Snow Removal at Extreme Temperatures

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Snow Removal at Extreme Temperatures

Final Report

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16. Abstract

Extremely cold winter storms (below about 10°F) bring about different considerations for taking care of roads than warmer winter storms, where granular salt and salt brine are cost-effective measures of melting snow and ice when used in combination with other operations (e.g., plowing). At temperatures lower than about 10°F, either extremely large quantities of salt are needed or no amount of salt can melt snow or ice pack. Best practices for using chemicals during extremely cold winter storms include: waiting until the end of the storm, using deicers in daylight hours only, mixing salt with $MgCl_2$, $CaCl_2$, and/or agriculture by-products, and using high application rates. Despite their environmental and hidden costs (air pollution, sedimentation, spring cleanup & disposal), abrasives are frequently used during extreme temperatures to provide temporary traction. Best practices for using abrasives during severe cold includes prewetting with liquid deicers (although not plain salt brine—it may freeze) or hot water. Innovative strategies continue to be tested at severe temperatures, including conductive pavements and geothermal systems, which have demonstrated to be potentially effective tools.

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Contents

1 Introduction

In the U.S., northern tier and mountain states will have much colder temps and greater snow amounts than the southern tier. However, even the southern tier may experience severe to extreme temperatures occasionally. In addition to geographical location, intensity of precipitation, and cost, *pavement temperature* is a key parameter to consider when selecting the operational strategies and/or the application rate of materials for removing snow and ice from roads during winter storms. Traditionally, large amounts of salt (sodium chloride, NaCl) are used for snow and ice control on roads, which works well down to approximately 10 ºF (-12.2°C). As the pavement temperature gets colder, higher volumes of salt are required to achieve a reasonable level of service (LOS). As such, the use of salt is no longer cost-effective and highway agencies thus utilize other chemicals either alone or as pre-wetting agents to enhance the performance of salt (Ohio DOT, 2011) or apply abrasives to provide a traction layer on pavement. Abrasives are usually used at pavement temperatures below 12°F (-11ºC), and on roads with low traffic and low LOS (Blackburn et al., 2004). Furthermore, plowing is the most commonly used tool for snow removal, especially when the temperatures are extremely low.

Based on the field experience by Montana Department of Transportation (DOT) professionals, there are a number of variables that affect road conditions when ambient and surface temperatures get very cold (e.g., below 0°F), listed as follows:

- Level of Service
- Forecasts and recovery
- Wind or turbulence from vehicles
- Preventive vs. Reactive strategies
- Roadside design and maintenance impacts on drifting
- Rural vs. Urban environments
- Performance and storage of winter chemicals

Level of Service – This is the stated decision of how important or critical a particular road is to the traveling public and what the goals are of the agency maintaining the road. For instance, how many hours of the day, staff hours or effort, equipment dedicated to the job and what types of materials can or will be used for the effort. Some agencies will also try to establish a time factor, in hours, for recovery after the event has passed. The LOS guide is a document to be used and distributed within the agency and to customers served. A major component for determining LOS is the traffic count. Simply said, the more motor vehicles, the higher the LOS. A lower LOS is generally assigned to rural roads because of their less importance to the majority of traffic. It does not mean that such roads are less important to the agency but that the opportunity for accidents and limiting freight deliveries is reduced simply because of the number of vehicles and a road closure would affect fewer people.

Regardless of the LOS dedicated to a road, extremely cold conditions limit the options for maintenance. High performance chemicals, with low effective temperatures, often have little to no effect on snow-packed or icy surfaces. This does not mean that they cannot be used but it means that they must be used in a different way with different expectations and outcomes. Extreme cold can cause more damage to equipment. Carbide steel cutting edges on plows may break more frequently in the cold. Managing and storing diesel fuel and starting cold vehicles requires special considerations and a higher grade of fuel. Drivers and equipment operators must dress for the weather and protect themselves especially when in remote areas. Communication between drivers and their "sheds" is critical in case an emergency arises.

Forecasts and recovery – "Forewarned is forearmed". Knowing that a cold spell with snow is coming is very important to the choices for managing roadways. The concepts and benefits of "anti-icing" are well established but along with the guidelines for when to anti-ice is the warning of wind conditions. A normally dry and cold road allows snow to blow across the surface whereas a cold but "wet" road will cause snow to stick. The snow dilutes the chemical and will cause a snow-pack or ice condition. A forecast must include the information regarding the temperature when the event begins, if wind is accompanying the event, the low temperatures to be expected, the volume of snow and the duration of the event.

Anti-icing may be appropriate in some situations and environments but will be discussed later. Providing or maintaining "traction" for the greatest length of time is the ultimate goal. The tools the field winter maintenance professionals chose and the timing for their use is critical. The impact of sunshine on a cold and dry day can warm portions of the road enough to cause melt and snow accumulation. Not much can be done about this, but knowing it can happen and knowing where it usually happens is good information to share with the maintenance crew. Conversely, shade caused by buildings or trees can make snow-packed roads harder to deice or cause a quicker freeze-up than roads exposed the sun.

Wind or turbulence from vehicles – The moisture content of snowfall in very cold conditions is very low. This "dry" snow does not pack well and is readily disturbed by wind or vehicle turbulence. Often when a cold front arrives, it is accompanied by wind. Once the cold has settled in, the wind often dissipates but this is dependent on the region. Veteran plow drivers want a frozen but dry road surface when the storm hits. It is helpful to remove or push back snow from areas that could cause drifting snow to blow across a road. A safety concern is the loss of visibility during these conditions. Dry snow is readily airborne from passing traffic and snowplows can create "white-outs" from plowing shoulders. While "non-critical" shoulder plowing could be done during the evening hours when traffic is reduced, vehicle lights tend to make white-out conditions worse. Using shadow vehicles or posting signs warning of snow removal equipment can help alert drivers. Public relation campaigns warning of the concept of driving into whiteouts is important and appreciated by the public.

Preventive vs. Reactive strategies – Much is known and written with regard to anti-icing. Furthermore, it is noted that having chemical, frozen into the mix of snow and ice, will speed recovery on the backside of the storm. The "boiler plate" ice will more quickly break-up when temperatures start to moderate. So, if a forecast calls for a storm to come in "warm" and dump snow before it turns cold, anti-icing may be a good strategy simply to get some chemical into the mix of snow and ice. Reactive can be termed as the effort to try to rid the road surface of ice or, to deal with an ice-packed road to provide temporary traction. This is where a viable role of abrasives comes into to play. The problem with abrasives is they tend to bounce and scatter from the traveling surface during application and vehicle traffic if they are not prewet with liquid deicers or hot water.

Some countries, such as Finland, that deal with arctic conditions for long periods of time have little to no expectation of recovery to a bare road after an event. Their frozen roads may stay that way for months without relief. As a result, they have developed a strategy of using hot water to wet abrasives before applying it to ice and snow-pack. The warm and wet abrasives quickly freeze to the surface and provide traction until they are covered up with additional snow and then the sanding treatment is repeated. The same result can be achieved using chemicals for wetting the abrasives before application. This is referred to as "pre-wetting." Pre-wetting can easily be accomplished with equipment and spray tanks already in use on plow trucks. As temperatures begin to moderate, heavier applications of liquid chemical with rock salt, mixed with abrasives, can result in a "slurry" application that will burn through ice-pack and still provide some traction before actual break-up occurs. Type and performance of chemicals will be discussed later. Knowing the local climate and historic weather events will provide guidance to managers for the potential use of solid and liquid chemicals as well as the need for abrasives when required.

Roadside design and maintenance impacts on drifting – Elevated road surfaces are common not merely for drainage and visibility but for reducing snow drift. Road cuts are notorious for accumulating blowing snow. Road design and snow fences are important considerations especially in open and windy areas. However, roadside vegetation can often be overlooked regarding its role in drift control. Desirable vegetation should be cultivated and encouraged on roadsides for many reasons including soil stabilization, weed control, reduced costs for mowing, safe driver visibility and snow drift reduction. In the west, alfalfa is trucked from one site to another on a daily basis. Seed from this plant is blown off trucks and is quickly established on the roadside. This can be a problem plant because it is desirable to animals such as deer, elk and antelope and the animals can be lured to the roadside during dry conditions. Mowing this plant is a temporary solution because it simply grows back and is one reason it is a good crop for farmers. If left for winter, plants can and will cause small drifts to form across the roadway that can lead to a need for continuous plowing. Alfalfa is not the only form of vegetation that can result in drifting but is a common problem. Sowing short growing and native grasses with some wild flowers for color is the best solution for many problems associated to roadsides and is attractive for travelers.

