snow and ice from the road was very important to 22 respondents and somewhat important to 1 respondent. The ability of plowing to reduce the number of vehicle passes was very important to 17 respondents and somewhat important to 7 respondents. The ability of plowing to reduce treatment material usage was very important to 19 respondents and somewhat important to 4 respondents. The ability of plowing to reduce personnel hours was very important to 17 respondents and somewhat important to 6 respondents. Finally, supplemental comments from one respondent indicated that the ability of plowing to reduce operator fatigue was important.

Next, the type of plow blade inserts being used was asked of respondents (Figure 7). In many cases, respondents indicated more than one blade type was in use. The most common blade in use was carbide steel, used by 22 agencies. This was followed by combination blades, which used multiple materials together, such as rubber steel and carbide, which were used by 15 agencies. A fair number of agencies reported using standard steel blades, while only a limited number used full rubber, rubber encased steel or ceramic blades. Finally, one respondent used a multi-sectional articulating blade type (JOMA and PolarFLEX).

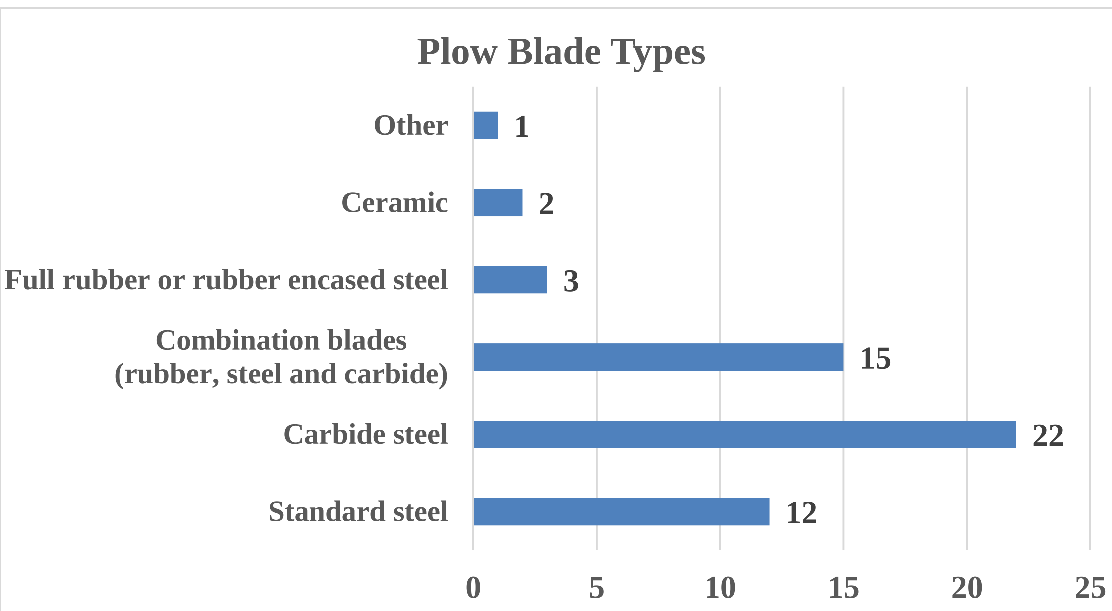

Figure 7: Plow blade types in use by agencies

The lifespan of each blade type expressed in miles was the next piece of information sought from respondents. Specifically, respondents were asked how many plow miles their agency achieved per blade set. Most respondents did not provide a specific mileage; rather, they indicated that blade life “varies”. Summaries of the relevant information provided that was pertinent to answering this question (with blade type in parentheses) included:

- Without cover blades and with plow saver valve we can push 3600 miles with a set (carbide steel).
- In an average winter, we will go through 1 set of blades (combination blades).
- 4000-5000 (carbide steel, combination blades).
- Unsure for miles, normally 40 to 50 hours on state roads (standard steel blades) [equates to 1200 to 1500 miles].
- 300+ depends on surface conditions (combination blades).
- It varies widely, high performance blades such as the JOMA 6000 can last multiple seasons. Rubber blades may only make a few passes. (carbide, rubber blades).
- Varies by type of blade. JOMA's last 4-8 times as long as standard carbide. (carbide, combination blades).
- Depends on storm - 32 [units not specified, may be hours].
- 5000 [type not specified in earlier responses].

As these results indicate, the life of specific blade types can vary greatly. Carbide blades were indicated to last 3,600+ miles, steel blades from 1,200 to 1,500 miles and combination blades (specific material not indicated) 300 miles. The life of full rubber and ceramic blades was not provided by any respondent.

The time required to change a blade factors into the cost of plowing. In light of this, respondents were asked approximately how many man hours were required to replace blade inserts for one truck. Responses to this question were straightforward, with the average reported time for blade changes being 1 to 2 hours. Standard steel blades were reported to require ½ to 2 hours to change, carbide steel blades 1 to 2 hours, combination blades 4 to 5 hours, full rubber blades 1 to 2 hours and ceramic blades 1 to 2 hours. Aside from the time required for combination blade changes, the 1 to 2 hour threshold appears to be fairly standard across blade types. The hourly loaded labor rate for the staff charged with changing blades averaged $31.21 ranged from $19.00 to $40.00.

Finally, respondents were asked for any additional feedback they might have on the specific costs or benefits (ex. effective for snow and ice removal, expensive to replace inserts, etc.) regarding plowing, plow types, and blade inserts. This was an open-ended question, and the responses received included:

- We studied the use of cover blades and without cover blades, also use of front plow hydraulic control valve or not, if properly utilized and enforced, we can triple blade life without cover blades and with plow saver valve versus cover blade without valve, or no valve with cover blade.
- From 2013 reports WYDOT average 3 12 foot blades sets per truck.
- Will only use Joma Blades. Cleaning of roadway is best and longevity of blade life has led us to this determination.
- The winter guard and Joma Black cats are good for their noise reduction and vibration reduction on the plows also reduce operator fatigue.
- Operator training and buy in is curtail to efficient/effective operations.
- The high performance blades Joma 6000 and Polar Flex clear pavement better. They reduce operator fatigue because of reduced noise, shock and vibration. They also last much long than other blades. Our standard carbide blades are the dowel type from Kennametal.

- The longer a blade lasts the less injuries your employees suffer replacing blades.
- Plow set up is critical to the effectiveness of a plowing strategy.
- Multi sectional blades, to be specific JOMA has reduced our down time and increased safety due to more snow and ice being removed. We also now use less salt because of this.

As these responses indicate, combination blades are viewed to provide the benefits of reduced noise, vibration and driver fatigue while also having a longer life. One other benefit from the use of a longer lasting blade was identified as a reduction in employee injuries during the course of changing blades (less changes equals less opportunity for injury).

Abrasives

Abrasive use formed the second component of the basic winter maintenance activities considered by the survey. In light of this, respondents were asked whether their agency employed abrasives as part of their maintenance activities. A total of 23 respondents indicated that their agency uses abrasives in their winter maintenance operations, while 1 agency indicated it did not. For those agencies that indicated abrasives were used, it was of interest the location(s) or situations where such materials were employed. Figure 8 presents the locations where agencies indicated they were applying abrasives. Abrasives were most commonly cited as being used on hills, followed by low temperature events, shaded areas intersection approaches and curves. Only a limited number of respondents indicated system-wide use of abrasives as opposed to spot treatments. However, use during low temperature events the use of abrasives could move to system-wide, although respondents were not asked to give an indication of whether this could be the case. "Other" locations where abrasives were indicated as being used included locations affected on a case by case basis by temperatures and blowing, under the direction of the deputy director, low salt areas, low volume roads, locations outside of PM 10 (particulate matter) attainment areas and on gravel roads.

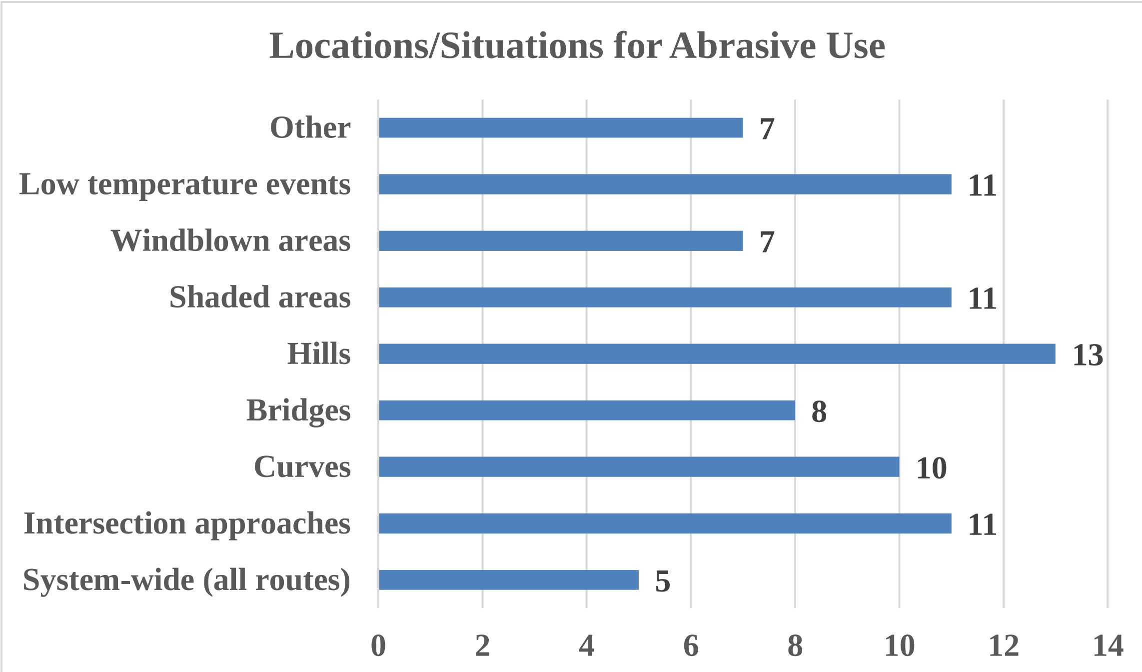

Figure 8: Locations where abrasives are used

Next, respondents were asked what abrasive materials their agency used. Nine respondents indicated that their agency used abrasives without a salt mix, while 19 agencies used an abrasive-salt mix. When abrasive-salt mixes were used, the average of salt versus abrasives used was 21 percent. The range of mixtures was 7 percent salt to 93 percent abrasive to 50 percent salt to 50 percent abrasive. Abrasive gradations/sizes ranged from 1/4 inch to 1/2 inch, with the most common size being 3/8 inch. Minus 4 gradation, #9 stone and #20 sieve were also cited as abrasive sizes, but these were limited.

The cost of abrasives is of particular interest given that they are a low-cost treatment option. In light of this, respondents were asked to provide information on the average cost per ton of abrasives and abrasive-salt mixtures used by their agency. Abrasive costs per ton were an average of $9.32, with reported prices ranging from $4.00 to $16.00 per ton. Abrasive-salt mixes had an average cost of $20.86 per ton, with reported prices ranging from $15.00 to $35.00 per ton.

The quantity of abrasives used each year were of interest to this work. Consequently, respondents were asked how many tons of abrasives (straight and/or salt-mixed) were applied annually by their agency. Respondents indicated that their agency used anywhere from 50 tons up to 358,371 tons of abrasives and abrasive-salt mixes total, with an average tonnage of 59,521.

The use of abrasives may be done to achieve different benefits. In light of this, respondents were asked how important different benefits of using abrasives were from their perspective. A large number of respondents indicated that the ability to provide traction was a very or somewhat important benefit of abrasives. Figure 9 illustrates the responses to this question. Most respondents indicated that ease of application was an important benefit of abrasives, although some did not consider it a benefit. The low cost of the material was viewed by an equal number of respondents as being a very or somewhat important benefit of abrasives as well. Other comments provided respondents indicated that low temperature performance, visibility to the public (shows that an application was made), absorbance of solar radiation to aid in melting and being a material that can remain on gravel roads after winter were also considered to be benefits of abrasives.

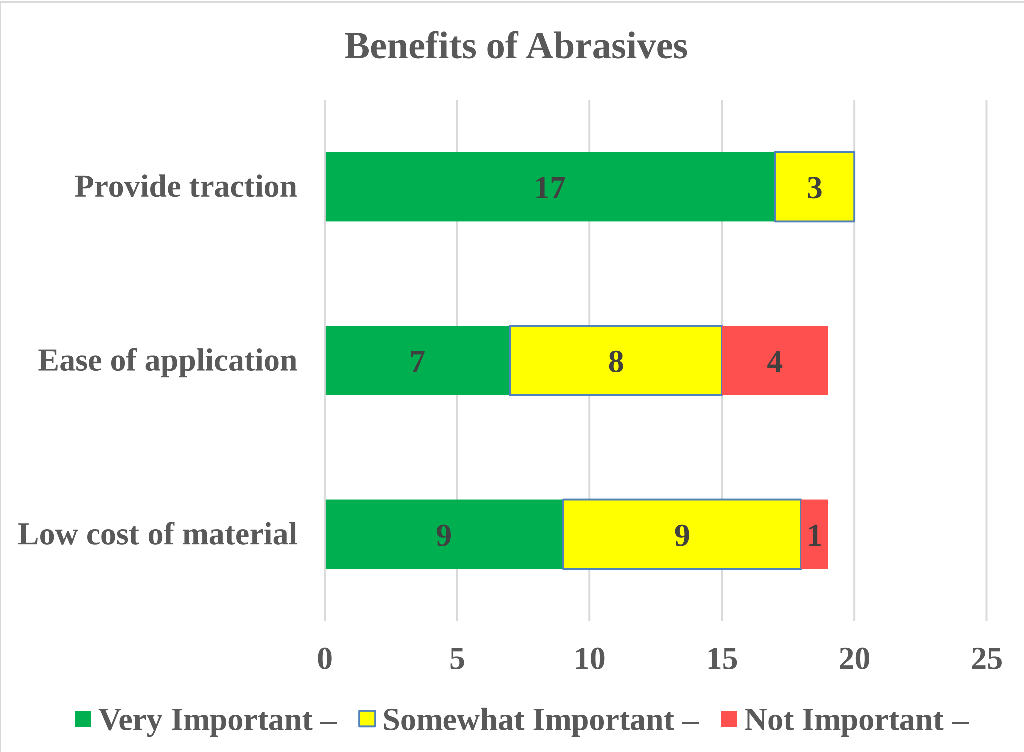

Figure 9: Benefits of abrasives

Abrasives are a material that remains after the winter season, and it was also of interest to see if agencies performed any abrasive clean-up activities in the spring. A nearly even split among respondents was made to this question, with 11 indicating their agency had a clean-up program in place while 10 agencies did not. A total of 11 respondents indicated agency staff performed these operations, while three respondents indicated that their agency contracted out clean-up activities to private firms. The average clean-up cost per mile was $85.66, with reported costs ranging from $62.95 to $120.00 per mile. Disposal costs were indicated as being factored into these figures, although some respondents indicated that the cost was $0.00 and that abrasives were reused to maintain shoulders. When asked if the abrasives were recycled, 4 respondents indicated that they were, while 3 indicated they were not. Only one respondent commented that the abrasives were reused with new stockpiles during the following winter season. Other respondents indicated that abrasives were recycled for use as shoulder material, construction of berms and as fill.

Respondents were also asked for feedback on the importance of the negative aspects of using abrasives. Figure 10 illustrates the feedback received regarding this question. As the figure illustrates, the entry of abrasives into waterways was very or somewhat important to the highest number of respondents. The inability of abrasives to provide deicing capacity was very or somewhat important to most respondents. Similarly, increases to dust/air pollution were a concern. Finally, windshield damage was acknowledged by most respondents, although it was generally not viewed by most as being a very important negative of abrasives. Finally, one respondent provided the comment that the costs of clean-up and the potential to clog drainage systems were also negative aspects of abrasives.

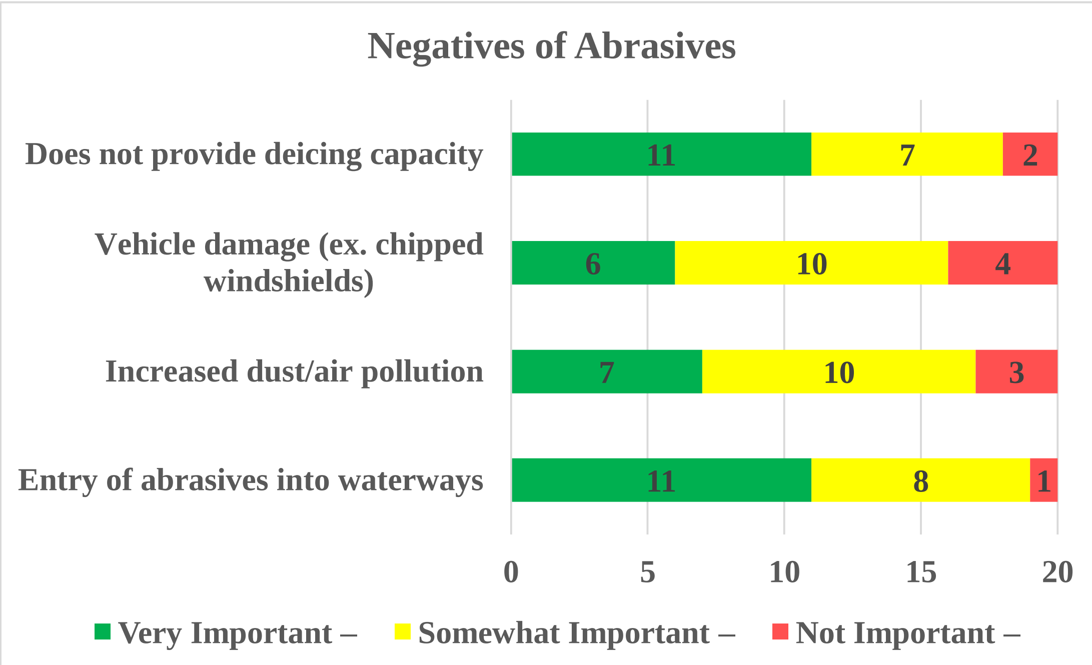

Figure 10: Negative aspects of abrasives

Finally, respondents were asked if they had any more information or values for the benefits or costs of abrasive use. One respondent indicated that broken windshield claims from abrasive use were $5,000 annually. Another respondent indicated that their agency was able to save $20,000 to $30,000 annually by removing all abrasives from use on black top roads and using them only on gravel roads. This was on a system of 108 lane miles, so the savings from eliminating abrasive use would be $185 to $277 per lane mile.

Intermediate Practices

Intermediate winter maintenance practices were those that employed the use of solid salt (NaCl) or salt brine for anti-icing and deicing (in addition to basic activities such as plowing and spot abrasive use). A total of 23 respondents indicated their agency used intermediate practices, while zero respondents indicated that their agency did not use such practices. Those who indicated their agency used Intermediate practices were asked what their agency's LOS using current practices was and what would it be using only Intermediate practices. Summaries of the relevant information provided that was pertinent to answering this questions included:

- No change.
- If we used more of the intermediate practices we would be able to recover roads quicker.

- MDT currently uses multiple strategies. If we were to employ only intermediate practices as defined in this survey our LOS would decrease. It's necessary to use the right tool at the right time and place to achieve the best results.
- Main application in NH is salt. Abrasives are the exception. Those roads that are type 1-A to type 4 use virtually only salt unless temperatures are too low in which a sand/salt mix is applied to allow traction.
- LOS B as before.
- Our level of service would be decreased some using these intermediate practices, however using the anti-icing and deicing capabilities of salt or salt brine can achieve a decent level of service.
- This District went all road salt or brine usage in 2009, level of service has increased during this period.

As these responses indicate, there was not a clear picture provided regarding the impacts of using salt/salt brine versus other approaches (ex. abrasives, advanced chemicals). One respondent indicated that LOS B would be achieved using intermediate practices, which is generally what would be expected using deicing agent in addition to plowing to maintain a roadway surface. This was further confirmed by supplemental reports and documents provided by respondents. Other respondents indicated that the use of intermediate practices would produce an acceptable LOS, which indicates that the use of salt in lieu of or in addition to abrasives produces a better LOS than plowing and abrasives alone would.

Next, respondents were asked to describe what the impact of Intermediate practices been on the mobility of the public. Summaries of the relevant information provided that was pertinent to answering this questions included:

- Increased LOS over basic practice.
- Maintain bare roads after a storm versus season long pack.
- Seems to work very well.
- The mobility of the travelling public has improved.
- Within 12 hours full mobility.
- Increased mobility and safety.
- Positive impact; salt works well to maintain desired LOS.
- Mobility has been greatly improved with the use of these intermediate practices. We can in most cases prevent the bonding of snow to the pavement and can melt accumulated snow and ice through the use of salt and salt brine.
- Winter mobility measured in Idaho as percent of time water is on the roadway below 32 degrees, mobility in District 5 has been 2010-2011 - 51%, 2011-2012 - 60%, 2012-2013 - 68% and 2013-2014 -78%.

As these responses indicate, the use of Intermediate practices has improved public mobility compared to basic practices. As one would expect, the capacity of salt/salt brine to facilitate melting and produce bare pavement has a significant impact when used with other approaches (ex. plowing) to assure public mobility in a reasonable time period following a storm event.

It was also of interest to better understand the safety impacts (i.e. crash occurrence) of Intermediate versus other practices. In light of this, the next question asked respondents if their agency observed a reduction in crashes using Intermediate practices compared to other winter maintenance practices. Summaries of the relevant information provided that was pertinent to answering this questions included:

- No change.
- Yes.
- Yes.
- We have not quantified this. As the LOS improves so does the traffic count and travel speed which could account for more accidents.
- Yes, compared to abrasives and plowing only intermediate practices are an improvement.
- Yes.
- Yes.
- This is the only practice we use. No observed impact on crash records.
- Yes.
- Yes, reports submitted.

As the responses received indicate, the use of Intermediate practices was viewed as being more beneficial to safety than other practices. However, caution should be taken in interpreting these responses, as respondents may have been thinking of basic practices in this comparison as it was the only alternative presented by the survey questions at this point in the survey. Still, the responses are logical, as the use of salt/salt brine produces a better road surface compared to the use of abrasives and plowing alone. Consequently, a better road surface should result in fewer crashes compared to a snow packed surface.

Respondents were next asked if they had any information on the number of applications needed to achieve an LOS for a given condition using Intermediate versus another practice. Nearly all respondents indicated that they did not have such information available. Some of these respondents further indicated that the number of applications needed was dependent on the type of storm, length of storm, temperatures, wind, precipitation type and so forth. Still, one respondent did indicate that the use of salt had reduced the number of applications by 2 to 3 over abrasives.

<u>Solid Salt</u>

The use of solid salt versus salt brine was the next focus of the survey questions. A total of 20 respondents indicated that their agency used solid salt, while two indicated solid salt was not used. The average quantity of salt used by agencies was 183,500 tons, with a range of 500 tons (county) to 800,000 tons (state DOT) reported. The approximate cost of salt per ton (delivered) averaged $71.04, with the range of reported costs being $48.63 to $90.00. Application rates varied widely by agency, ranging from 25 pounds per lane mile up to 600 pounds per lane mile. These rates vary based on the nature of the storm being addressed, which explains the wide range of values reported by respondents.

The next item that feedback was sought on regarded the views of respondents on the importance of different aspects associated with the use of salt. The results of this question are presented in Figure 11. In most cases, the aspects cited were very or somewhat important to the respondent and their agency. The exception was the difficulty in applying or handling salt, which was largely rated as not important to respondents. In addition to the different aspects cited, additional feedback from respondents included indication that the public expected salt to be used, do not over apply salt for environmental or corrosion concerns, and that the use of spinners had been discontinued on 90 percent of the vehicles since they threw material onto the shoulder and foreslopes rather than the road itself.

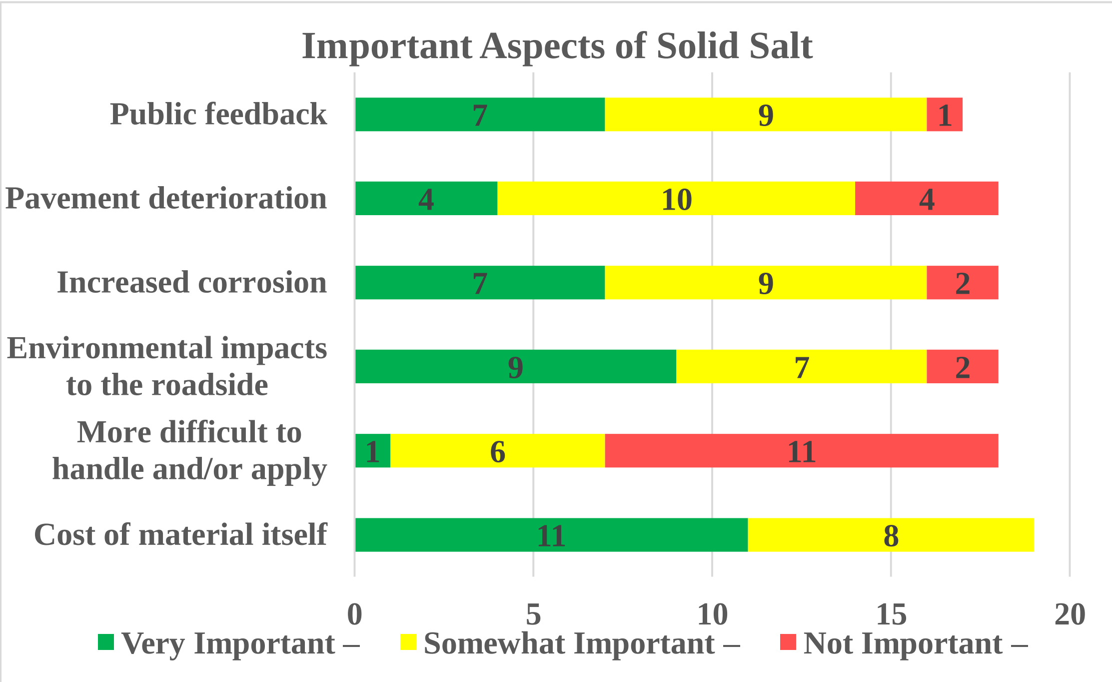

Figure 11: Importance of various aspects of solid salt

Next, respondents provided feedback on the benefits associated with the use of salt. The results of this question are presented in Figure 12. As the figure illustrates, respondents indicated that cost, ease of use, snow and ice clearance and melting capacity were all very or somewhat important. In the case of melting capacity and snow and ice clearance, respondents were unanimous regarding the importance of solid salt. An additional benefit provided by one respondent was that solid salt has a lower purchase cost than other deicing materials.

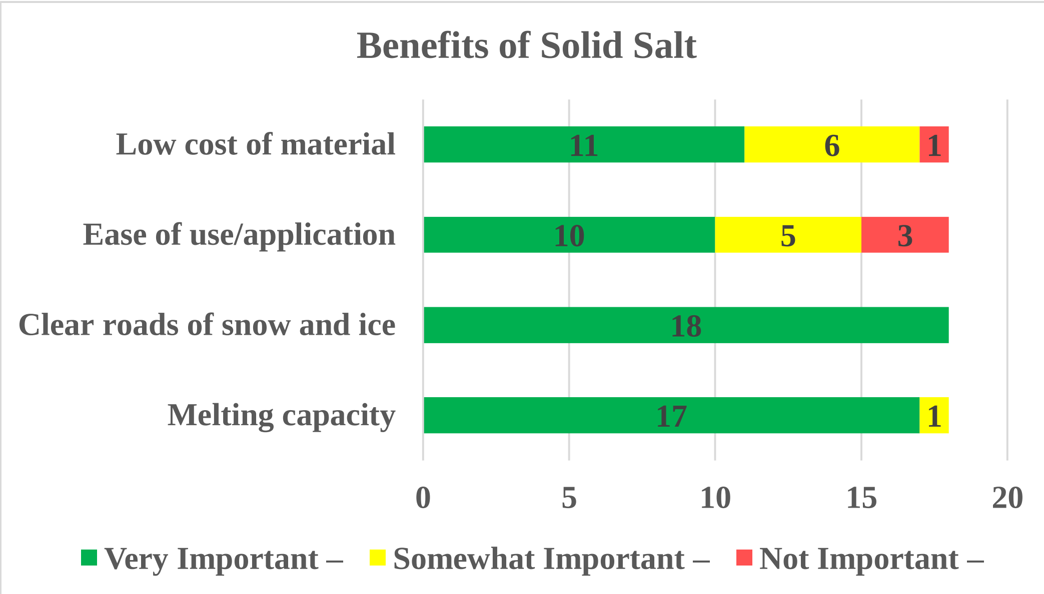

Figure 12: Benefits of solid salt

Salt/Abrasive Mixes

Next, respondents were asked if their agency used a salt/abrasive mix. A total of 19 respondents indicated that their agency did use such a mix, while 2 respondents indicated their agency did not. The average percentage of solid salt in the mixture was 26 percent, with the range being between 4.5 percent and 50 percent. Application rates varied widely by agency, ranging from 100 pounds per lane mile up to 1,200 pounds per lane mile. On average though, the rates cited by respondents were in the 200 to 400 pound per lane mile range. Again, these rates vary based on the nature of the storm being addressed, which explains the wide range of values reported by respondents.

Salt Brine

The use of salt brine by agencies was of interest to the work, and the next portion of the survey sought feedback regarding this aspect of Intermediate practices. A total of 20 respondents indicated that their agency used salt brine, while 2 respondents indicated their agency did not. On average, respondents indicated their agency used 2,371,480 gallons of brine per year, with a range of 15,000 to 15,893,383 gallons reported. Seventeen respondents indicated their agency manufactured its own brine, while 2 indicated that brine was purchased. In the 2 cases where brine was purchased, the respondent indicated that the agency also manufactured brine. The average cost of brine, including delivery was $0.16, with a range of $0.05 to $0.35 reported.

Most respondents provided feedback regarding the application of salt brine in gallons per lane mile, while a few others provided brine application rates per ton of salt (prewetting). An average application of 43 gallons per lane mile was reported by respondents, with reported rates ranging from 11 to 100 gallons per lane mile. An average of 7 gallons of brine used to prewet 1 ton of salt was cited by respondents, with a range of 6 to 10 gallons per ton.

Next, respondents were asked for feedback regarding their views toward different aspects associated with the use of salt brine. The results of this question are presented in Figure 13. As the figure illustrates, most of the aspects of salt brine were cited as being somewhat important to respondents. One exception was the difficulty in handling and applying the material, which was rated as not being an important factor by half of respondents. Additionally, a majority of respondents indicated that the cost of salt brine was a very important aspect. Additional feedback provided to this question included mention that salt brine is used because the respondent's agency wanted no complaints from the public about closed roads. Other feedback included mention that the brine being used by a particular agency was corrosion inhibited (discussed later in this text), while another indicated that their agency did not over apply due brine to environmental and corrosion concerns.