Rural versus urban environments – We have discussed open roads and snow movement but urban environments are different. Traffic loading is greatly increased in urban environments and with traffic comes the need for greater traction more of the time. As such, a manager may want to consider anti-icing with a high performance chemical even if a severe cold storm is forecasted and the roads are in a dry state. Snow can and will accumulate in town because traffic speeds are less than 45 mph often and so air convection is not enough to move snow off the road surface and it begins to accumulate. Once the snow-pack forms, pre-wetting of salt/sand can help maintain traction at intersections during the event. Getting traction back as soon as possible in urban environments is crucial while limiting the use of abrasives that can contribute to poor air quality and require cleanup to avoid clogged drains and sedimentation.

Performance and storage of winter chemicals – Use the chemical you can afford and one that works for your environment. Use historic data to look at how many days you have temperatures below the working range of salt brine. There are different perceptions on that temperature but a good rule of thumb is 15°F. Salt will continue to work below that temperature but the required quantity increases significantly for decreasing temperatures. Salt brine is a good product in temperate areas. However temperatures can and do drop low enough to freeze tanks, pumps and plumbing. Small lines delivering salt brine to pre-wetting and anti-icing systems can freeze and become closed if used infrequently. Often mixtures of agro-based products and higher performing chemicals are mixed with salt brine in an attempt to improve its performance in cold temperatures. Some informal laboratory tests have been done to see what percent of mixture is required to make a difference in salt brine. The results indicate a rather large percent is needed to change salt's inherit performance.

The storage ability of chemicals cannot be overstated. In rural areas, chemicals still play a valid role in winter maintenance but the quantity on hand is usually less. Smaller storage tanks are more prone to freezing than large ones. Diluting high performance chemicals, such as magnesium chloride ($MgCl_2$), by half again its volume with water will lower the freeze point of the chemical to nearly -30°F and ensure its freeze protection and handle ability for use pre-wetting solids. This is not necessarily a good practice for chemical used in direct anti-icing because loss of overall performance due to dilution.

In summary, extremely cold conditions bring different considerations for taking care of roads in the winter. Many of these considerations are learned and common sense to the professionals working these climatic areas over the years. But, there are some newer strategies that need to be modified to be used in this environment or perhaps not used at all. One of the hidden benefits to the cold is the lack of moisture. The closer the temperatures get to the thawing point, the more slippery snow packed roads become. Extreme cold is not slick compared with warmer moisture laden surfaces. If tires are spun or locked up during vehicle braking, friction is produced creating moisture between the tire and surface and slipperiness will occur so driving methods must also change with conditions. Winter maintenance managers and staff must assess their areas on a large and small scale to determine their needs.

2 Strategies for Extreme Temperatures

A comprehensive literature review and detailed survey analysis are available in Appendix A and B, respectively. Based on existing knowledge and research, several strategies for winter maintenance during extremely cold storms have been used by various DOTs. These include plowing, chemical usage, and abrasives. Each of these strategies has best practices to improve performance at extremely low temperatures.

2.1 Plowing

Plowing is the most ubiquitous method of removing snow and ice from roadways. Survey respondents rated it as the most common strategy used during extremely cold winter storms. Snowfall during low temperature storms tends to be drier and is initially easily blown off a dry road surface with light wind or turbulence from vehicular traffic. However, continued snowfall could contribute to packed snow or less-traveled lanes could see early snow accumulation. Snow with low moisture content and at temperatures far from the melting point can be more easily plowed from a road surface. Frequent plowing can help prevent snow and ice from sticking to the road surface.

The development of hard pack snow or ice at extremely low temperatures can be more problematic than at warmer winter temperatures because chemicals that can help break up snow and ice are less effective and more expensive at cold temperatures (more is needed and/or more expensive chemicals are needed). Many DOTs and counties rely on underbody plows to remove hard packed snow and ice. A scarifying blade can be used on front plows, but they are less effective at removing the pack (they more commonly scrape and put groves in the pack to help deicing) and they may wear down more quickly (CTC & Associates, 2010). The following types of blades or plows were specifically mentioned in the survey for low-temperature plowing: new cutting edges, serrated cutting edges, Joma blades, rubber mounted carbide cutting edges, anti-vibration cutting edges, triple edged plow blade (one of which is a serrated blade to cut ice or hard pack), tow plows, and underbody scrapers.

2.2 Chemical Usage

Use of deicing chemicals was the second-most common strategy by survey respondents (76 percent). Solid salt and salt brine were regularly mentioned by survey respondents although with frequent warnings about needing greater application rates and being less effective. Over half of the survey respondents indicated they use salt even at low temperatures. However, half also use $MgCl_2$ and about a third also use $CaCl_2$. Almost 20 percent use agro-based products in addition to salt. Potassium acetate and calcium magnesium acetate are used much less frequently. Keys for successful chemical usage include using a combination of salt or salt brine with other products such as $MgCl_2$, $CaCl_2$ (flake version mentioned several times) or agro-based products (beet products mentioned several times). IceSlicer was also mentioned several times as an alternative to plain salt for low-temperature effectiveness.

Chemicals applied before a storm for anti-icing may cause more problems during extremely low temperature storms. Anti-icing can cause snow to stick to the road surface sooner than it would otherwise at cold temperatures, and several survey respondents specifically mentioned anti-icing is not recommended for severe cold.

While some survey respondents indicated chemicals are not used for deicing at extremely low temperatures, others recommend deicing after the storm, during daylight hours or rising temperatures. All of these can help return a road to safe, bare dry conditions. Applying chemicals early usually resulted in continuously needing more chemicals. Prewetting of salt and abrasives was highly recommended, specifically using better low-temperature products such as $MgCl_2$, $CaCl_2$, and agro-based products. Because salt works slower at colder temperature, one recommendation was to apply abrasives on top of salt to provide traction and give salt some time to melt the snow/ice.

Tips for using chemicals in Extreme Temperatures:

- Applying chemicals early may lead to overuse
- Limit chemical usage to daylight hours or rising temperatures after the storm
- If chemicals are needed during a storm, try prewetting salt or abrasives with low-temperature products ($MgCl_2$, $CaCl_2$ or agro-based products)
- Try using abrasives on top of salt to provide traction and give salt time to work

Storage and handling of chemicals during severe cold can be more problematic, with salt caking, chunking, clumping and freezing and salt brine freezing/crystallizing in lines. Solutions offered by survey respo*ndents included: covered/inside storage or wind protection, testing salt deliveries for moisture* content, using anti-caking agents, using mixers, and adding additives to salt brine.

2.3 Abrasives

Abrasives are typically used at pavement temperatures below 12°F and on roads with low traffic and low level of service (Blackburn et al., 2004). Heated 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 (Perchanok, 2008; Dahlen and Vaa, 2001). Hot water in particular results in a sandpaper-like appearance on compacted snow and ice and is commonly used at airports in Norway during periods of prolonged cold temperatures (Klein-Paste and Sinha, 2007). Use of abrasives was the third most popular strategy according to the survey, with 68 percent of respondents indicating they use abrasives for extremely cold winter storms. Abrasives were particularly more common to low volume roads, whereas high volume roads received more chemical treatment. It may be appropriate on some stretches of rural roads to simply treat with abrasives throughout the winter season if extreme temperatures and prolonged snow cover is common and there are no expectations of a bare road.

2.4 Innovations

Technology continues to improve winter maintenance practices and strategies. A conductive asphalt pavement runway, SNOWFREE, at O'Hare International Airport demonstrated effectiveness during a -10°F storm (Derwin et al., 2003). A geothermal system used in Abo Pass in Japan that relies on spring water and a hot spring was used successfully to melt snow and ice in a location where the average minimum temperature is 0°F.

3 Conclusions

Successfully implementing a highway winter maintenance program requires appropriate selection of chemicals or pavement treatments for snow and ice control, obtaining the right equipment, having well-trained staff, making informed decisions, and proper execution of strategies and tactics. There is a substantial amount of knowledge in the published domain, regarding best practices of winter maintenance in the following categories respectively: *chemical usage*; *operational strategies*; *weather forecasting*; *winter maintenance equipment*; and *pavement treatments*. However, most of these best practices are versatile and there are limited research dedicated to best practices of snow and ice control at extremely low temperatures, which highlights the need for more research in this field.