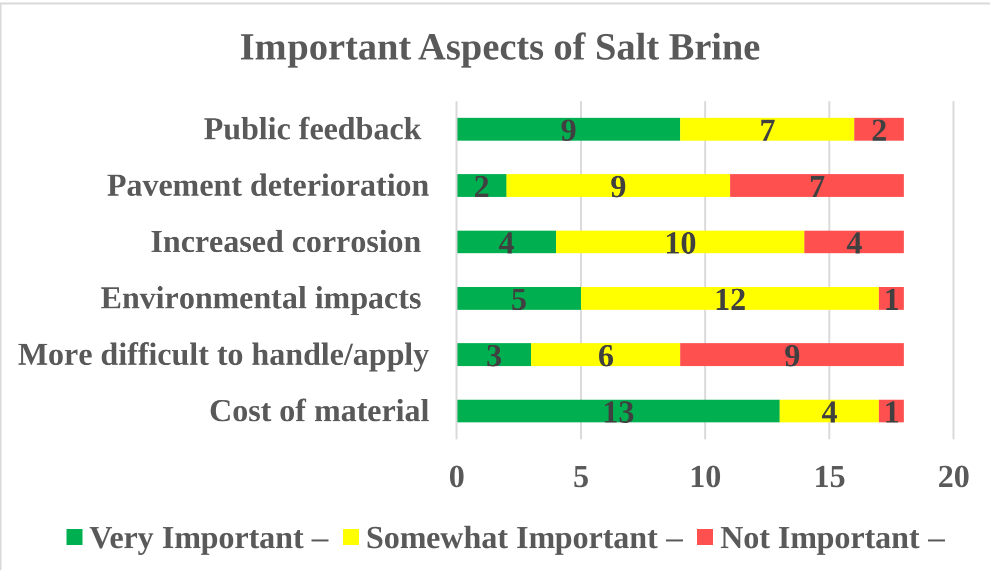

Figure 13: Importance of various aspects of solid salt

Respondents were also asked for feedback on the benefits of salt brine. The results of this question are presented in Figure 14. As the figure indicates, a majority of respondents specified that each of the aspects listed was very important. None of the respondents to the question indicated that the listed aspects were not important. Additional comments provided to this question included that brine was useful in frost prevention on bridges and roadway striping wear is reduced compared to abrasive and anti-skid usage. Further, manpower savings for roadway sweeping were produced through brine usage, and reportable accidents and slide off accidents were reduced.

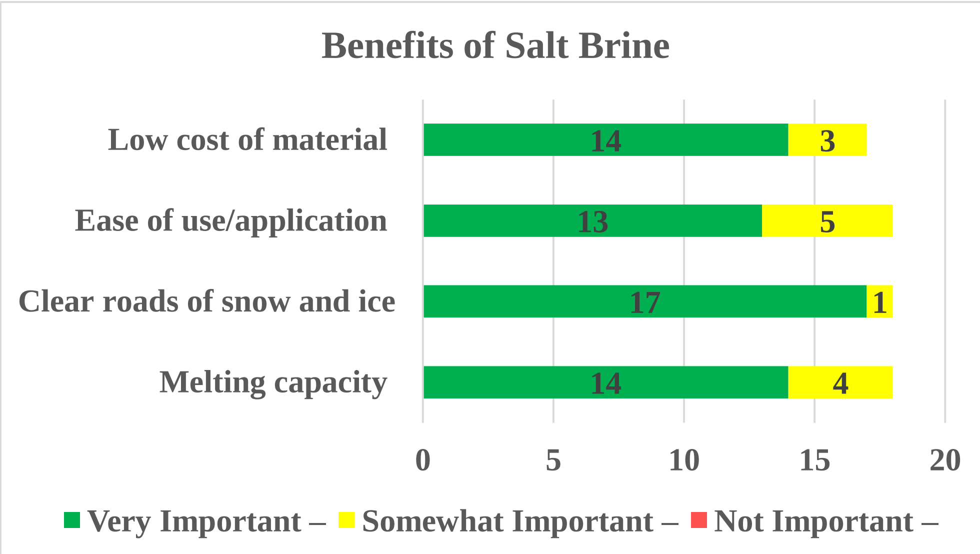

Figure 14: Benefits of salt brine

Salt brine can be used in a prewetting and pretreating capacity, so the next series of questions focused on this aspect of use. A total of 16 respondents indicated that their agency used salt brine in prewetting or pretreating operations, while 5 indicated their agency did not. Eleven respondents indicated that abrasives were prewet, 10 respondents indicated solid salt was prewet, and one respondent each indicated that Ice Slicer and an abrasive/solid salt mix were prewet. Prewetting operations were conducted at the pile by 6 agencies, at the spinner by 12 agencies, by a slurry spreader at 6 agencies and by shower wetting a truckload at 6 agencies. The brine applications made to solids were reported as gallons per ton by some respondents and as percentages by others. The average application by those who reported gallons per ton was 8.9 gallons per ton, with a range of 5 to 17.8 gallons. For those who reported use as a percentage, an average of 20 percent brine was used for prewetting solids, with a range of 10 to 23 percent. Respondents using slurry spreaders were asked if it has been able to reduce application rates, and if so by how much. Two respondents provided information for this question, with one indicating usage had decreased by 20 to 40 percent, while the other reported a decrease of 30 percent. The percentage of brine being used for direct application (i.e. pretreating roadways) was an average of 25 percent of salt brine was used in this manner, with a range of 15 to 90 percent.

Of interest to this work were the costs associated with the use of salt brine. To this end, the next survey question asked respondents to provide an estimate of the annual cost associated with producing and applying salt brine at their agency (equipment, materials, labor, etc.). Only limited information was available related to this aspect of brine use. Three respondents provided values for this question which included $326,849.50, $100,834 and $4,000,000 to $6,000,000. The lane miles maintained by each of these agencies were 23,000, 17,049 and 76,000 respectively. Based on these, general values for estimated costs associated with brine production and application on a per lane mile basis would be $14.21, $5.91 and $52.63 to $78.94, respectively. However, care must be taken to remember that these figures are on a per lane mile basis, and if the number of storms were factored in, they would likely drop significantly.

Respondents were asked for their views regarding the benefits of prewetting. The results of this question are presented in Figure 15. As the figure indicates, the primary benefits of prewetting were viewed to be achieving a faster melt on the pavement surface and reducing the amount of granular product lost to the environment because of bounce and scatter. Reductions in personnel and patrol hours were viewed to be benefits by most respondents, although both of these were listed as benefits that were not important to one respondent. Finally, reductions in the use of granular material were cited by all respondents as being very or somewhat important benefits of prewetting.

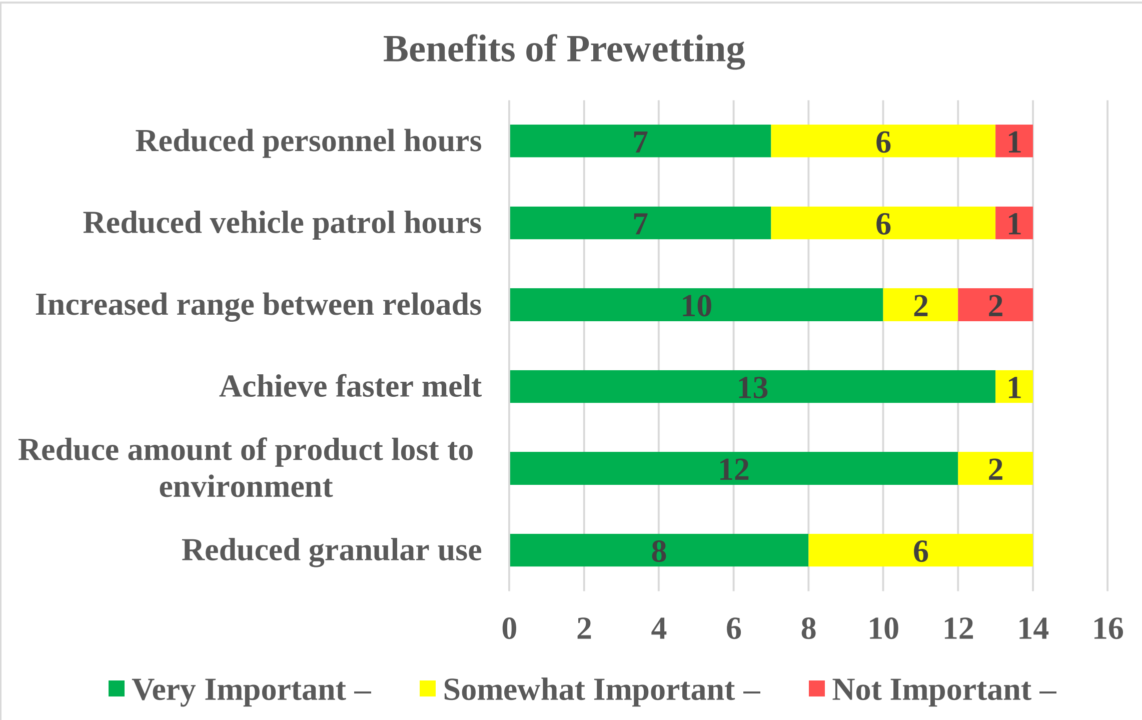

Figure 15: Benefits of prewetting

Anti-icing

The conduct of anti-icing operations using salt or salt brine was the next focus of the survey. A total of 15 respondents indicated that their agency conducted anti-icing using salt or salt brine, while 3 respondents indicated that their agency did not. The equipment used to apply anti-icers varied by agency and included tank trucks and spreader bars (7 agencies), dump trucks with tanks (9 agencies) and standard plow trucks (1 agency). Only limited information was provided by two respondents on the estimated annual costs associated salt/salt brine anti-icing operations (including equipment, materials, labor, etc.). The average cost for these operations was $68.41 per lane mile, with a range of $39.47 to $100.00 per lane mile reported.

When asked about the benefits associated with anti-icing with salt and/or salt brine, respondents replied predominantly in a positive manner. The results of the benefits associated with anti-icing are presented in Figure 16. As the figure illustrates, improved safety was universally viewed by respondents as a very important benefit of anti-icing. All other benefits were also rated as very or somewhat important by the majority of respondents, with the exception of one agency indicating that reducing the number of application vehicles needed for operations was not an important aspect of anti-icing. Additional comments provided to this question indicated that anti-icing applications on bridge decks reduce the occurrence of frost and that anti-icing applications also decrease amount of time for the salt to become active as it is already in solution and does not need to melt into a brine.

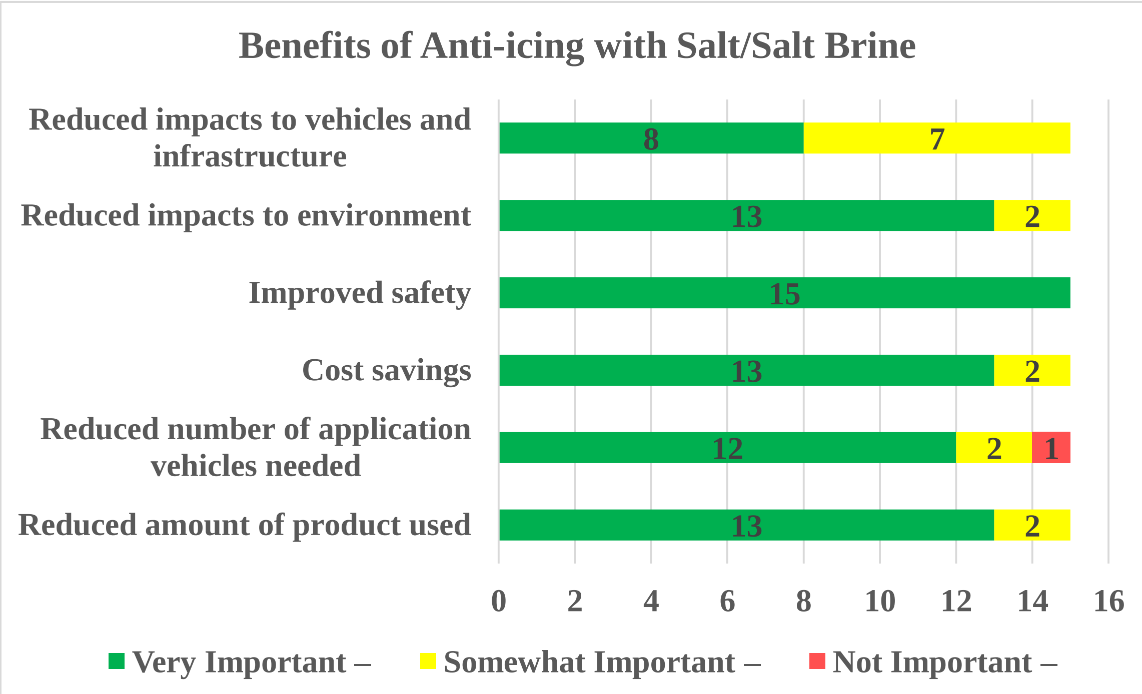

Figure 16: Benefits of anti-icing with salt / salt brine

A total of 18 respondents indicated that their agency produced its own salt brine. In line with this, the different costs associated with the production of brine were of interest. Therefore, follow-up questions were posed that sought information on the costs of brine-making such as the cost of equipment, transport, materials, maintenance, labor, etc. Unfortunately, only a limited number of respondents provided feedback to these questions, and in most cases, responses indicated that the information being sought was not available or tracked. In light of this, the following information that is presented should be considered as a supplemental point of reference and may or may not represent the true costs associated with a particular aspect of brine-making.

The average cost of brine-making equipment was $89,273, with reported costs ranging from $7,000 to $250,000. Only one response was provided regarding the cost to transport brine from a production location to another site. The respondent indicated that the cost of transport was "16-31% of haul cost (Haul cost is labor to haul, brine production cost and the cost of the transport to haul)". Input materials used in making the brine were reported by one respondent as "51-56% of haul cost" and a second respondent as $1,563,901. Fuel costs associated with the transport of brine were indicated as being included in the equipment cost by two respondents, while a third indicated a cost of $0.035 per gallon. Similarly, two respondents indicated that transport truck maintenance was included under equipment costs, while a third indicated a cost of $80.00. Finally, labor costs were cited as $50.00 (units such as per hour or season not specified), $256,245 (units not specified, but assumed to be the annual cost for all production in the respective state) and "13-18% of haul cost". As these collective values indicate, there appear to be different approaches to tracking and reporting the costs of brine-making, when values themselves are tracked. In light of these responses, it is difficult to assign a specific cost to the production of brine.

The final question sought feedback on the benefits of brine-making. The results of this question are presented in Figure 17. As the figure indicates, all aspects of brine making were rated by respondents as being very or somewhat important. The ability to make brine on an as-needed basis was the benefit most widely indicated as important by respondents. Information provided by one respondent indicated that the cost of brine per gallon was $0.10 when produced by the agency and $0.30 when purchased from a vendor. Another respondent indicated that their agency had reduced the use of salt by 30 percent when using brine.