Conventional practices for fighting winter storms at extremely low temperatures focus on the use of abrasives and plowing. Chemical usage still holds great promise in improving the effectiveness and efficiency of snow and ice control under such conditions, as new cost-effective chemical anti-icers or deicers emerge on the market. There is still room in improving operating strategies, weather forecasting, and equipment, so as to optimize the timing of winter maintenance operations and to maximize the outcome (level of service) and resilience of winter maintenance with the limited resources at hand. Pavement treatments generally bear higher cost per lane mile than the use of chemicals for snow and ice control, and thus should be targeted for problem locations where the best return on investment can be expected. Despite the limited reports, certain technologies (geothermal heating, conductive pavement heating, etc.) seem to indicate positive performance at cold temperatures (15°F or lower). Continued research and development can be expected in all these enabling technologies, while efforts are made to advance the knowledge base underlying the key interactions and processes between the pavement, snow/ice, and chemicals.

Strategies for extremely cold winter storms:

- Plowing
- Applying prewet abrasives
- Chemicals (new cost-effective low-temperature performance chemicals are still emerging)

In order to validate the effectiveness of identified best practices of winter maintenance at extremely low temperatures, field and laboratory testing is recommended to obtain quantitative benefits and comparisons. Field testing provides realistic storm and highway conditions, but a laboratory test may be able to simulate a larger variety of road–weather scenarios and provide more control over test variables. A recommended starting point is to document successful practices by various agencies so as to provide a framework for detailed test parameters and conditions.

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Appendix A: Literature Review

Introduction

Winter maintenance operations play an important role in assuring the safety (1,2,3,4,5,6,7,8,9,10,11,12,13), mobility (14,15,16) and productivity of highways enduring wintery weather. Winter highway maintenance activities offer direct benefits to the public such as fewer accidents, improved mobility and reduced travel costs. They also offer indirect benefits such as sustained economic productivity, reduction in accident claims, continued emergency services, and improved traveler experience. The operators and maintainers of highway networks are facing increasing demands and higher customer expectations during inclement weather, while confronting unprecedented budget and staffing constraints and a growing awareness of environmental challenges inherent in the use of chemicals and abrasives for snow and ice control. Despite dwindling or flat budgets, significant expenditures are still made with respect to winter highway maintenance activities. The U.S. spends $2.3 billion annually to keep highways clear of snow and ice (17); in Canada, more than $1 billion is spent annually on winter highway maintenance (18). In addition to labor costs, these funds are spent on a variety of materials, equipment and practices. Maintenance agencies are continually challenged to provide a high level of service (LOS) and improve safety and mobility in a cost-effective manner. To this end, it is desirable to use the most recent advances in the application of anti-icing and deicing materials (19), winter maintenance equipment and sensor technologies (20), and road weather information systems (21) as well as other decision support systems (22). Such best practices are expected to improve the effectiveness and efficiency of winter operations, to optimize material usage, and to reduce associated annual spending and corrosion and environmental impacts (23, 24, 25, 26).

Winter events present a variety of weather and pavement conditions that require various strategies to maintain the desired LOS of the roadway, often a combination of mechanical removal, anti-icing, deicing, sanding and possibly snow fencing. According to the 80-20 rule (also known as the Pareto principle), for many events or processes, roughly 80% of the effects come from 20% of the causes. This is true in the case of winter highway maintenance activities, in which a small fraction of the winter storms (extremely cold storms) tend to cost a majority of the annual budget for snow and ice control. As such, it is important to synthesize the state of the knowledge and the state of the art on ice prevention and snow and ice removal at extremely cold temperatures (e.g., below 15°F or -9.4°C).

A comprehensive literature search has been conducted to address this need, with a focus on best practices, emerging technologies, and relevant studies in the published domain (e.g., by DOTs, UTCs, SHRP, FHWA, NCHRP, APWA, and AASHTO). Wherever possible, efforts have been made to incorporate practices used in other fields (such as airports, cities, and counties) and by agencies beyond the U.S. (e.g., Canada, China, Japan, and European Countries). The following sections provide a summary of best practices in the following categories respectively: *chemical usage*; *operational strategies*; *weather forecasting*; *winter maintenance equipment*; and *pavement treatments*.

Chemical Usage

This section describes the availability of various winter chemicals for the prevention of ice bonding to pavement or for ice melting and removal, especially at extremely cold temperatures. Best practices of winter chemical usage are implemented to *apply the right type and amount of materials in the right place at the right time* for snow and ice control. Chemicals can be applied prior Prior to application onto roadways, liquid chemicals can also be added to abrasives or solid salts to make them easier to manage, distribute, and stay on roadways (pre-wetting). For simplicity, the term *deicer* is used hereafter to refer to all chemicals used for anti-icing, de-icing and pre-wetting operations. The relative performance and impacts of deicers have been extensively studied (Levelton Consultants, 2003 (24); Shi et al., 2009 (25)24, 25).

There are primarily five types of chemicals available in North America for snow and ice control on roads, i.e., sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KAc), and calcium magnesium acetate (CMA). All of these chemicals serve as freezing point depressants and have their own characteristics and impacts on the environment. While improving roadway safety and mobility, the use of these chemicals can lead to corrosion and environmental costs that should be taken into account (27). With the increased use of road salts, the general public and the trucking industry are increasingly concerned about the corrosion damage that snow and ice control operations may cause to motor vehicles (28, 29, 30). In addition, the corrosion damage of road salts to the transportation infrastructure (steel bridges, large span supported structures, parking garages, pavements, etc.) has significant safety and economic implications (31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43). Finally, the environmental impacts of road salts have been a subject of research since their usage became widespread during the 1960s for highway maintenance (26, 44,45,46,47). One study published in 1992 estimated that road salt imposed infrastructure corrosion costs of at least $615 per ton, vehicular corrosion costs of at least $113 per ton, aesthetic costs of $75 per ton (if applied near environmentally sensitive areas), and uncertain human health costs (48). Chlorides are generally considered the most corrosive winter maintenance chemicals (25). Often, commercially available, corrosion-inhibited versions of these chemicals are used to reduce their deleterious impacts on vehicles and infrastructure.

Chloride-based salts are the most common chemicals used as freezing-point depressants for winter road maintenance applications. According to a 2007 survey, most state Departments of Transportation (DOTs) continue to rely on chloride salts and abrasives (49) for winter highway maintenance. NaCl, or rock salt, is the most widely used chemical due to its abundance and low cost (50). It can be used as rock salt for de-icing, as salt brine for anti-icing, or added to sand or other abrasives to prevent freezing. A near record 20.3 million tons of NaCl were sold in 2007 in the U.S. (51). The Salt Institute suggested application rates of NaCl at 100 to 300 pounds per lane mile (30 to 90 kg per lane km) of solid material, and at 45 to 165 gallons per lane mile (105 to 388 liters per lane km) of 23% liquid salt brine. However, NaCl is rarely used and minimally effective below pavement temperatures of 10°F (52).

Table 1: Eutectic Temperature vs. Effective Temperature for Several Deicers

Deicer (Eutectic Concentration, Eutectic Temperature)	Minimum Effective Temperature (°F)	Reference
Sodium chloride, NaCl (23.2%, -6°F)	15	53
	14	54
	17.6	55
	14	56
Magnesium chloride, $MgCl_2$ (21.6%, -28°F)	-4	57
	5	53
	5	54
	5	31
Calcium chloride, $CaCl_2$ (30%, -60°F)	-20	53
	-13	54
	-13	31
Potassium acetate, KAc (50%, -76°F)	-15	53
	-26	58
Calcium magnesium acetate, CMA (33%, 14°F; or granular, -18.4°F)	14	57
	23	31