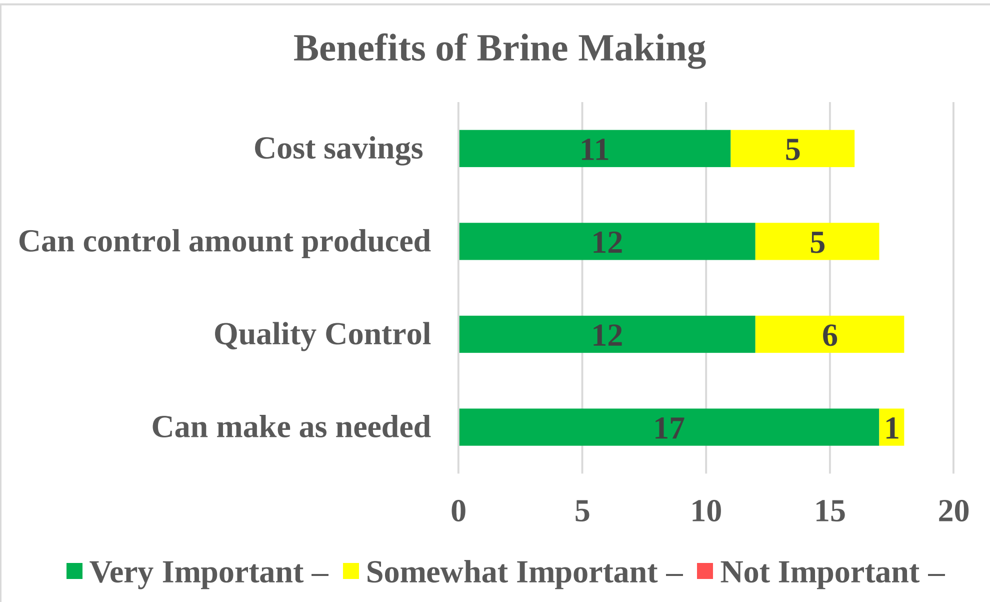

Figure 17: Benefits of brine-making

Advanced Practices

Advanced winter maintenance practices were those that employed the selection and use of alternative chemicals, corrosion-inhibited liquids and/or treated or chemically enhanced solid chemicals to match performance with environmental conditions for anti-icing and deicing (in addition to Basic and Intermediate activities such as plowing and use of salt, salt brine and/or abrasives). A total of 14 respondents indicated their agency used Advanced practices, while 7 respondents indicated that their agency did not use such practices. Those who indicated their agency used Advanced practices were asked to describe how much these practices impacted their organization's LOS.

- Ability to improve LOS in colder temps. Save on corrosion related to vehicle and infrastructure. Air and water impact reduction.

- Our use has been experimental. Where advanced practices have been tried the feedback has been positive.
- Utilizing advanced practices have allowed us to maintain a very high LOS regardless the intensity of the storm.
- We have had a dramatic reduction in corrosion to our equipment. Faster melt down of the roadways. Elimination of hard pack and the elimination of all street sweeping.
- Major impact in a positive way. Reduced crashes, more rapid melt down, no bond of frozen precipitation.
- Improves LOS at colder temperatures
- We only use beet juice as an enhancer. It has helped us in cold temperatures and also with bounce and scatter. It has had a positive impact on our level of service, but it is not quantified.

As these responses indicate, the use of Advanced practices has led to improved LOS, particularly when storm events involve colder temperatures. A specific LOS level achieved through their use was not specified by any user however. As a follow-up question, respondents were asked what the impacts of Advanced practices have been on public mobility. Once again this was an open-ended question that received written responses. Summaries of the relevant information provided included:

- Increased LOS sooner due to higher performing materials and application strategies when temperatures are below 10°F.
- Roads generally clear faster.
- Good.
- Safer roads. Fewer vehicle crashes.
- Increased mobility. Safer roads in less time.
- Improves LOS at colder temperatures.
- Allows us to provide better mobility in cold temperatures and also keep more salt on the road leading to better melting and improved mobility.

Again, these responses are indicative that Advanced practices have enhanced public mobility, particularly during colder temperature events, by producing safer roadway surfaces. Finally, respondents were asked whether any change in crashes had been observed from the use of Advanced practices. Only limited responses were provided to this question, with 4 respondents indicating that crashes had changed, 1 respondent indicating there had been no change and 2 respondents indicating that changes were unknown. In the cases where changes were indicated, no figures were provided to illustrate the extent of these perceived changes.

<u>Corrosion Inhibitors</u>

Next, the survey sought information related to specific aspects of Advanced practices, beginning with corrosion inhibitors. Corrosion is a significant impact of winter maintenance operations, affecting the equipment and infrastructure of the agency itself as well as the vehicles of the general public. To address the issue of corrosion, agencies have begun to employ corrosion inhibitors in their winter maintenance operations. To understand the extent that corrosion inhibitors were employed, respondents were first asked if their agency used corrosion inhibitors with its winter maintenance products. A total of 6 respondents indicated their agency used inhibitors, 4 indicated they were used in some locations and 4 indicated inhibitors were not used.

Next, respondents were asked what corrosion inhibiting product(s) their agency used. Responses included the following:

- Ice Ban, Apex [Envirotech].
- Frezgaurd, Headwaters.
- Ice B Gone liquid.
- Safe Melt, Triethanolamine.
- Provided by supplier within the material. Not applied or purchased separately.
- We use beet juice.

As these responses indicate, a number of different products (mostly proprietary from vendors) are employed as corrosion inhibitors.

Respondents were also asked to provide the approximate cost of the material used (per gallon or per ton). Information provided indicated the following costs for each respective product:

- Ice Ban - $0.78 per gallon.
- Headwaters [brand] - $650.00 per ton.
- Ice B Gone - $1.50 per gallon.
- Safe Melt - $1.21 per gallon.
- Beet juice - $1.25 per gallon.

Additional information related to costs provided by one respondent indicated that a tank, pump, hose and nozzle setup cost approximately $3,000.00 to facilitate stock pile treating.

The benefits of using corrosion inhibitors were the next area of focus for the survey. Respondents were asked to rate the importance of different benefits of corrosion inhibitor(s). The results for this question are presented in Figure 18. As the figure indicates, feedback from respondents indicated that all of the listed benefits of inhibitors were very or somewhat important. Reduced corrosion to the agency vehicle and equipment received a slightly more positive rating than reducing corrosion to the public's vehicles or infrastructure.

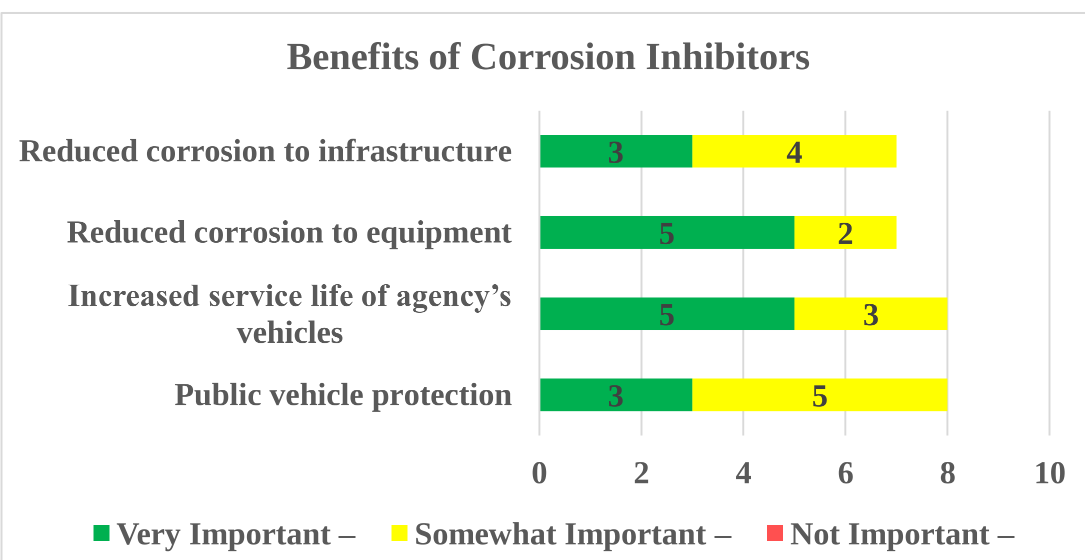

Figure 18: Benefits of corrosion inhibitors

Inhibited Salt Brine

The next portion of questions focused specifically on inhibited salt brine use. A total of 2 respondents indicated their agency used inhibited salt brine, 3 indicated it was used in some locations and 8 indicated inhibited salt brine was not used. Reported application rates averaged 36 gallons per lane mile, with a range of 25 to 60 gallons per lane mile cited. The cost of inhibited salt brine was $0.12 to $0.50 per gallon. The equipment used to apply inhibited salt brine included direct liquid application units, pre-wet solid spreaders, brine tank trucks and saddle tanks with spinners. Responses when asked when and where inhibited salt brine was used included for prewetting, anti-icing and deicing, on interstate corridors prior to a storm, and on every road. Three respondents indicated that their agency had used inhibited salt brine in a prewetting operation. No respondents had information on the number of applications needed to achieve an LOS for a given condition versus another product. Responses when asked to provide an estimate of the annual cost associated inhibited salt brine operations at an agency (equipment, materials, labor, etc.) indicated that this information was not tracked or available.

Next, respondents were asked to rate the importance of different aspects related to using inhibited salt brine. The results for this question are presented in Figure 19. Given the limited number of respondents that indicated the use of inhibited salt brine, the feedback provided to this and follow-up questions was low. As the figure indicates, environmental impacts of the material to the roadside were important to respondents, as was increased corrosion. Difficulty in handling and application was not as big of a concern to respondents. Aside from these items, remaining aspects were rated variably among respondents in terms of importance.

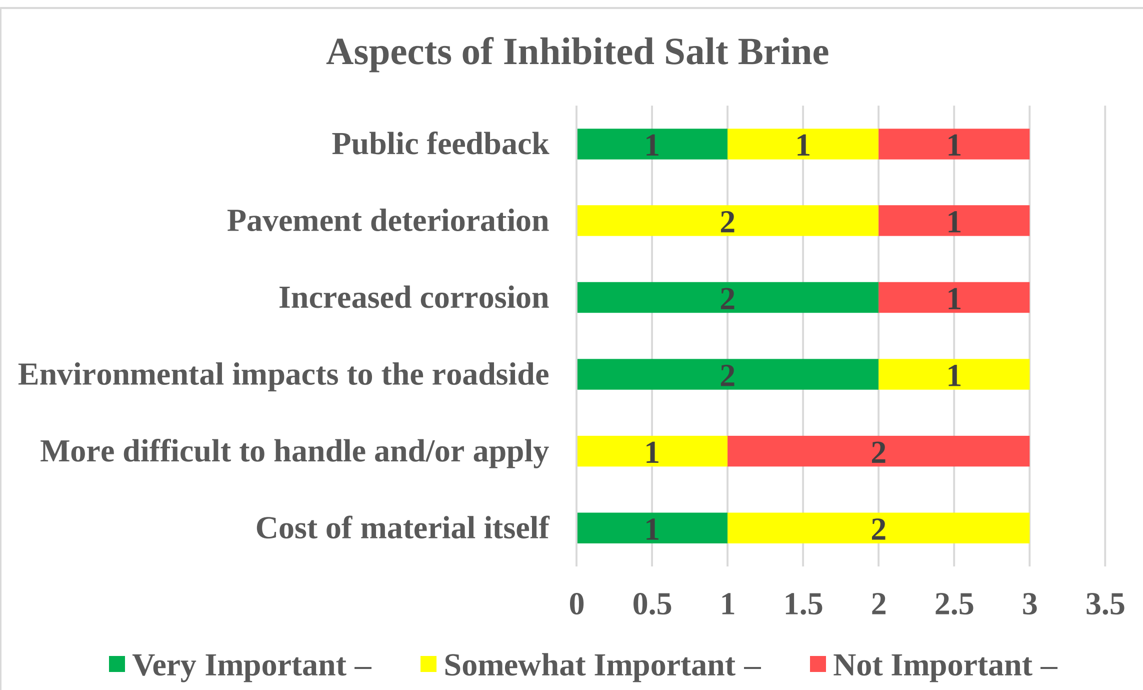

Figure 19: Importance of aspects for inhibited salt brine

A follow-up question sought feedback on the importance of the benefits related to inhibited salt brine. The feedback received to this question is presented in Figure 20. As the figure illustrates, improved safety was cited as a very important benefit by all respondents. Reduction of salt/sand use, better low temperature performance and cost savings were all rated as very or somewhat important by respondents. Reductions in the number of application vehicles was not viewed as important by 2 or the 3 respondents.

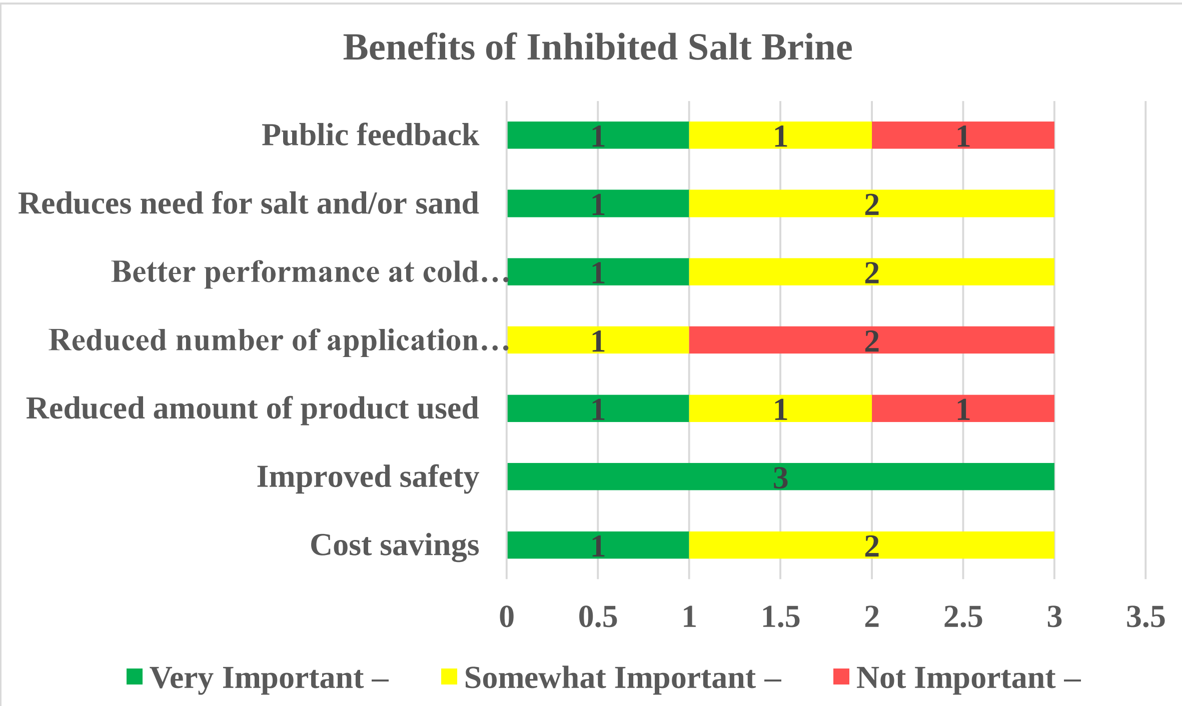

Figure 20: Benefits of inhibited salt brine

Magnesium Chloride

The next portion of the survey sought feedback on the use of Magnesium Chloride ($MgCl_2$) by agencies. A total of 10 respondents indicated that their agency used $MgCl_2$, while 3 agencies did not. Magnesium Chloride can be used in different forms, and 7 respondents indicated that their agency used an inhibited liquid, 2 indicated an uninhibited liquid was used, and 1 indicated an inhibited solid was used. No agency indicated the use of an uninhibited solid form of $MgCl_2$. Reported application rates for inhibited solids ranged from 180 to 220 pounds per lane mile (1 respondent), application rates for inhibited liquids ranged from 20 to 50 gallons per lane mile or 8 to 10 gallons per ton of solids (4 respondents), and application rates for uninhibited liquids were cited as being ½ gallon per lane mile (1 respondent). Reported costs for each material were $150 per ton for inhibited solids, $1.00 to $1.50 per gallon for inhibited liquids and $1.20 per gallon for uninhibited liquids.