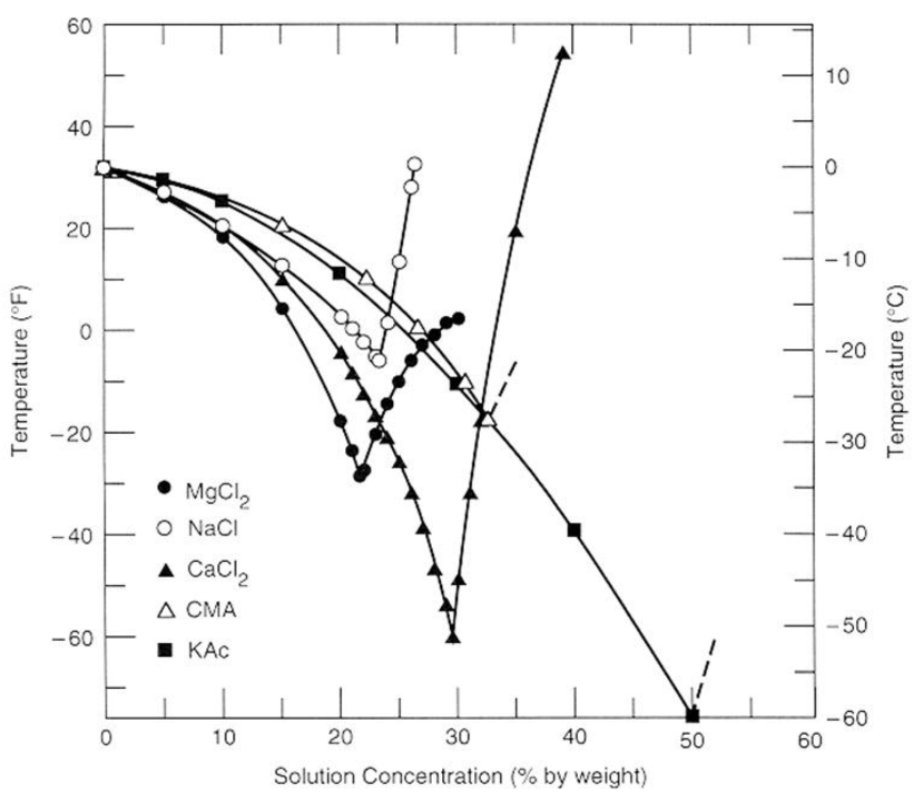

Figure 1: Freezing Point of Common Road Chemicals

Eutectic temperature is the minimum temperature a deicer solution remains in liquid form, which depends on the concentration of the deicer (usually expressed as percent weight of the solution). During the process of melting snow or ice, additional water is produced and the deicer is diluted, which may cause the solution to re-freeze. Thus, the eutectic temperature can be significantly different from the effective temperature for a deicer; and Table 1 presents the comparison of eutectic and effective temperatures for some common deicers. Most chemicals cease to be effective long before the eutectic temperature is reached. As temperatures drop below 15°F, NaCl and CMA are no longer as cost-effective and other deicers may be needed for snow and ice control. Similar to U.S., Nordic countries have reported the use of NaCl blended with liquid $MgCl_2$ or $CaCl_2$. Rock salt covered with a blended carbohydrate by-product has been proven as a good traction providing deicer. More high performance brines need to be developed when winters get more severe (59).

Figure 1 presents the eutectic curves of some common deicers, i.e., their freezing point temperature as a function of their aqueous solution concentration. It shows that NaCl generally performs best for melting above 15°F and stops melting altogether at -6°F. At extremely cold temperatures (15°F and lower), other chlorides and acetates are often used to supplement NaCl for ice-melting as they have a lower freezing point (60). Calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$) which exhibits better ice-melting performance than salt brine at cold temperatures is used by many DOTs in a brine solution for anti-icing or to pre-wet rock salt (61). However, $CaCl_2$ and $MgCl_2$ are more costly than NaCl, and they can be difficult to handle. At low relative humidity, their residue on roads can attract more moisture than NaCl, resulting in dangerous, slippery conditions under certain circumstances (62, 63, 64).

Field studies have shown $CaCl_2$ to be more effective than NaCl, owing to its ability to attract moisture and stay on the roads (65). The Maine DOT (66) conducted field evaluation of various approaches to treating an Interstate highway during a low-temperature January 2011 snowstorm that lasted about 7 to 8 hours. The agency found that applying pre-wetted sand with a 70/30 blend of salt brine and Ice B'Gone (a proprietary $MgCl_2$ blend) was more cost-effective relative to two other approaches (three applications of salt, or early salting followed by sanding). When temperatures fall between 0°F to 10 °F, crews in Alberta apply salt mixed with a small percentage of sand plus heavy application of liquid deicer ($MgCl_2$ or $CaCl_2$) to melt the ice on the road. The re-freezing problem will occur and deicing agents may be diluted by drifting snow. Manitoba's search for an alternative environmentally friendly deicing agents lead to an alcohol by-product produced by a nearby Crown Royal plant that was found to be effective. Other deicing agents containing sugar beet by-products are also being explored (66). A two-year study for the Colorado DOT found NaCl (liquid brine or solid), abrasives (non-volcanic), and Ice B'Gone have the lowest cost per lane mile, whereas, pre-wet abrasives, CMA, potassium acetate, and potassium formate were considered to be more costly per lane mile. Moreover, a CDOT staff survey respondent mentioned that Clearlane had been very useful because it worked in very cold temperatures (25). Cuelho et al. established best practices for removing snow and ice from roadways through laboratory and field experiments (67). The work found that anti-icing materials improved the ability of a plow to remove snow from the pavement surface, even at temperatures lower than 14ºF. $CaCl_2$ performed best on asphalt surfaces at all temperatures, while KAc performed best on concrete at all temperatures (0 ºF, 10 ºF, 15 ºF and 30 ºF) (67).

Table 2: Approximate Cost of Common Deicers

Deicer	Approximate Cost/Weight	Reference	Application Rate, Cost/Area
Sodium chloride (NaCl)	\$26/ton	56*	170-890 lbs/12-ft lane mile ($13\text{-}68\ g/m^2$), $\$0.0003/m^2$
	\$36/ton	68	
	\$20–42/ton	25	
	\$66–79/ton	60	
Magnesium chloride ($MgCl_2$)	\$95/ton	56	100-150 lbs/12-ft lane mile ($8\text{-}11\ g/m^2$), $\$0.0002/m^2$
	\$95/ton	68	
Calcium chloride ($CaCl_2$)	\$294/ton	56	Used along with NaCl in U.S., $\$0.03/m^2$
	\$120/ton	68	
	\$267/ton	60	
Calcium magnesium acetate (CMA)	\$670/ton	56	200-500 lbs/12-ft lane mile ($15\text{-}39\ g/m^2$), $\$0.004/m^2$
	\$1280/ton	68	
Potassium acetate (KAc)	NA	56	0.9 to 9.1 gal/1000 ft^2
Salt mixed with Calcium Chloride (NaCl and $CaCl_2$)	\$98/ton	56	5 to 12 gal $CaCl_2$/ton of NaCl, $\$0.01/m^2$

* Cost reported in 2009 US dollars. NA: Not Available.

Laboratory data demonstrate that, relative to NaCl, the use of $CaCl_2$ for comparable deicing performance between 0 and 10°F within 1 hour, would introduce five times fewer chloride anions and ten times fewer cations (69). Another laboratory study demonstrated that at 15°F and 5°F $CaCl_2$ produced more undercutting of ice on pavement materials than NaCl (70). Yet another laboratory study demonstrated that at 23°F the relative area deiced by chemicals followed the order of NaCl>$CaCl_2$>CMA>Urea, whereas their relative rate at which the chemicals debonded ice from pavement followed the order of $CaCl_2$>NaCl>Urea>CMA (71). Granular $CaCl_2$ can be combined with NaCl to increase the effectiveness of NaCl in cold conditions, as $CaCl_2$ acts quickly, gives off heat, and forms initial brine with moisture in the air (72). Based on a study sponsored by Colorado DOT, magnesium chloride (liquid), calcium chloride (liquid), Clearlane, potassium acetate, Ice B'Gone, De-ice, unspecified Agro-based, and sodium acetate were believed to be the best when it comes to low effective temperature, whereas abrasives, potassium formate and sodium chloride were considered to be the less effective (25).

In addition to chlorides, acetates such as potassium acetate (KAc) and calcium magnesium acetate (CMA) are used for anti-icing, but they are generally much more expensive. However, KAc and CMA can be more effective, less corrosive to carbon steel, and not as environmentally harmful as chlorides. Approximate costs of common deicers from several references are compiled in Table 2.

Additives such as agricultural by-products (ABPs) or organic by-product enhancers are also blended with these primary chemicals to improve their performances in snow and ice control. Known additives are corn syrup, corn steeps, and other corn derivatives; beet juice-sugared or de-sugared; lignin/lignosulfonate; molasses (usually from sugar cane); brewers/distillers by-product; and glycerin. A variety of agro-based chemicals are being used either alone or as additives for other winter maintenance chemicals (73). Agro-based additives increase cost but may provide enhanced ice-melting capacity, reduce the deicer corrosiveness, and/or last longer than standard chemicals when applied on roads (74). Furthermore, agro-based additives utilize renewable resources and have low environmental impact. Alkoka and Kandil examined a deicing product named Magic, which was a blend of ABPs and liquid $MgCl_2$ (75). The working temperature of the product was found to be down to -20ºF. Pesti and Liu evaluated the use of salt brine and liquid corn salt on Nebraska highways and found liquid corn salt to be more cost-effective because it achieved bare pavement conditions quicker than salt brine and contributed to more significant road user savings (76). Fu conducted field testing in the City of Burlington, Canada of two different beet molasses based materials (30% beet juice + 70% salt brine) and regular salt brine (23% NaCl) used as pre-wetting and anti-icing agents over nine snow events. The results indicated organic materials for pre-wetting under low temperatures did not perform significantly better. With a higher cost than regular brine, organic materials can reduce the amount of chlorides released into the environment. However, the results from this study are limited to the application rates and the observed winter conditions (77). The Swedish National Road and Transport Institute evaluated the friction characteristics of three types of mixtures. A brine made with 30% sugar beet flour used to pre-wet salt resulted in no significant friction improvement. Longer term performance was observed with sand mixed with hot water (78). Fay and Shi (19) developed a systematic approach to assist maintenance agencies in selecting or formulating their deicers, which integrates the information available pertinent to various aspects of deicers and incorporates agency priorities.

Recently, bio-derived freezing point depressants have been developed for airport runway or roadway applications. For each gallon of biodiesel produced, approximately 0.76 lb (0.35 kg) of crude glycerol is also produced and there is an urgent need to better utilize this by-product with added value (79, 80). Crude glycerol is also very cost-effective as it is available at \$0.02 per gallon, but it may need to be purified before used for snow and ice control. The addition of succinate salts and glycerol to salt brine will enhance anti-icing performance at cold temperatures to the level comparable to $MgCl_2$ or KAc at reasonable costs, while producing substantial savings through reduced application rates, reduced corrosion to metals, and reduced impact on concrete or asphalt materials. These chemical blends can be very cost-effective for certain road weather scenarios. For instance, a "Supermix" (85% salt brine, 10% De-ice, and 5% $CaCl_2$) was found to exhibit positive field performance when used for anti-icing above 15°F at 40 gallons per lane-mile or for pre-wetting above 2°F at 10 gallons per ton (81). Some Ohio counties have found that blending salt brine with 10–15% agro-based product or less than 10% $CaCl_2$ "can provide a significant increase in the residual of salt on higher volume roads when anti-icing and lower the effective working temperature of brine when pre-wetting at the spinner" (82). Taylor *et al.* evaluated the brines made of glycerol, NaCl, $MgCl_2$, and commercial deicers individually and in combination and concluded that the blend of 80% glycerol with 20% NaCl showed the greatest promise in good laboratory performance and low negative impacts (83). Nonetheless, this finding should be considered with caution, because this blend has very high viscosity and its dilution allows anti-icing application but reduces effectiveness. Furthermore, the use of glycerol may pose potential risk to water quality.

Developing deicer compositions using sustainable resources such as by-products of agricultural processes offers many advantages. This approach is beneficial to the environment by reducing wastes, decreasing impact, and creating environmentally safe deicers. Janke et al. developed an environmentally friendly deicer or anti-icing agent from a by-product of a wet milling process of corn called steepwater. The deicer formulation is noncorrosive, inexpensive, water soluble, and readily available in large quantities. Tests have shown that successful inhibition is achieved with the addition of these steepwater solubles to chloride salts (84). Similarly, Kharshan et al. demonstrated the successful increased corrosion protection of carbon steel using corn extracts (85). It is suggested that an amount of 20 to 60 gallons per lane mile of the steepwater deicer be applied to effectively clear snow and ice from roadways. When applied to roadways, the steepwater deicer is not easily removed by passing vehicles or wind and remains in contact with the road, which provides continued snow and ice removal with decreased application rates. Ice melting tests were conducted on about 20 square yards of 3.5-inch-thick snow comparing steepwater concentrated at 50% by weight of dry substance to an industrial salt/sand mixture. The steepwater demonstrated higher melting performance than the salt/sand mixture with respect to both duration and strength. In addition, the steepwater deicer also showed active ice melting at temperatures as low as 7.5°F, whereas the salt/sand mixture ice melting stopped around 20°F (84). Montgomery et al. proposed a deicer formulation, derived from corn steepwater, in which glucose and corn steep water is combined with sodium hydroxide to form a biodegradable deicer solution with a low freezing point around -26°C (86). Furthermore, corrosion testing resulted in little effect on mild steel. Mild steel bolts were immersed in and sprayed with various concentrations of steepwater and showed no oxidation after four months (84). Janke et al. proposed a noncorrosive, environmentally safe deicer composition made from vinters condensed solubles acquired from the processing of wine. This wine by-product deicer has a low freezing point of -20°F and is primarily carbohydrate-based (87).

In summary, chemicals are used during extremely cold winter storms for snow and ice control and can be a cost-effective option. There are still ongoing efforts to characterize and improve deicer performance at low temperatures.

Operational Strategies

Successful winter maintenance is reliant on a number of factors, including the selection and proper execution of operational strategies and tactics that are effective under the prevailing conditions. This is particularly true when handling maintenance activities in extreme temperatures, particularly below 15ºF (-9.4ºC). In the last two decades a transition in strategy from the use of abrasives to the wider use of chemicals has occurred in North America (88). A second transition in strategy has also occurred during that time, from deicing to anti-icing operations wherever possible (89). As temperatures become lower, such strategies may not be entirely appropriate. Often, the focus of agencies shifts to plowing operations and the use of abrasives (with some use of salt despite lower effectiveness) as temperatures become lower (66). However, other operational strategies may also be available that can be effective at low temperatures and consequently, there is a need to summarize these different strategies.

In practice, most agencies currently take a toolbox approach customized to their local snow and ice control needs and funding, staffing, and equipment constraints. Depending on the road weather scenarios, resources available and local rules of practice, DOTs use a combination of tools for winter road maintenance and engage in activities ranging from anti-icing, deicing (including direct liquid or slurry applications), sanding (including pre-wetting), to mechanical removal (e.g., snowplowing), and snow fencing. When the pavement temperature drops to below 10 ºF (-12.2ºC), the use of salt would become no longer cost-effective and highway agencies thus utilize other chemicals either alone or as pre-wetting agent to enhance the performance of salt (82) or apply abrasives to provide a traction layer on pavement. A recent synthesis completed for the Clear Roads pooled fund specifically examined strategies for maintaining roads at extreme winter temperatures (66). This included a summary of current literature, as well as agency practices for snow and ice removal at low temperatures. State practices identified through interviews with winter maintenance professionals included (66):

- Use of Abrasives
- Use of Deicing Agents
- Plowing
- Controlling Blowing and Drifting Snow
- Snow Storage

The Clear Roads report also provided information from a Maine DOT study that compared different operational strategies for a low temperature storm in January 2011. Operational strategies included delayed sand application, which was found to be cost-effective and provided traction until the road temperature reached 10 ºF, three applications of salt, which was effective but more expensive, and salting early and then sanding, which found that salt was ineffective as it was too cold for application (66). Collectively, these approaches showed the differences of outcomes that can result from different operations on the same roadway during the same storm at low temperatures.

Use of Abrasives

Recent surveys of state highway agencies (49, 66) indicated that abrasives are recognized to have their place at low temperatures, despite environmental concerns. During heavy snowfall, sand and grit are often used to provide traction. It is known that abrasives (e.g., sand) can pose negative impacts to water quality and aquatic species, air quality, vegetation, and soil and incur hidden costs (e.g., cleanup cost). Depending on its particle size, sand may contribute greatly to air pollution, can potentially cause serious lung disease, and is listed as a carcinogen (90). Sand also poses significant risk for water quality and may threaten the survivability of aquatic species especially during spring runoff (88). Even after cleanup, 50 to 90 percent of the sand may remain somewhere in the environment (91). The detrimental environmental impacts of abrasives generally outweigh those of chlorides and the use of abrasives requires at least seven times more material to treat a given distance of roadway, compared with salt (92). A literature review for the Wisconsin DOT highlighted the limitations of the use of abrasives in winter maintenance (93). The report noted that abrasives, especially those not pre-wetted, had limited effectiveness on roads with higher vehicle speeds. This indicates that the use of abrasives will not necessarily improve operations or mobility on many roads. Additionally, the report noted that abrasives do not necessarily contribute to reduced accidents, which was based on the work by Kuemmel and Bari (94). In 2001, Nixon (95) suggested that "significant changes may be needed in regard to abrasives usage in winter maintenance" and presented a matrix of recommended sanding practices by road type and traffic speed. Schlup and Ruess (96) provided a balanced perspective on the use of abrasives and salt, based on their impact on security, economy, and the environment.