The different materials were applied using standard equipment, including dump trucks and spreaders for solid materials and direct liquid application units or tanks with sprayer bars for liquid applications. Use of $MgCl_2$ included when temperatures dropped below 5 degrees Fahrenheit in trouble areas (intersections), in deicing operations at higher elevations, for prewetting/pretreating and anti-icing operations (including as a stock pile treatment), and within salt brine mixtures. Seven respondents indicated that their agency had applied $MgCl_2$ in combination with other products (like pre-wetting), while 2 respondents indicated this was not done. Most respondents indicated that their agency did not have any information on the number of $MgCl_2$ applications needed to achieve an LOS for a given condition versus other products. However, one respondent did indicate that the material in use (inhibited solid) extended the same LOS achieved by salt applications down to about -5°F to - 8°F below zero, with LOS being about the same as utilizing a sand-salt mixture at these same temperatures but for a fraction of the cost.

Only limited information was provided by respondents on the annual costs associated $MgCl_2$ operations at their agency (such as equipment, materials, labor, etc.). One respondent indicated that their agency ordered "roughly 100 ton or less [inhibited solid], so a minimal cost and operations". A second respondent (municipality) indicated their agency costs were $6,000. Aside from this information, remaining respondents indicated that this information was not tracked or broken out separately.

Next, feedback was sought regarding the importance of different aspects related to $MgCl_2$ use. Feedback to this question is presented in Figure 21. As the figure illustrates, corrosion, environmental impacts and material cost were most highly cited as being very or somewhat important concerns to respondents. In other cases, such as public feedback and pavement deterioration, most indicated that these were somewhat of a concern. The application of $MgCl_2$ presented mixed feedback regarding importance, with some respondents indicating it was an important factor while others did not.

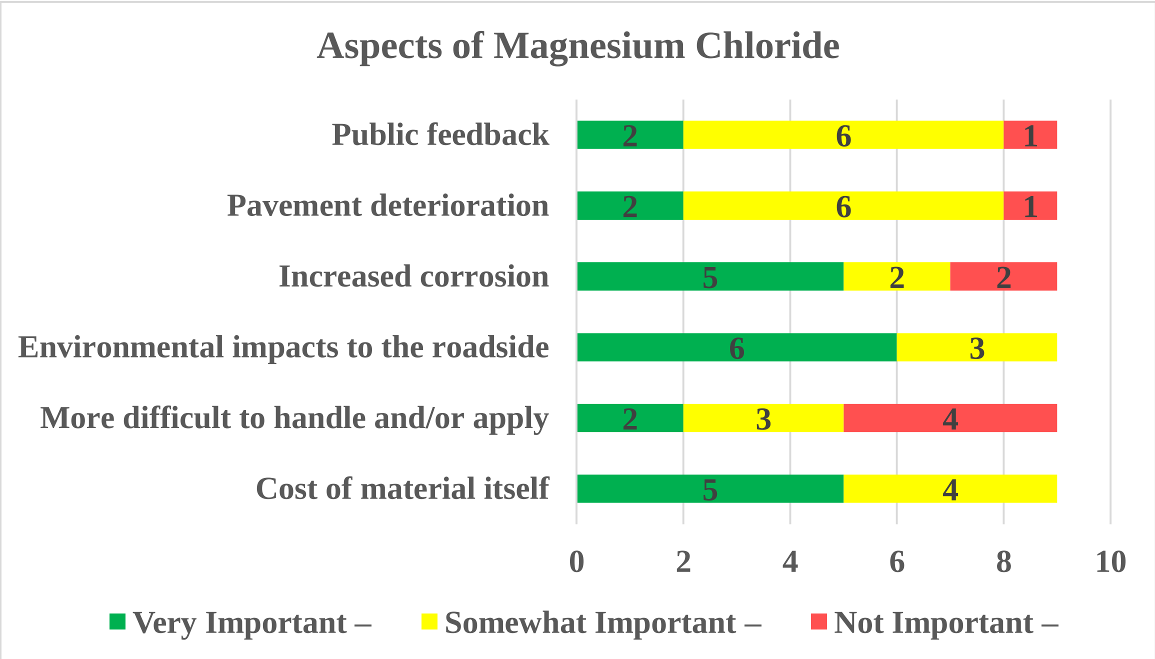

Figure 21: Importance of aspects for Magnesium Chloride

A follow-up question asked respondents to indicate the importance of various benefits associated with $MgCl_2$. The results of this feedback are presented in Figure 22. The most important benefit of $MgCl_2$ was its better performance in cold temperatures. Other benefits were mostly rated as being very or somewhat important to respondents. The only benefit that was not highly rated in terms of importance was $MgCl_2$ not being an animal attractant.

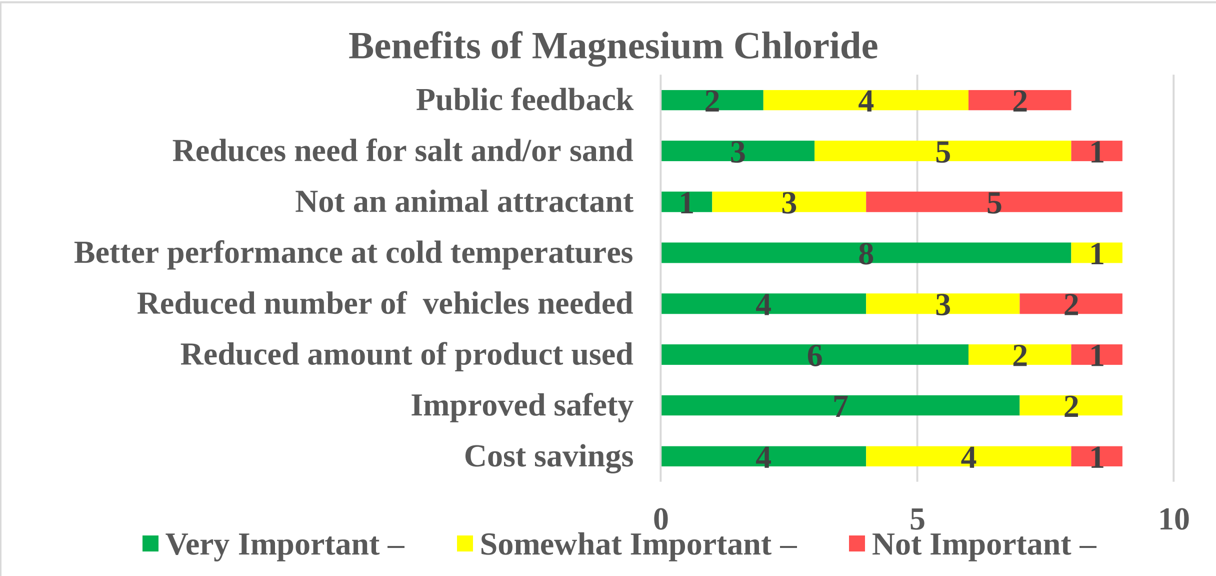

Figure 22: Benefits of Magnesium Chloride

The potential savings of using a Magnesium Chloride versus a straight salt brine was the next item respondents were asked to provide feedback on. The feedback received regarding this question is presented in Figure 23. Most (although not all) of $MgCl_2$ users indicated that the material provided a longer duration of black ice prevention. Some respondents also indicated a reduction in the number of treatment applications required during a storm was achieved, while only two indicated that vehicle refresh rates were lowered.

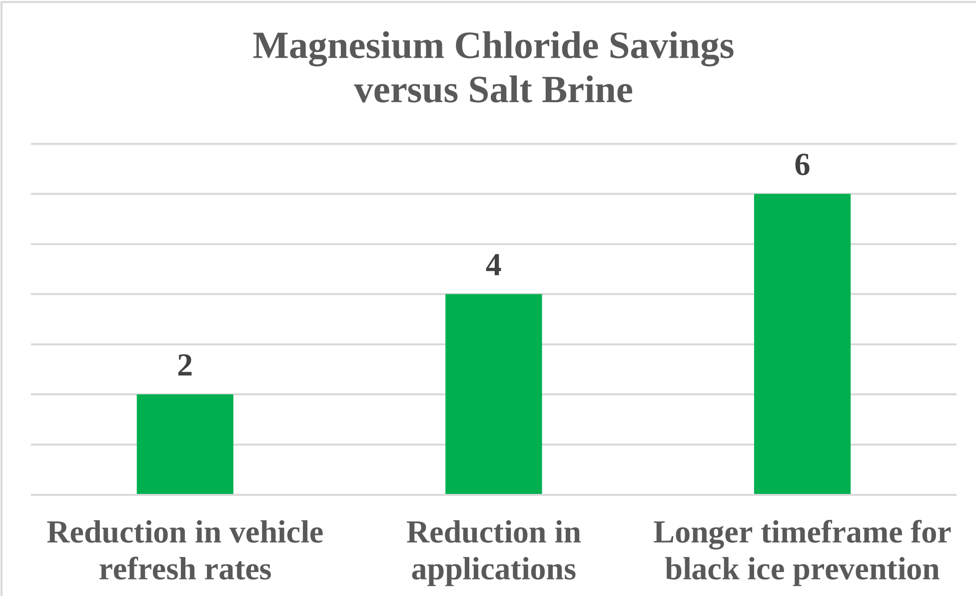

Figure 23: Potential savings of Magnesium Chloride versus salt brine

<u>Calcium Chloride</u>

Calcium Chloride ($CaCl_2$) was another Advanced practice material that was of interest to the work. A total of 9 respondents indicated that their agency used $CaCl_2$, while 4 agencies did not. Calcium Chloride can be used in different forms, and 4 respondents indicated that their agency used an inhibited liquid, 5 indicated an uninhibited liquid was used, 1 indicated an inhibited solid was used and 2 indicated an uninhibited solid form was used. Application rates were only provided by two respondents; the application rate of inhibited liquid used for prewetting salt was 8 gallons per ton, while the application rate for inhibited solid materials was 360 pounds per lane mile. Reported costs for each material were $1.00 to $1.21 per gallon for inhibited liquids, $0.80 to $1.09 per gallon for uninhibited liquids and $450 per ton for uninhibited solids. Information on the cost of inhibited solid materials was not provided by any respondent.

The equipment cited by respondents as being used to apply $CaCl_2$ was fairly standard and included pre-wetting systems, spreader trucks, saddle tanks on trucks spraying at the spinner, spray wands and bars, tank trucks and V-box spreaders. When asked where $CaCl_2$ was used, respondents indicated it was used when temperatures were below 10°F, systemwide depending on temperature, in stockpile treating of sand for gravel roads, and mixed with salt (granular and brine) for temperatures below 20°F. The use of $CaCl_2$ in prewetting was especially highlighted in the follow-up question, which asked if an applied this material was used in combination with other products (like pre-wetting). Seven respondents indicated that their agency used $CaCl_2$ in prewetting, while 1 agency indicated it did not.

Next, feedback was sought regarding the importance of different aspects related to $CaCl_2$ use. Feedback to this question is presented in Figure 24. As the figure illustrates, the majority of aspects that feedback was solicited on were cited as being very or somewhat important to respondents. Only 1 respondent indicated that pavement deterioration was not important, while 2 respondents indicated that difficulty in handling or applying the material was not important.

Collectively, the feedback received on the different aspects of $CaCl_2$ use indicates that agencies are aware of the issues associated with the material and recognize their importance.

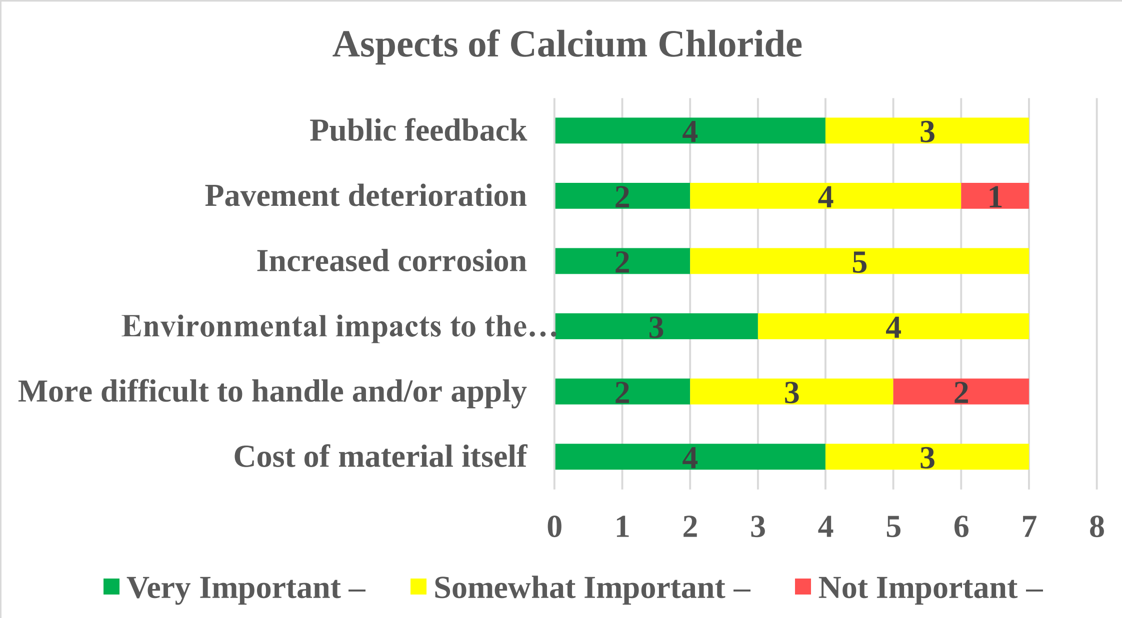

Figure 24: Importance of aspects for Calcium Chloride

A follow-up question asked respondents to indicate the importance of various benefits associated with $CaCl_2$. The results of this feedback are presented in Figure 25Figure 22. As indicated, respondents all agreed that the benefit of $CaCl_2$ having better cold temperature performance was a very important advantage. For other benefits, the results were generally mixed between the benefit being perceived as very or somewhat important. Reduction in the number of maintenance vehicles applying material was cited as not being important to 2 respondents, while the material not being an animal attractant was not important to 4 respondents.

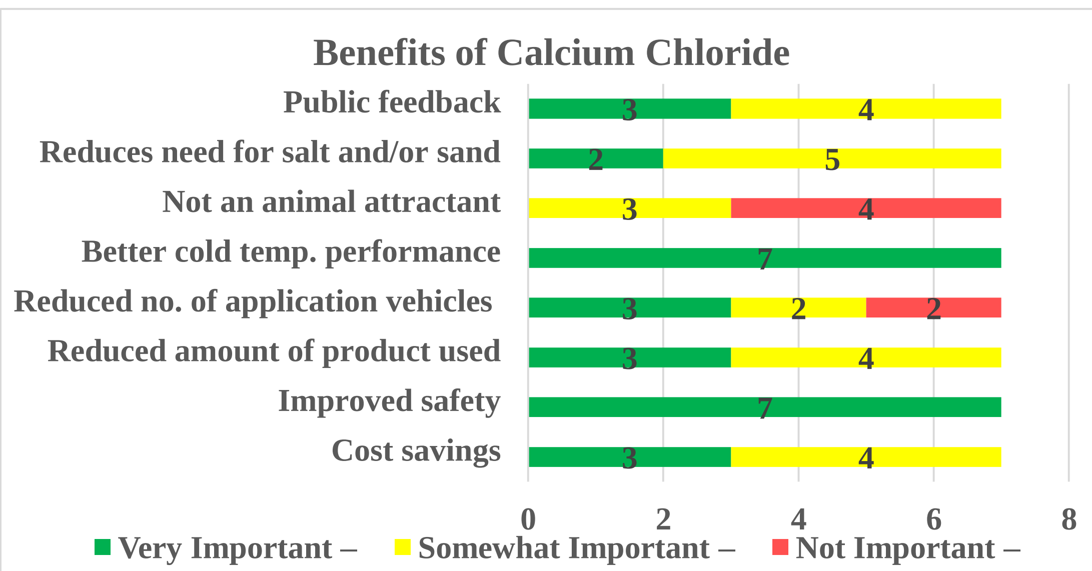

Figure 25: Benefits of Calcium Chloride

Blended Products

Blended products, specifically agricultural byproducts blended with de-icing and anti-icing chemicals, were the final Advanced practice material covered by the survey. Five respondents indicated that their agency used blended products, while 7 respondents indicated their agency did not use them. Only two respondents provided feedback on the types of blended products their agency used, which included an 80 percent salt brine/ 20 percent Ice B Gone mix and blended liquid $CaCl_2$ with forestry by-product [unnamed]. Four respondents indicated the product they used was inhibited (none indicated an uninhibited product was used). Specific application rates were not provided by any respondent, although one did note that the quantity of product used would vary depending on whether prewetting or pretreating was being performed. The prices reported for blended products ranged between $0.50 per gallon and $1.38 per gallon.

Respondents indicated that blended products were applied using a variety of equipment, including tankers, trailers, pretreating at the spinner, spray wands and bars, and plow trucks with saddle tanks. Blended products were cited as being used in a variety of ways, including all roads when temperatures were greater than 20°F, for stock pile treatment, as a pretreatment and retreatment on roads to prevent bonded precipitation. Three respondents indicated that their agency applied blended products in combination with other products, while 2 respondents indicated that their agency did not. One agency reported that one application of blended products reduced application of non-blended products by 50 percent. Information on estimates of the annual cost associated blended product operations (equipment, materials, labor, etc.) was not provided by any respondent.

Next, feedback was sought regarding the importance of different aspects related to blended product use. Feedback to this question is presented in Figure 26. As the figure illustrates, environmental impacts and the material cost were very or somewhat important aspects of blended products to all respondents. Pavement deterioration, increased corrosion and the handling and/or application of blended products were all rated similarly by respondents. Finally, public feedback was rated as being somewhat important by 3 respondents and very important by 2 respondents, indicating that listening to the feedback and needs of the public does receive consideration in using blended products.

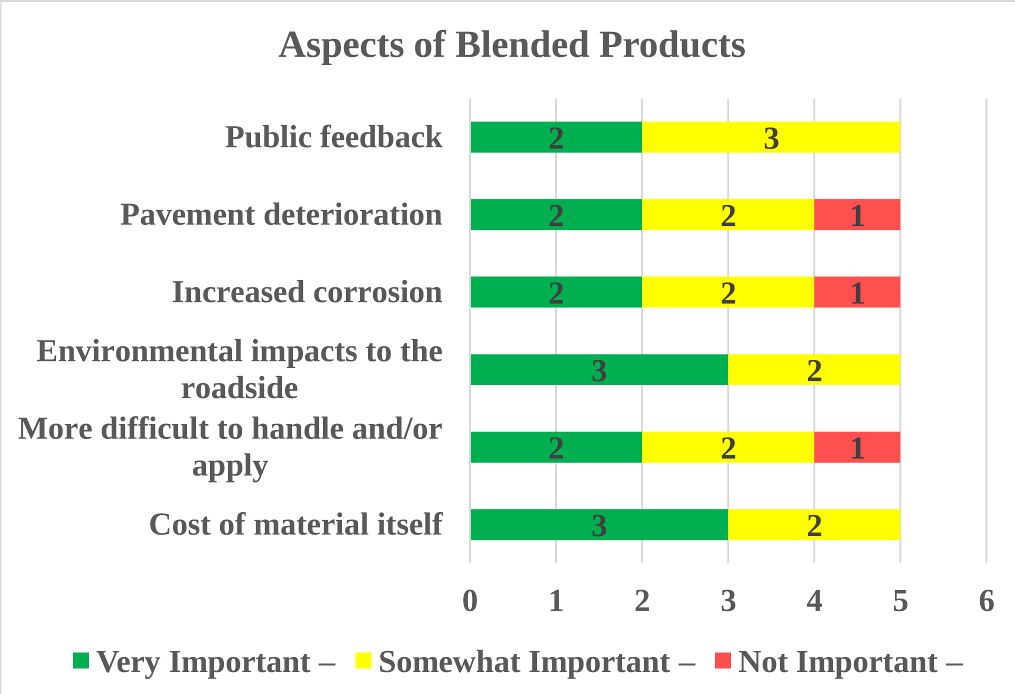

Figure 26: Importance of aspects for blended products

A follow-up question asked respondents to indicate the importance of various benefits associated with blended products. The results of this feedback are presented in Figure 27Figure 22. As indicated, respondents were largely positive regarding the improved cold temperature performance and safety offered by blended products. Reduced need for salt/sand or other materials, as well as longer lasting applications and cost reductions were also viewed favorably as benefits from blended products. Reduction in the number of maintenance vehicles applying material was cited as not being important to 1 respondents, while the material not being an animal attractant was not important to 2 respondents.

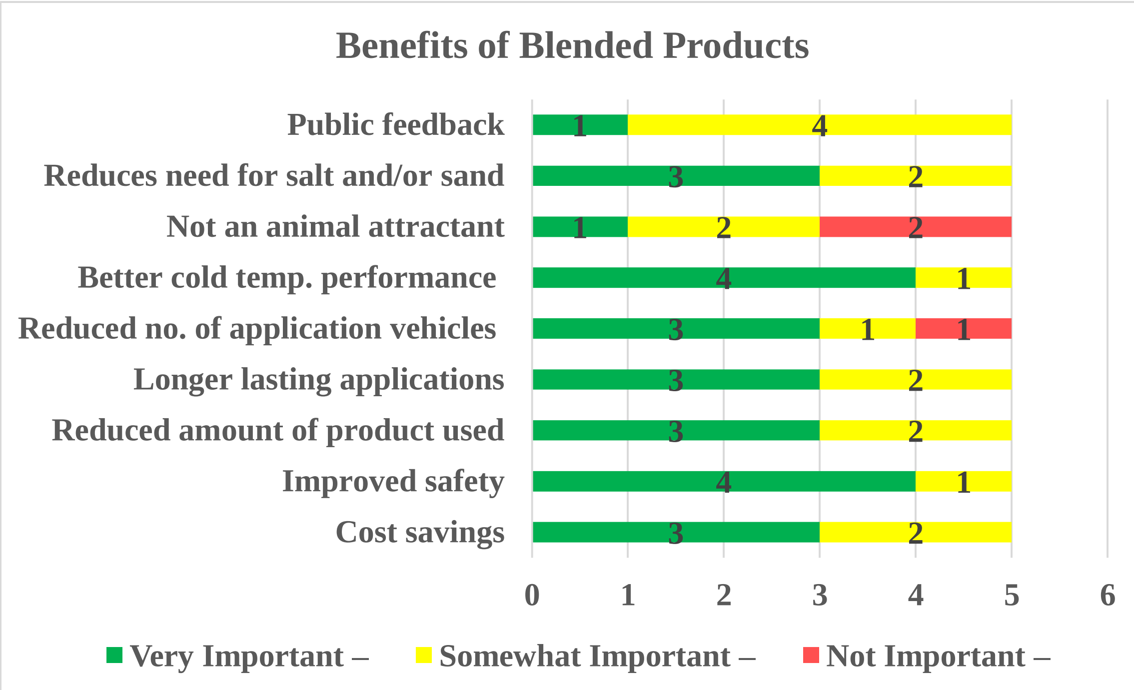

Figure 27: Benefits of blended products

Chemical Selection to Achieve LOS

The final section of the survey sought feedback from respondents on how their agency went about selecting different winter maintenance chemicals to achieve a targeted Level of Service. Unlike previous sections of the survey where a response of "No" to an initial screening question regarding one of the three maintenance practices would allow a respondent to skip over an entire section, questions in this section were posed to all participants. As a result, the responses received for this portion of the survey were higher than those in previous sections.

The initial question posed to respondents asked what factors went into their agency's selection of specific winter maintenance products. A total of 19 respondents answered this question, and the responses are presented in Figure 28. As the figure indicates, all respondents indicated that effectiveness of the material is a factor in its selection. Availability and cost were the next most frequently cited factors, which is reasonable given that these aspects play a role in the procurement process. Meeting LOS objectives and environmental impacts were each factors considered by 13 agencies, while public feedback and ease of use were considered by 10 agencies apiece. In summary, the results of this question illustrate that numerous factors are considered by agencies when selecting conducting product selection, some of which are considered more broadly than others.

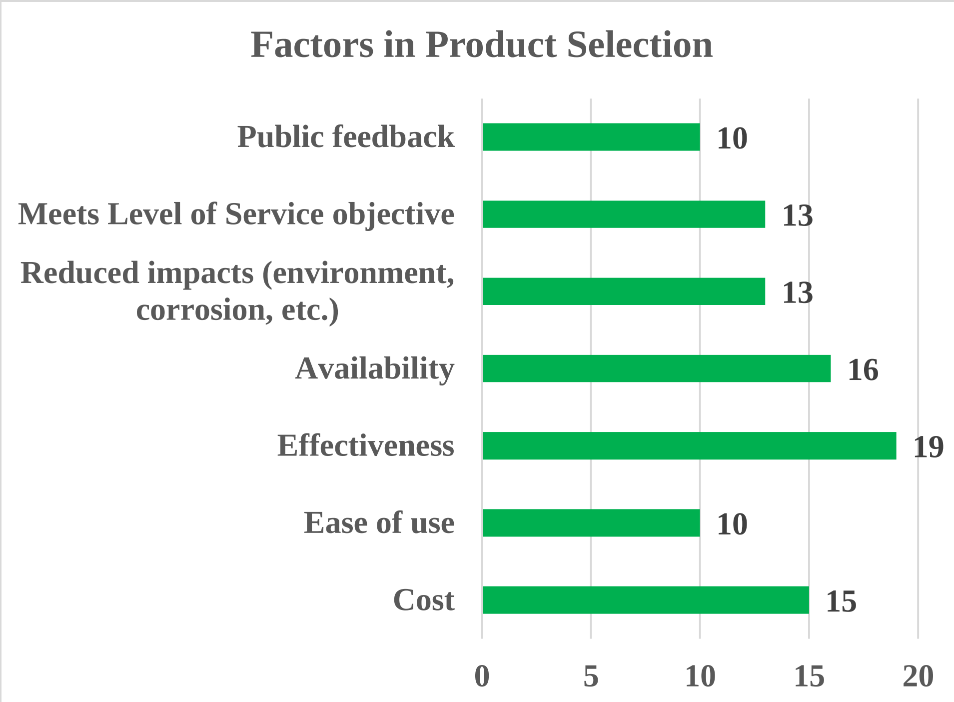

Figure 28: Factors in product selection

Next, respondents were asked if their agency modified its snow and ice control products selection to better meet a prescribed LOS. Twelve respondents indicated that their agency had modified product selection in order to meet LOS targets, while 7 respondents indicated that their agency had not made changes. Responses that indicated changes had not been made are not indicative of the previously discussed factors not being accounted for; rather, it is possible that the selection process already in place was appropriate in incorporating the factors that were important to that particular agency. In light of this potential, a follow-up question was posed that asked what products were used, what product the agency switched to, why the switch was made, and whether the switch has proven to be more effective. This was an open-ended question, and responses provided included:

- Used to just use 5% salt/sand. We are now pre wetting with 5/10 gallons per ton of salt brine or geo brine, and a direct app to the highways we have seen much less pack on the roads and far faster recoveries with the new practices.
- More salt brine applications.
- Continue to increase usage of salt brine. Continue to promote the practice of pre-wetting.
- We have gone to using more blended salt brine, we feel it is the best cost effective method we use.
- Agency only uses salt products. Timing and rates have been modified to achieve the desired LOS.
- We used a salt/sand combo of regular salt. When we switched to treated salt only we reduced our overall salt consumption by 20% and sand by 70% (sand is still used on gravel).
- Brine.

- We had been using regular salt and sand then switched to pre-wet inhibited salt. We now use less salt per season and have a dramatic reduction in rust.
- Main products are plain salt and treated salt.
- Addition of beet juice over the last several years.
- Switched from principally anti-skid mixed with salt to solid salt and salt brine usage. The switch has been very effective for both mobility during winter storms, accident reductions, reduced labor in spring clean-up, reduced winter-time broken windshield damage claims (none) and cost savings.

As many of these responses indicate, there has been a shift towards a greater use of salt brine, both in prewetting/pretreating applications. Many responses also referred to the use of various granular salt products (inhibited and uninhibited), which is in line with the results from the practices portion of the survey, where responses dropped off after the section of Intermediate practices. In several cases, material use was reduced compared to past practices when changes were made to achieve a given LOS.

The final survey question asked respondents whether their agency received any feedback (positive, negative, constructive) on any of the products used (e.g., rock salt, brine, $MgCL_2$, $CaCl_2$, blended products, pre-wet/pre-treated, or corrosion inhibited). Once again, this was an open-ended question, and the feedback received included:

- Negative feedback with sand-salt mix due to accumulation over the season, public perception is out of sight out of mind. Positive feedback with controlling costs for salt and overall winter maintenance.
- We have received less customer complaints with regards to vehicular corrosion after switching to corrosion inhibited salt brine from corrosion inhibited magnesium chloride.
- Prewetting and brine have been very positively received.
- The public feels salt brine is rusting their vehicles.
- All positive in how quickly we achieve our LOS
- The public likes salt and calcium. They do not like brine.
- Mostly negative in regards to vehicle corrosion and from reducing the amount of overall sand use.
- Some concern with ground water infiltration by chlorides. $MgCl_2$ for anti-icing causes slick conditions at times.
- Positive feedback.

As these responses illustrate, the feedback received by agencies was mixed. Some responses indicated that the public had concerns related to salt and corrosion (particularly with brine), while other responses indicated a favorable impression of salt use by the public. In cases where salt was an issue, it appears that the public was more inclined to see abrasives used, despite the potential for other types of vehicle damage to occur. In one instance, the respondent indicated that public complaints fell following the use of corrosion inhibitors, which is encouraging. Additional public concerns were related to chloride infiltration of groundwater. Finally, one respondent noted that use of $MgCl_2$ for anti-icing caused some slickness at times.

Follow-up Survey Results

Advanced Practices

Advanced winter maintenance practices were those that employed the selection and use of alternative chemicals, corrosion-inhibited liquids and/or treated or chemically enhanced solid chemicals to match performance with environmental conditions for anti-icing and deicing (in addition to Basic and Intermediate activities such as plowing and use of salt, salt brine and/or abrasives). The materials of interest to the survey included:

- Corrosion Inhibitors
- Corrosion Inhibited Salt Brine
- Magnesium Chloride – Solid
- Magnesium Chloride – Liquid
- Magnesium Chloride - Corrosion Inhibited Solid
- Magnesium Chloride - Corrosion Inhibited Liquid
- Calcium Chloride – Solid
- Calcium Chloride – Liquid
- Calcium Chloride - Corrosion Inhibited Solid
- Calcium Chloride - Corrosion Inhibited Liquid
- Blended Products - Agricultural byproducts blended with de-icing and anti-icing chemicals
- Blended Products - Corrosion Inhibited

In a survey focused entirely on obtaining information on these advanced practices, a total of 11 responses were received from 10 individual agencies. Among the respondents were 7 states and three municipalities.