Abrasives are typically used at pavement temperatures below 12.2ºF (-11ºC), and on roads with low traffic and low LOS (97). Pre-wetting has shown to increase the performance of solid chemicals or abrasives and their longevity on the roadway surface, thereby reducing the amount of materials required (89). Pre-wetting with deicing agents helps abrasives stick to the roadway, as does pre-wetting with hot water (98, 99). Dahlen and Vaa (100) found that "by using heated materials or adding warm water to the sand it is possible to maintain a friction level above the standard, even after the passage of 2,000 vehicles".

The current developments of snow and ice control in many European countries focus on increasing road safety, reducing salt/abrasive materials use, and achieving higher service levels at similar or lower costs. To reduce salt usage, new spreading systems and methods are being evaluated such as pre-wetting with ABP modified brines or direct application of liquids. Observations were made on two runways in Norway during operation under cold weather conditions. A new sanding method based on a mixture of sand and hot water has been adopted at some airports in Norway. This method showed promising results as a long-lasting effect was observed along with the prevention of sand from being blown to the side by operating aircraft. However, an event occurred where the treated surface lost its frictional properties (101). Klein-Paste et al. published a report that describes the specifications of a new sanding method that has been adopted at different Norwegian airports. The new method of wetting the sand with hot water before applying it onto the runway surface results in a sanding pattern where the particles are bonded to the surface, creating a sandpaper-like appearance. Its performance in practice, optimization, negative effects, and limitations are also discussed (102). During the winter of 2003-2004, field tests comparing salt pre-wet with hot water versus pre-wet with brine showed similar performance on thick ice and that pre-wetting with hot water provided better friction improvements on thin ice (103). Vaa and Sivertsen observed that Norway's winter maintenance operations and found that mixing hot water and sand was an effective alternative to salting when temperatures were low. While a specific temperature associated with this operation was not specified, subsequent text indicated salting was performed down to 12ºF (-8ºC) (104). Similar work in Norway observed that pre-wetting salt with hot water produced higher friction levels and was more rapid at deicing, although a temperature range for this approach was not specified (105).

Chemical Deicers, Plowing, and Snow Fencing

The NCHRP Report 577, while focusing on the mitigation of the environmental impacts of snow and ice materials, also provided guidance on application rates and temperatures for different maintenance operations. Anti-icing was cited as being applicable down to an air temperature of 10ºF, deicing applicable down to 0º F, pre-wet and dry abrasives were applicable at all temperatures, and abrasive/salt mixes were applicable down to -1ºF (106). Additionally, pre-wet salt could be applied at temperatures down to -1ºF.

The NCHRP Report 526 provided guidelines for snow and ice control methods and operations. It provided several figures for temperatures that different strategies were effective. Anti-icing was considered effective at air temperatures above 15 ºF, while deicing was applicable in conditions below 20ºF. Nonetheless, chemical application rates may in some cases be excessive in order to achieve effectiveness (107). Mechanical removal (e.g., plowing) was indicated to be effective at low temperature pavement conditions (below 12º F) where deicers are not effective. Abrasives were indicated to be effective at all temperatures, while combinations of strategies (e.g., abrasives and chemicals at low temperatures) can also be effective in many cases.

Bazlova et al. developed an automated decision support system for winter road maintenance operations in Russia (108). This included a module that provided recommended operations for air temperatures below 19º F. Recommended operations in this specific case for a dry road surface included the use of 15% to 20% NaCl (50 g/m^2) during the day and 5% to 10% NaCl (30 g/m^2) at night. Guidance for other extreme temperature conditions, including a wet or snow covered road surface were not specified by the authors.

In the U.S., northern tier and mountain states have much colder temps and greater snow amounts than the southern tier. However, even the southern tier may experience severe to extreme temperatures occasionally. In addition to geographical location, intensity of precipitation, and cost, pavement temperature is a key parameter to consider when selecting the operational strategies and/or the application rate of materials. Traditionally, large amounts of NaCl are used for snow and ice control on pavement, which works well down to approximately -12.2ºC (10 ºF). As the pavement temperature gets colder, higher volumes of salt are required to achieve a reasonable LOS. As such, the use of salt is no longer cost-effective and highway agencies thus utilize other chemicals either alone or as pre-wetting agents to enhance the performance of salt (82) or apply abrasives to provide a traction layer on pavement.

Rochelle (109) evaluated various chemicals for anti-icing in the laboratory and found that "the presence of chemical, regardless of chemical type, increased the friction of the pavement surface and reduced the shearing temperature as compared to non-chemically treated substrates for all pavement types, all application rates and all storm scenarios". Chemicals (especially $CaCl_2$) used at low temperatures were indicated to have the potential to create an ice film. Packed snow and thin layers of ice can be difficult to remove at low temperatures, although scarifying or ice chipping blades have been effective in such cases (66). As such, a combination of chemicals and snowplowing is considered the best practice for snow and ice control at extremely low temperatures. Boselly et al. established winter maintenance operations procedures for the Arizona DOT, which included guidance on snow removal and chemical applications for a variety of different condition categories. Among these was an air temperature range below 12 ºF. Below this temperature, recommended operations included mechanical removal (e.g., plowing) without chemicals if snow and/or ice were unbounded to the pavement, application of chemicals if snow and/or ice were bonded, and the application of abrasives as needed (110).

Defined as "the practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant" (111), anti-icing (also known as chemical pretreatment) has proven to be a successful method of maintaining roadways during the winter season. Relative to deicing and sanding, anti-icing leads to improved LOS, reduced need for chemicals, and associated cost savings and safety/mobility benefits (89, 112, 114). Russ et al. (113) developed an anti-icing decision tree for the Ohio DOT, which aimed to help maintenance supervisors consider a number of factors, including: current road and weather conditions, the availability of maintenance personnel and the best treatment strategy. The approach took into consideration of whether the temperature for the upcoming day would be above 20 ºF, along with other factors, when deciding whether to pretreat. The 20 ºF threshold was established based on the feedback of ODOT personnel and their experiences in the field. The use of this threshold would seem to indicate that anti-icing is not necessarily an operational strategy that should be considered at low temperatures. As part of a synthesis on anti-icing operations, the Minnesota DOT indicated liquid NaCl being effective down to a temperature of -6ºF. However, the document also points out that anti-icing with solid or pre-wetted chemicals is not a good strategy when pavement temperatures are below 15ºF (114). Cuelho et al. established best practices for removing snow and ice from roadways through laboratory and field experiments (67). The work found that anti-icing materials improved the ability of a plow to remove snow from the pavement surface, even at temperatures lower than 14ºF. $CaCl_2$ performed best on asphalt surfaces at all temperatures, while KAc performed best on concrete at all temperatures (0 ºF, 10 ºF, 15 ºF and 30 ºF).

A recent Clear Roads study (115) synthesized the current practices of during-storm direct liquid applications (DLA) and found DLA to be "a valuable asset for the winter maintenance toolbox". The DLA benefits listed by the synthesis include: reduced application rates, reduced loss of materials, faster post-storm cleanup, quick effect, further prevention of bonding, expanded toolbox, accurate low application rates, reduced corrosion effects, and leveraging proven benefits of liquids. However, in all of the cases where DLA was used, the researchers found that it was not employed below pavement temperatures of 20 ºF.

Pre-wetting accelerates the dissolution of solid chemicals and enhances its melting action (116). Relative to dry salt, pre-wetted salt (with 10-mm or smaller particles) has been proven to be better retained on dry roads and its spreading leads to less wasted salt and quicker deicing effect (117). While pre-wetted salting may lead to significant salt savings (averaged at 25%), it "might not be applicable in all adverse winter weather conditions". When using liquid $CaCl_2$ to pre-wet solid NaCl, the author concluded that "in mild winters the use of prewetted salt may offer no additional benefits" (117). Luker et al. (118) compared the performance of dry rock salt and six pre-wetted salt mixtures in the laboratory. The rate of pre-wetting was explored at 4, 8, and 12 gallons of liquid chemical per ton of rock salt respectively, and the melting of compacted snow improved with the rate of pre-wetting. Pre-wetting salt slightly decreased its performance at relatively warm temperatures (–1°C and –5°C) in some cases but "all of the prewetted mixtures were effective at –10°C, unlike the dry rock salt".