Corrosion Inhibitors

Corrosion is a significant impact of winter maintenance operations, affecting the equipment and infrastructure of the agency itself as well as the vehicles of the general public. To address the issue of corrosion, agencies have begun to employ corrosion inhibitors in their winter maintenance operations. To understand the extent that corrosion inhibitors were employed, respondents were first asked if their agency used corrosion inhibitors with its winter maintenance products. Seven respondents (including four DOTs) indicated their agency used different corrosion inhibitors. Products/brands in use included:

- Aqua Salina products
- Beet Heet products
- Calcium Chloride with Boost
- Geomelt 55
- Geomelt S7
- Magnesium Chloride
- Ice B' Gone
- Magic Minus Zero
- Apex Meltdown Ingredient
- Freezgard CI Plus

- DowArmor
- Molasses

The approximate costs for these different materials were cited as follows:

- Calcium Chloride with Boost- $1.58 per gallon
- Aqua Salina- $1.01 per gallon
- Aqua Salina + IceBite- $1.29
- Beet Heet Concentrate- $1.67 per gallon
- Beet Heet Severe- $1.47 per gallon
- XO-Melt2- $1.17 per gallon
- Geomelt 55- $1.57 per gallon
- Geomelt S7- $1.33 per gallon
- Magnesium Chloride - $1.05 - $1.20 per gallon, $169.39 per ton
- Ice B' Gone - $1.40 - $1.50 per gallon
- Magic Minus Zero - $1.40 per gallon
- Apex Meltdown Ingredient - $0.73 per gallon
- Freezgard CI Plus – No price cited.
- DowArmor - $1.20 per gallon
- Molasses - $1.26 per gallon (mixed with Magnesium Chloride as a package)

Only two respondents (Maine and Ohio) provided further feedback regarding additional costs associated with corrosion inhibitors. Maine indicated that “Sometimes we get plugging of filters or segregation in the tanks. Sometimes the tanks have to be pumped out.” Ohio indicated that “shipping costs for additional drops, demurrage and flat fees of deliveries under 2000 gallons” were incurred.

The Level of Service (LOS) achieved by products using corrosion inhibitors was difficult for respondents to determine, given that inhibitors are used in combination with other materials. Responses regarding LOS included:

- Not sure what can be attributed to the inhibitors.
- Assists in corrosion prevention on PCC streets and equipment.
- High Level of Service.
- We are able to achieve the desired level of service when materials are applied at the proper rate and time.

Similarly, no information was available from any respondent regarding observed or perceived reductions in crashes following the adoption of corrosion inhibitors.

The benefits of corrosion inhibitors as rated by respondents are presented in Figure 29. As the figure indicates, most respondents indicated that all of the listed benefits of inhibitors were very or somewhat important. However, two respondents indicated that corrosion protection for the general public’s vehicles was not an important factor in corrosion inhibitor use.

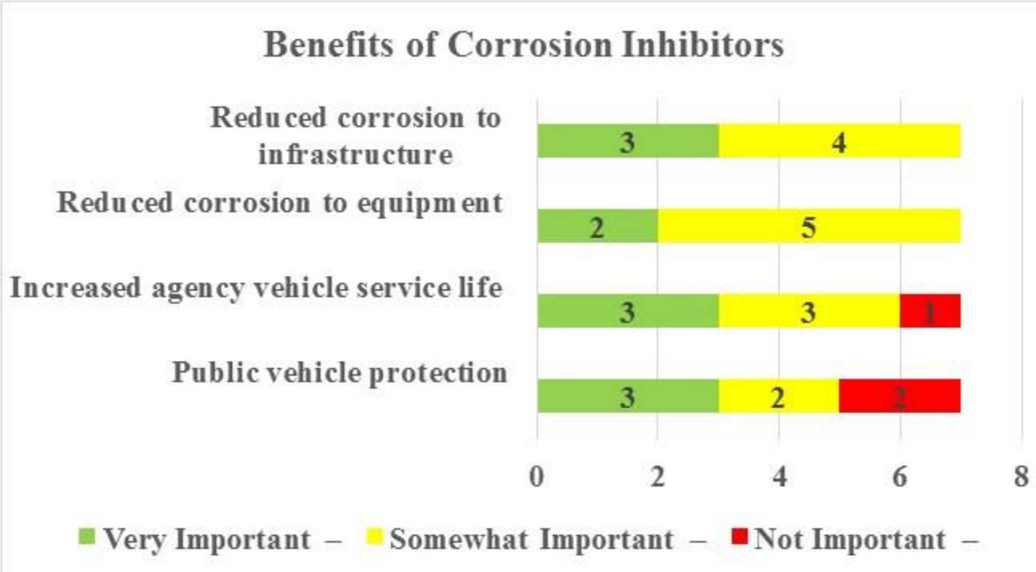

Figure 29: Benefits of corrosion inhibitors

Finally, additional thoughts provided by respondents related to corrosion inhibitors included:

- For the amount of corrosion reduction realized the additional costs do not justify the use. The base materials used for deicing are still corrosive enough that applying small volumes of liquids to offset the corrosiveness is somewhat trivial. While there is a "feel good" factor, in the field the results are minimal. For agency equipment we have seen much better success with pre-treatment of vehicles with new corrosion inhibitors and using salt neutralizers combined with frequent post storm cleaning.
- Use them for our magnesium chloride product, but not sure how much they really do in the environment. Most of the chlorides we use are from rock salt anyway.

Inhibited Salt Brine

Two respondents indicated that their agency used salt brine, both of which were municipalities. The limited responses for this material were expected, as a prior survey with 30 respondents found that only 6 agencies used inhibited salt brine. Cited application rates for this material ranged from 40 to 60 gallons per lane mile. Only one respondent provided a cost for the material, with that cost being $0.30 per gallon. Each respondent indicated that their agency produced its own salt brine. One respondent indicated that the estimated annual cost associated with corrosion inhibited salt brine operations at their agency (for aspects such as equipment, materials, labor, etc.) was $50,000.

Brine was applied using truck and trailer mounted spray systems and a 2000 gallon slide in unit with pencil nozzles. Corrosion inhibited salt brine was used on roads and bridges for a majority of storms and for bridge frost treatments by one agency, with the other using it for anti-icing and pre wetting of salt. Both respondents indicated that their agency had applied corrosion inhibited salt brine in combination with other products for activities such as prewetting. Only limited feedback was provided regarding the LOS achieved through the use of inhibited salt bring. One respondent indicated a “high” LOS was achieved, while the second indicated that the materials had a “great residual value, maybe some limited corrosion success”.

Respondents were asked to characterize the importance of different aspects associated with inhibited brine use. The cost of the material itself was a very important aspect of corrosion inhibited salt brine for both respondents, while public feedback was a somewhat important aspect to each. Difficulty in handling the material was somewhat important to one respondent and not important to the other. Environmental impacts were very important to one respondent and not important to the other. Finally, pavement deterioration was cited as very important to one respondent and somewhat important to the other.

The benefits of inhibited brine use, including cost savings, safety improvement, reduced product use and reductions in salt and/or abrasive use were each rated as very important to one respondent and not important to the other. Both respondents indicated that a reduction in the number of applications was not an important benefit, while better performance at cold temperatures was an important benefit. Finally, public feedback was cited as being somewhat or not important to one respondent each, respectively. One respondent provided the additional comment that “the GeoMelt we use is really more beneficial for residual value and lower operating temperatures. While considered less corrosive, we really don't see a great deal of benefit with that aspect of the product”.

Magnesium Chloride

Magnesium Chloride ($MgCl_2$) was cited as being used in some form by seven respondents. When broken down by type, one respondent used liquid $MgCl_2$ while six respondents used $MgCl_2$ as a corrosion inhibited liquid. The results to this matched those obtained in a general usage survey completed earlier, where only one respondent used $MgCl_2$ as a solid product and none used a $MgCl_2$ corrosion inhibited solid. The application rates used for $MgCl_2$ in different forms were as follows:

- Liquid $MgCl_2$
  - 1 gallon per lane mile dispersed with 200 lbs. of salt. (pre-wetting)
- Corrosion Inhibited Liquid $MgCl_2$
  - Direct application - 1-25 gallons per lane mile depending on temp.
  - Pre-wet application 4-8 gallons per ton of salt or sand or approximately 1-2 gallons per lane mile.
  - 8-10 gallons per ton to pretreat salt at the spinner.
  - 10 gallons per ton, prewetting.
  - 6-8 gallons per ton, prewetting.
  - 10 - 15 gallons for pre-wetting.
  - 25 - 35 gallons per lane mile for treatment.
  - 8-12 gallons per ton of salt, mostly a 75/25 blend. (pre-wetting)

The costs reported as being associated with the different forms of $MgCl_2$ were as follows:

- Liquid $MgCl_2$
  - $0.75/gallon
- Corrosion Inhibited Liquid $MgCl_2$
  - $1.05 - $1.20 per gallon depending on delivery site
  - $1.09 per gallon
  - $1.40 per gallon

- $1.26 per gallon
- Average cost is $169.39 per ton [Note that this state indicated a liquid was being used for prewetting and direct application, so it is not clear why a cost per ton was provided.]
- $1.26 per gallon.

Limited feedback was provided on the total estimated annual costs associated with Magnesium Chloride operations at each agency (equipment, materials, labor, etc.), and all feedback was provided for agencies using inhibited liquids. One respondent indicated that their agency used approximately 33,000 gallons of inhibited liquid per year. Two remaining respondents indicated that their material costs were $300,000 and $650,000 per year. Note that equipment and labor costs do not appear to be available or separately tracked.

Various equipment was reported as being used in applying the different forms of $MgCl_2$ previously indicated (all liquids). This equipment included:

- Saddle tanks, spraying units for older model trucks and built in onboard spraying system for newer models.
- Direct application - truck with 10 foot spray bar 1600-2500 gallon poly tank.
- Pre-wet application - sander chute by nozzle.
- Pretreat salt at the spinner.
- On board prewetting systems
- Stockpile blended to salt.
- De-icing trucks with mounted tanks and saddle tank on sanders.
- Saddle tanks with sprayers at the 3-6-9 o'clock positions in the chutes as the salt is dropping to the spinner for our conventional spreaders. We also us a Schmidt oatmeal ("slurry") spreader and anti ice with a slide in applicator.

The agency using straight $MgCl_2$ liquid indicated that the product was used with salt applications, with the liquid magnesium applied to the rock salt. Remaining applications of inhibited $MgCl_2$ liquids included:

- Typically whenever we make a salt application we apply the liquid magnesium to the rock salt.
- All road surfaces.
- Prewetting of salt at the spreader.
- Truck Spinner.
- It is used as a pre-treatment prior to storm events, used for pre-wetting with the application of anti-skid/salt materials and for ice removal during storm events.
- Mains, Submains, Hills, Residential streets and parking lots.

All six respondents indicated that their agency applied $MgCl_2$ in combination with other products (like pre-wetting). The LOS achieved by $MgCl_2$ products in all forms was not widely known. One respondent indicated that the use of inhibited $MgCl_2$ liquid produced a "high" LOS. Another respondent indicated that the LOS was "not certain, however it can be shown that the use of the magnesium will bring the roads to bare and wet conditions at a much faster rate". No information was available to or provided by any respondent on the number of applications needed for any form of Magnesium Chloride to achieve an LOS for a given condition versus another product.

Figure 30 presents the aspects of $MgCl_2$ used in both liquid forms. For inhibited liquids, the cost of the material was the greatest concern, albeit to three respondents. Pavement deterioration and environmental impacts were also a concern with inhibited liquids. Corrosion was a concern for uninhibited liquids, as one would expect. Environmental impacts and material cost were also a concern with uninhibited liquids, although as only one respondent selected these particular aspects. As only one agency cited the use of uninhibited $MgCl_2$ liquid, the benefits selected should be interpreted accordingly.

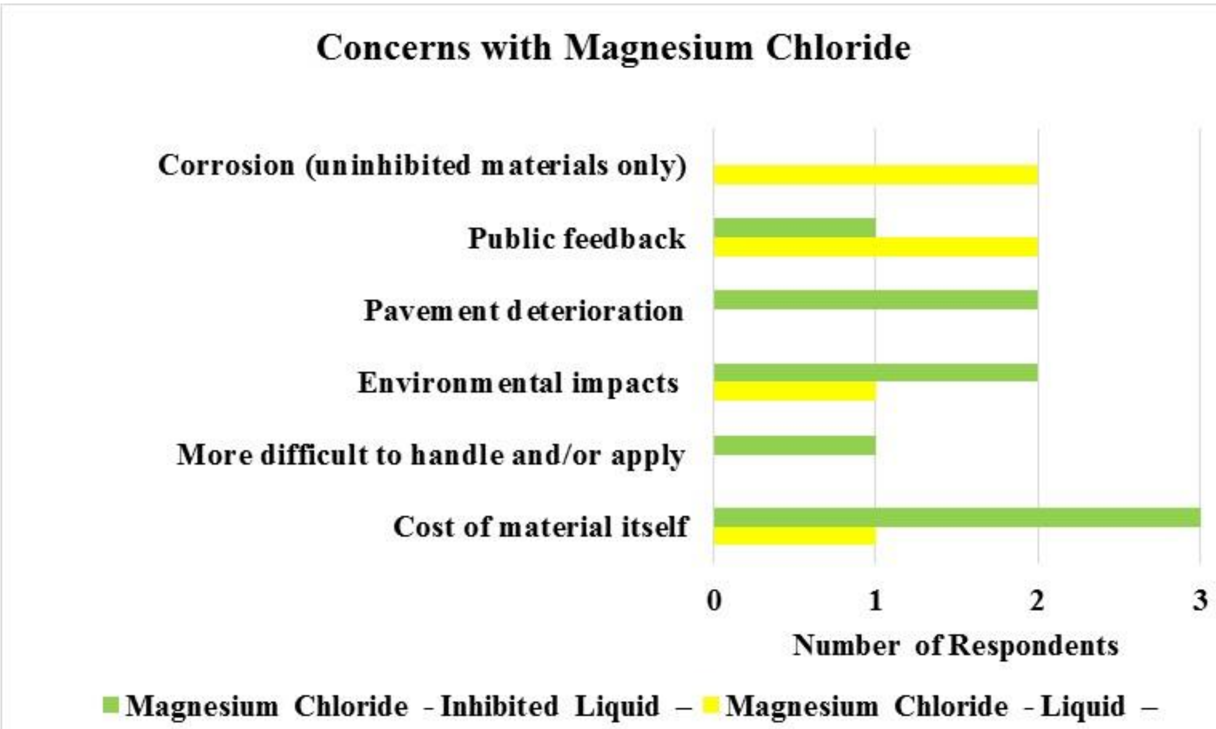

Figure 30: Concerns with Magnesium Chloride

Aside from not being an animal attractant, all cited benefits of $MgCl_2$ were selected by at least one respondent. The most frequently cited benefits were better cold temperature performance, reduced product use, improved safety and cost savings. Public feedback was also cited as a benefit of corrosion inhibited $MgCl_2$ liquid. Again, as only one agency cited the use of uninhibited $MgCl_2$ liquid, the benefits selected should be interpreted accordingly.