Devries and Hodne discussed the findings of work done by the Iowa DOT and McHenry County (Illinois) Division of Transportation using blended anti-icing and deicing agents. The blend that was identified as suitable for all weather conditions consisted of 85% salt brine, 10% De-ice, and 5 percent $CaCl_2$ (81). This "Supermix" was successfully used for anti-icing above 15°F at 40 gallons per lane-mile or for pre-wetting above 2°F at 10 gallons per ton. In sand pre-wetting applications, the mix was effective down to 2 ºF, although the mix was not applied at temperatures below 15 ºF. During the first year of using "Supermix" a significant reduction in the amount of $CaCl_2$ used was documented (from 23,000 gallons down to 2,704 gallons) (81).

Tabler examined the effects of blowing snow and snow fences on pavement temperatures and ice formation on roadways. It was found that areas protected with snow fences were as much as 10ºF warmer than on adjacent, unprotected pavement. This finding has impacts on low temperature maintenance operations, as it has the potential to allow for more treatment options to be available that may have higher ranges of effective temperatures (119). The control of blowing or drifting snow can create a layer of ice on pavements at low temperatures. Snow fences, snow ridges, general highway design (account for the potential of a design susceptible to drifting), plowing techniques and the use of Road Weather Information Systems (RWIS, to forecast likely drifting) have all been effective in addressing drifting at low temperatures. With regard to highway design, tools have been developed to account for blowing and drifting snow in the design process, such as SnowMan from the New York DOT (120).

Snow Storage

While not limited to extremely cold temperatures, winter storms can bring a significant quantity of snow that requires planning for storage and possible relocation. Highway agencies have indicated that snow storage is an effective strategy as it removes snow from the roadway environment that may be susceptible to drifting (66). The simplest solution for dealing with significant amounts of snow is to store the snow adjacent to the roadside, but this may not be feasible everywhere, especially in urban areas. Other options include: removing the snow to dedicated snow storage areas, which may be equipped with facilities to treat the melt water (impurities can include deicers, oil, grease, heavy metals, litter, and dirt); or using mobile snow melters (121). Due to the increased cost of removing snow adjacent to roadways, considerations should be made for snow storage in the planning process of road design or reconstruction (66).

Weather Forecasting

In order to meet winter road maintenance challenges, it is crucial to obtain and utilize accurate weather information (82). Otherwise, the consequences could be: excessive use of chemicals and materials, failure to respond in a timely matter to a storm event (resulting in greater crash risk and user delay), unplanned use of overtime staffing, etc. Improvements in weather information can help in all stages of winter storm response, including pre-, during and post-storm. Near-real-time weather and road condition information and customized weather service are valuable to the success of proactive maintenance strategies (122,123). Anti-icing is more sensitive to weather conditions than other winter maintenance practices, since anti-icing is a proactive practice that is sensitive to pavement temperature, dilution, and other factors (124). When considering the choice between spatially or temporally improved forecasts, Fu et al. found that improved spatial resolution of forecast data will provide greater expected benefit to service levels (125).

Mesonets are regional networks of weather information that integrate observational data from a variety of sources and aim to provide a more comprehensive and accurate picture of current weather conditions (126). Current mesonets include Washington State's rWeather, University of Utah's MesoWest, Iowa's WeatherView, and California's WeatherShare, to name a few. The Clarus Intiative is working at the national level to develop partnerships to establish a road weather observation network- providing integrated and quality atmospheric and pavement observations from mobile and fixed platforms (127, 128, 129). These data management systems are expected to maximize availability and utility of road weather observations and facilitate more accurate, route-specific forecasting of road weather conditions.

The SHRP sponsored research in the early 1990s examined the potential benefits of improved weather information (130, 131). The study analyzed the potential cost-effectiveness of adopting improved weather information (including RWIS and tailored forecasting services), which used a simulation model based on data from three U.S. cities. It indicated that the use of RWIS technologies can improve the efficiency and effectiveness as well as reduce the costs of highway winter maintenance practices. Ballard identified a number of benefits available from RWIS in California, including the increased ability to obtain meteorologically accurate data and the potential for data dissemination and exchange with other agencies (21). Strong and Fay found that Alaska's benefits from RWIS usage included: reduced staff overtime, less misdirected staff time, fewer wasted materials and equipment, and improved roadway level of service (132).

Shi et al. (122) examined the labor and materials cost for winter maintenance in the 2004-05 season for 77 Utah DOT sheds and established an artificial neural network model to treat the shed winter maintenance cost as a function of UDOT weather service usage, evaluation of UDOT weather service, level-of-maintenance, seasonal vehicle-miles traveled, anti-icing level, and winter severity index. The model estimated the value and additional saving potential of the UDOT customized weather service to be 11–25 percent and 4–10 percent of the UDOT labor and materials cost for winter maintenance, respectively. It was also estimated that the risk of using the worst weather service providers to be 58–131 percent of the UDOT labor and materials cost for winter maintenance. The UDOT Weather Information Program was estimated to feature a benefit–cost ratio of 11:1.

Ye (123) and Shi et al. (122) conducted three case studies to analyze the benefits and costs associated with the use of weather information for winter highway maintenance. The survey of winter maintenance personnel found that free weather information sources, private-sector weather providers, and RWIS were the most widely used weather information sources. Air temperature, wind, and the type and amount of precipitation were primary parameters of current and forecast weather conditions, whereas road weather elements (e.g., pavement temperature, bridge temperature, and pavement conditions) were also widely used in winter maintenance. The case studies collectively showed that winter maintenance costs decreased as the use of weather information increased or its accuracy improved. Table 3 summarizes the benefits and costs associated with weather information for winter maintenance. The study (123) recommended that the use of weather information be more focused towards the road environment, in order to develop better winter maintenance strategies. In addition, the maintenance agencies should continue to invest in road weather information with high accuracy (such as RWIS and customized weather service) and to ensure high usage of the existing road weather information services.

Table 3: Case Studies of Weather Information of Winter Highway Maintenance

Case Study State	Winter Season	Winter Maintenance Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit–Cost Ratio	Benefits / Maintenance Costs (%)
Iowa	2006–07	14,634	814	448	1.8	5.6
Nevada	2006–07	8,924	576	181	3.2	6.5
Michigan	2006–07	31,530	272	7.4	36.7	0.9

Note: The benefit–cost analysis only considered agency benefits and did not include benefits to motorists and society.

Winter Maintenance Equipment

This section describes various winter maintenance equipment to enable best practices of snow and ice control, especially at extremely cold temperatures. Cutting-edge equipment technologies can make maintaining winter roadways more efficient, safer and less costly. The advent of these technologies has facilitated the management of operations and saved resources and time (116). These technologies assist maintenance agencies in offering a higher LOS to roadway users, while being more sensitive to the surrounding environment.

The technologies for snowplows are constantly evolving, ranging from low-tech calibrated spreaders, to multi-purpose trailers (82), to high-tech vehicle guidance systems. Kroeger and Sinhaa, in developing a highway maintenance concept vehicle (HMCV), indicated that the use of advanced technology in anti-icing operations could potentially reduce accident rates by 73 to 80 percent (133). While this range was developed through a review of existing literature, it does indicate the potential that anti-icing coupled with technological advances (e.g., controllers) holds in improving safety. Numerous vehicle-based sensor technologies, including automatic vehicle location (AVL), mobile RWIS technologies (surface temperature measuring devices, on-board freezing point and ice-presence detection systems, and salinity measuring devices), visual and multi-spectral sensors, and millimeter wavelength radar sensors, have been developed in recent years to achieve improvements in winter maintenance efficiency and safety. Shi et al. (20) conducted a comprehensive literature review and practitioner surveys in 2007, the results of which show that AVL systems and road surface temperature measuring devices are the only ones that had matured and became fully operational; the remainders were still in the development and testing phases.