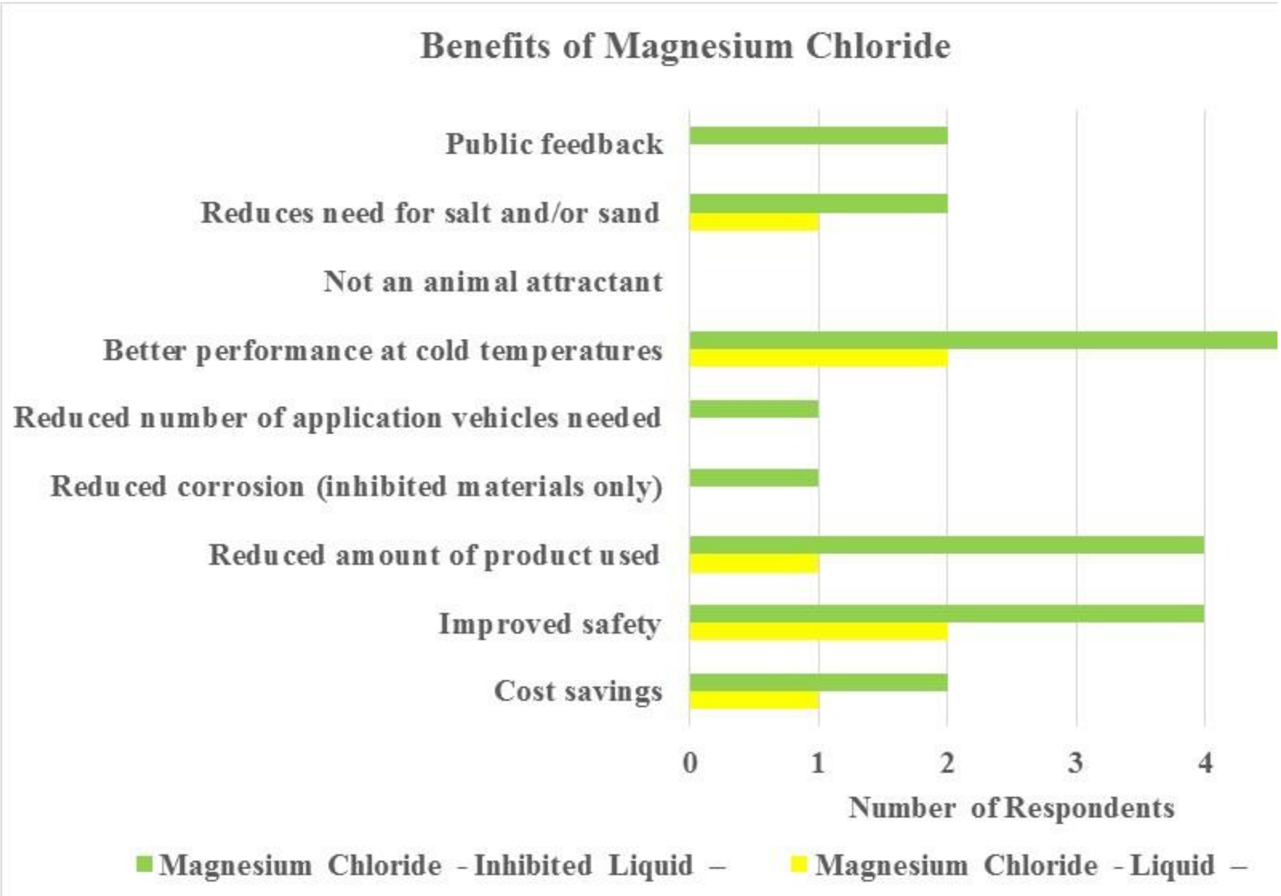

Figure 31: Benefits of Magnesium Chloride

One final comment was received regarding the use of inhibited $MgCl_2$ liquid. The respondent indicate that "we only have a few maintenance units (about 25%) that prefer to us magnesium chloride. Most prefer not to use it because of handling the material and if it is used wrong or at the wrong time it is not as forgiving as salt. We have not seen the cost benefit over using salt".

Calcium Chloride

Calcium Chloride ($CaCl_2$) in different forms (solids and liquids either uninhibited or corrosion inhibited) were used by four responding agencies. One agency used uninhibited $CaCl_2$ solid, three agencies used uninhibited $CaCl_2$ liquid and two agencies used corrosion inhibited $CaCl_2$ liquid. All three respondents indicated that their agency had used $CaCl_2$ in combination with other products (prewetting). Application rates for these materials were reported as follows:

- Solid $CaCl_2$
  - Data not provided
- Liquid $CaCl_2$
  - 30 gallons per lane mile to 300 gallons per lane mile. Never used straight, always in a blended liquid with brine or brine and beetheet. 80/20 blend, 20% Calcium Chloride. Application rate depends on the reason for use.

    - 40 gallons per lane mile on roads for anti-icing. 20 - 35 gallons per ton for pre-wetting.
    - We apply the mixture at 7 to 9 gallons of liquid per ton. We typically mix it with salt brine at a 10% solution of Calcium Chloride to 90% brine.
- Corrosion Inhibited Liquid $CaCl_2$
    - We apply the mixture at 7 to 9 gallons of liquid per ton.

The costs reported as being associated with the different forms of $CaCl_2$ were as follows:

- Solid $CaCl_2$
    - Data not provided
- Liquid $CaCl_2$
    - $0.55 per gallon
    - $0.65 per gallon
    - $0.69 per gallon
- Corrosion Inhibited Liquid $CaCl_2$
    - $1.58 per gallon

Equipment for applying solid materials was not reported. The equipment used to apply the liquid materials included "bulk 6000 gallon semi tankers, saddle tanks on salt trucks for pre-wetting" and "on board wetting tanks to pre-wet the salt with the Calcium Chloride brine solution at the spinner. Occasionally apply Calcium Chloride directly to the salt in the bed of the truck using an overhead shower system". Uses for the materials were as follows:

- Liquid $CaCl_2$
    - We use it as a brine enhancer during periods of extreme cold to pre-wet the salt at the spinner or to wet an entire load in the bed of the truck.
    - Pre-treating, pre-wetting, direct liquid application.
    - When pavement temperatures drop below 15 degrees we use it in lieu of salt brine for pre-wetting.
- Corrosion Inhibited Liquid $CaCl_2$
    - We use it as a brine enhancer during periods of extreme cold to pre-wet the salt at the spinner or to wet an entire load in the bed of the truck.
    - We use inhibited calcium chloride on new pavements.

Regarding the LOS achieved using $CaCl_2$, more generalized responses were provided. These included:

- LOS is very high but we never use straight calcium.
- We are able to achieve the desired level of service when materials are applied at the proper rate and time.
- Enhanced results when pavement temperatures go below 15 degrees.

None of the respondents had information available regarding the number of applications needed for form of Calcium Chloride to achieve an LOS for a given condition versus another product.

Estimates of the costs associated with $CaCl_2$ (equipment, materials, labor, etc.) were provided by two respondents. The total costs cited were $10,000 and $50,000, with the third respondent indicating these costs were unknown.

Regarding concerns with different aspects of $CaCl_2$, two respondents were concerned with the cost of uninhibited liquids and the potential for corrosion with it, while one respondent indicated concern with its environmental impacts to the roadside and pavement deterioration. For inhibited $CaCl_2$ liquid, two respondents were concerned with the cost of the material. The benefits of $CaCl_2$ cited by respondents included cost savings, reduced amount of product used, better cold temperature performance, reduced need for sand and salt, not serving as an animal attractant and improved safety for both uninhibited and inhibited liquids. Reduced corrosion was cited as a benefit of corrosion inhibited liquid. Additional thoughts provided on $CaCl_2$ included the following:

- Great tool during cold events. However with the inhibited material almost being double in cost, we only use it for newer pavements during the first year in lieu of salt.

Blended Products

Blended products, specifically agricultural byproducts blended with de-icing and anti-icing chemicals, were used by two respondents. One agency used an uninhibited product, while the other used an inhibited product. The types of products used and their respective costs were as follows:

- Uninhibited
    - GeoMelt - $1.20 per gallon
    - BioMelt - $1.20 per gallon
- Inhibited
    - Aqua Salina + IceBite- $1.29 per gallon
    - Beet Heet Concentrate- $1.67 per gallon
    - Beet Heet Severe- $1.47 per gallon
    - XO-Melt2- $1.17 per gallon
    - Geomelt 55- $1.57 per gallon
    - Geomelt S7- $1.33 per gallon

One respondent estimated the annual cost associated blended product operations (equipment, materials, labor, etc.) to be $50,000. Uninhibited products were applied at a rate of 40 gallons per lane mile, while inhibited products were applied “according to manufacturer recommendations”. Application equipment included on board wetting systems, namely liquid tanks on trucks and trailers with sprayers.

Respondents indicated that blended products had been used for both blending with salt brine for anti-icing, pre-wetting and to deice roadways. In line with this, both respondents indicated that blended products have been applied in combination with other products (prewetting). One responded that their agency was able to achieve the desired level of service when materials are applied at the proper rate and time, while the other respondent noted that blended products provided increased residual value and lower operating temperatures. Information on the number of applications required to achieve a given LOS versus other products was not provided, but one respondent note that “for pre-treating roads, the blended material can last significantly longer than straight salt brine”. In such cases, salt brine could last 1 to 3 days, while the blended product remains on the surface 2 to 3 times longer than that if there is not an immediate storm event.

Only the cost of the material itself was a concern associated with the use of blended products for both respondents. Cost savings, improved safety, reduced amount of product used, longer lasting applications, reduced number of application vehicles needed, better performance at cold temperatures, and reduced need for salt and/or sand were all cited benefits provided by blended products.

Chemical Selection to Achieve LOS

A final series of questions sought information from respondents on how their agency went about selecting different winter maintenance chemicals to achieve a targeted Level of Service. Ten respondents provided feedback on the factors used in deciding what snow and ice control products are used. Figure 32 presents the different factors cited as being important in selecting a particular product. As indicated, cost, effectiveness and availability were all important factors, as was the ability of a product to meet LOS objectives.

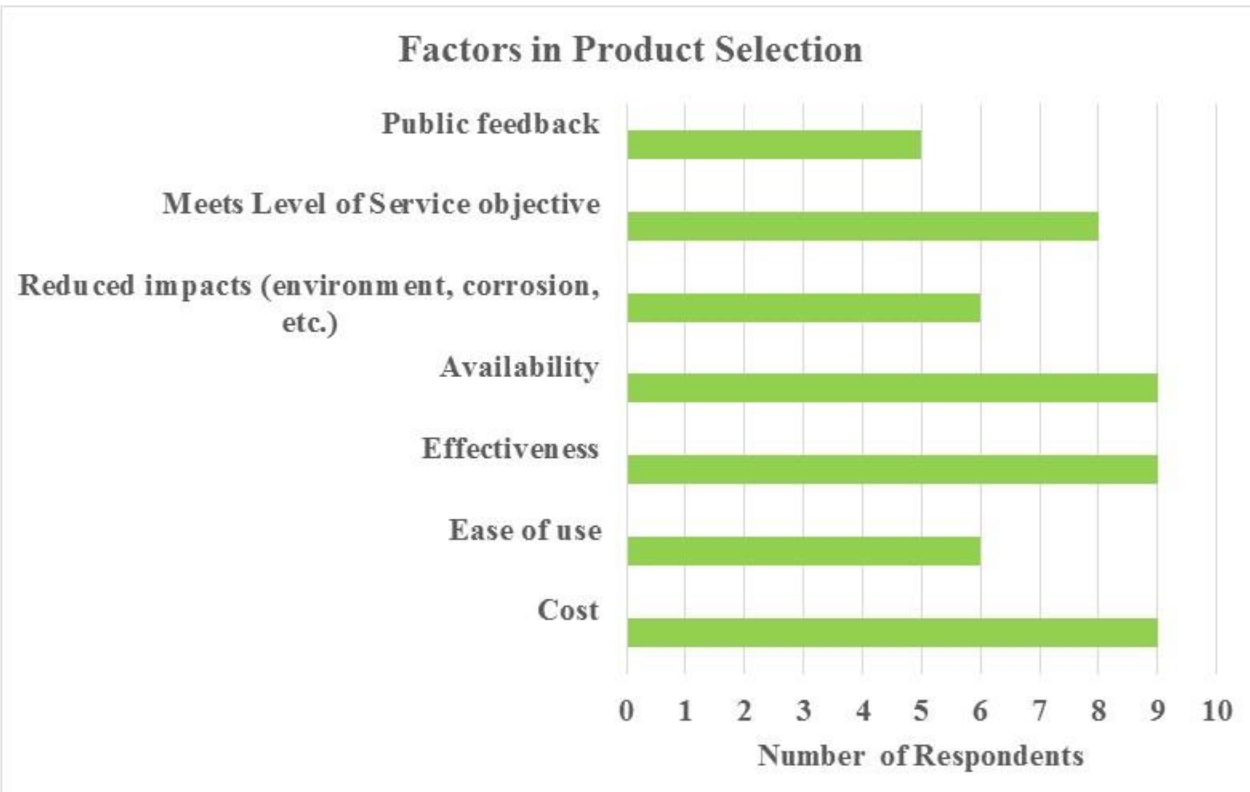

Figure 32: Factors in product selection

Six respondents indicated that their agency had modified its snow and ice control products selection to better meet the prescribed level of service, while four indicated that their agency had not done so. Respondents were also asked for additional feedback on what products were used, what product were switched to, why, and if the switch had proven to be more effective. Responses to these questions included:

- Trying organic blend decider in Chicago area. Feedback has been positive.

- We only have a few maintenance units that still use magnesium (approx. 25%). Most prefer not to use it because of handling the material and if it used wrong or at the wrong time it is not as forgiving as salt. We have over the past several years been switching more to salt brine
- Just the pretreating and pre wetting operations using salt brine and rock salt.
- We switched from a deicing approach, using vast amounts of winter sand, to more of an anti-icing approach back in 2001. The switch has been very effective in reducing cost, improving LOS, and saving money.
- Our District increased our salt content in the anti-skid / salt mixture from 0-30% to 50% (slurry) for this winter season to increase snow and ice removal effectiveness. It has proven to be more effective.
- We started with straight salt brine and moved toward blends. We typically always blend sugar beet based products with salt brine to improve residual performance, unless we have a high probability storm with warm pavement temperatures. Still utilize calcium chloride for pre-wetting at colder pavement temperatures and in our blends. With having a system where we can blend multiple products the ability to "mix for the storm" which creates added flexibility.
- Using liquids, none were used prior.

Regarding public feedback on any of the Advanced materials being used, respondents provided the following information:

- Negative feedback from the use of magnesium chloride due to corrosion concerns.
- Positive feed-back on salt brine usage since it leaves a residue that the public can see when it dries. Positive feed-back from the maintenance crews because the refreeze is easier to control.
- In recent years, people tend to object to any use of calcium or magnesium chloride, on the basis that those chemicals, and not rock salt, are causing corrosion of vehicles.
- Public just want bare roads.
- We have received positive feedback from the traveling public on the improved winter road conditions and less windshield damage due to flying rock.
- Positive feedback on the excellent LOS we are achieving. Our operation is based in a high service level community so expectations are high.
- Positive feedback
- We have received negative comments on the use of brine.

CLEAR ROADS

research for winter highway maintenance

Lead state:
Minnesota Department of Transportation
Research Services
395 John Ireland Blvd.
St. Paul, MN 55155