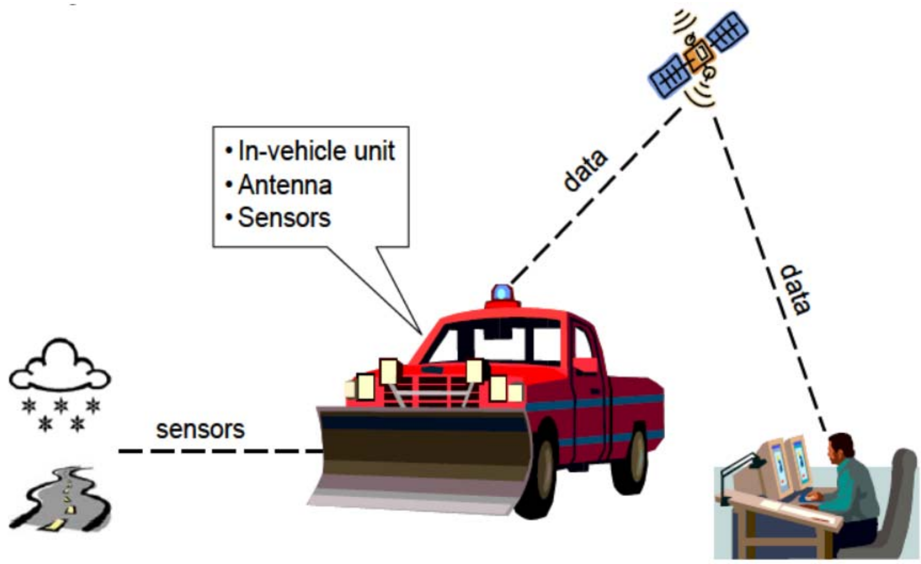

Figure 2: Schematic of AVL system

AVL

As illustrated in Figure 2, the AVL technology incorporating global positioning systems (GPS) has been used to track and provide real time information on winter maintenance operations, such as: type of applied material, application rate, position of plow blade, pavement temperature, etc. (134). AVL integrates vehicle location information with other information from the vehicle to provide temporally and spatially referenced information on a maintenance vehicle's activities. AVL can assist in storm response through vehicle tracking and dispatching capabilities. It can also guide storm event planning by providing previous storm event histories. AVL can also help agencies simplify tracking and reporting requirements, thus decreasing the paperwork and time required to manage winter maintenance activities.

There is a rich repository of documented experience on lessons learned and best practices for use of AVL in winter maintenance operations. Some of the major themes include: the need for thoughtful integration of AVL into an existing vehicle fleet and with the variety of expected users and sensor packages, and the need to consider the communications requirements of the various technologies. Through several years of demonstration and evaluation, many of the problems which plagued earlier AVL deployments (e.g., sensor protection, communications availability, and GPS accuracy), have been addressed. The level of support from the vendor community has improved as AVL vendors have become flexible, adapting and customizing systems to fit specific customer requirements. Vendors also provide customized maps, statistical analysis, and reports as requested by the customer. Table 4 presents some examples of AVL implementation in the U.S. and Canada (135). Colorado, Kansas, Iowa, Maryland, Michigan, Minnesota, and Virginia in the U.S. as well as Ontario, Canada have implemented AVL technologies (136).

Table 4: Examples of AVL implementation in North America (3)

Study	Location / Duration	Findings
Anderson [2004]; Roosevelt *et al.* [2002]	Northern Virginia, VA, USA / 1996 – 2000	The pilot test performed reasonably well in mapping vehicle location. Several areas needed for potential improvement (e.g., short update speeds, temporary in-vehicle unit installation).
FHWA [2003]; CompassCom [2003]	Wayne County, Detroit, MI, USA / 1997	There was a 3 to 4 percent reduction in "deadhead" miles (the distance where the vehicle is not actively treating the road) on freeway routes. The results showed reduced salt consumption, reduced operational costs, quick response time, and reduced fatigue for dispatchers and drivers during peak operations.
Maryland Bureau of Highways [2005]	Howard County, MD, USA / 2000-01	The system allowed managers to monitor maintenance real-time. Call volume concerning road conditions was decreased. It allowed the 911 dispatchers to route emergency vehicle.
Anthony [2004]	Vaughan, ON, CAN / 2001-02	AVL implementation resulted in a significant decrease in complains, better coordination, better information for city council members and residents, and better management of in-house and contract services.
Meyer and Ahmed [2003]	Kansas, USA / 2003	The benefit-cost ratio would be at least 2.6. Benefits included more timely response, improved resource management, reduced material costs, reduced legal costs, etc.

To implement AVL, both initial (capital) and on-going (operations and maintenance) costs should be considered (20). The capital costs will be highly dependent on the level of software development and customization required, while the operations and maintenance costs will be based primarily on the cost of communications. These costs are estimated based on different type of requirements. Through several years of demonstration and evaluation, AVL users generally plan to sustain or increase their use of the technology. During the winter of 2009-2010, Wisconsin DOT implemented AVL. They estimated a benefit/cost ratio in the range of 1.05-1.89, depending on the cost of salt and percent reduction in salt usage (20).

Road Surface Temperature Devices

Pavement temperature is a key parameter for winter maintenance decision-making (e.g., timing and application rate of anti-icing or deicing); and it may fluctuate greatly as a function of time, location, pavement type, chemical presence, etc. As such, it is highly important to be able to monitor the temporal and spatial distribution of pavement temperature in a real-time fashion (137). The benefits of road surface temperature measuring devices have been demonstrated by DOTs. In 1999, the Missouri DOT conducted a research project to evaluate the benefits of the Sprague RoadWatch™. The project included a laboratory test as well as a field evaluation of 50 mirror-mounted pavement temperature sensors distributed throughout the state. The laboratory test results indicated that the sensors were accurate within ±1°F (±0.6°C) between 5°F and 38°F (-15°C and 3.3°C, respectively). Field personnel from the control group were allowed to use weather forecasts, air temperature and past experience to make winter maintenance decisions. Field personnel from the test group had access to road surface temperature via infrared (IR) sensors in addition to weather forecasts, air temperature and past experience. Excluding the savings from personnel and equipment, the project estimated a material savings of $185,119 during the winter of 1998-99. Assuming one year as the life of the sensors, the project team calculated the benefit/cost ratio to be 9.49 (138).

TowPlow and Other Plow Configurations

Lannert discussed the use of wider front plows to clear one 12-ft lane in one pass in Missouri using a 14 foot wide plow. The cost of this conversion was less than $400 per foot of plow. The benefits obtained from this practice included: a reduction in the number of passes needed, saved fuel, and reduced labor (139). The use of trailer plow (*TowPlow*) was also discussed, which produced the benefits of one snowplow truck and operator clearing over 24 feet of lane at high speeds while reducing fuel usage through the elimination of multiple plows. The author noted that towplows also can reduce an agency's capital investment needs by 20% to 30% and still achieve the same amount of work (139).

Table 5: Cost Comparison of TowPlow vs. Regular Plow Truck

Parameter Comparison

Equipment	*Fuel Efficiency (mpg)*	*Labor Cost ($/hr)*	*Operational Speed (mph)*	*Fuel Cost ($/gal)*
TowPlow	3	40	25	3.8
Regular Plow Truck	5	40	30	3.8

Operational Comparison (per hour)

Equipment	*Labor ($/hr)*	*Fuel ($/hr)*	*Total ($/hr)*
TowPlow	$ 40.00	$ 31.67	$ 71.67
Regular Plow Truck	$ 80.00	$ 45.60	$ 125.60

Operational Comparison (per mile)

Equipment	*Labor ($/mi)*	*Fuel ($/mi)*	*Total ($/mi)*
TowPlow	$ 1.60	$ 1.27	$ 2.87
Regular Plow Truck	$ 2.67	$ 1.52	$ 4.19

Several State DOTs currently are using the TowPlow including Iowa, Minnesota, Missouri, Nebraska, Utah, and Wisconsin among others. The TowPlow, designed and first utilized by the Missouri DOT and manufactured by Viking Cives Ltd. of Mount Forest, Ontario, Canada, allows the snowplow driver to clear two lanes of pavement at once, reducing road and shoulder clearing time. The TowPlow's greatest advantage is the ability to clear two lanes of pavement at one time, reducing fuel costs and allowing one driver to complete work that would normally require two. The driver can plow the shoulder while plowing one driving lane or the driver can plow two driving lanes simultaneously (140). Macfarlane discussed the use of a plow truck equipped with a reversible plow and wing. In addition, dedicated left-hand cast plows and wings lack flexibility due to use only on multi-lane, wide-median highways (141). A better solution is the use of a reversible plow and switchable wing mounting which could be used for all multi-lane and conventional operations by swinging the plow and mounting the appropriate wing. The trials by the New Brunswick DOT in 1995 identified several benefits, including: improved plowing efficiency and equipment versatility, reduced run-up collisions, and operators of plows having improved visibility due to the elimination of the snow cloud generated by a right-hand wing equipped lead truck. Limitations included: drivers being disoriented when carrying the left-hand wing as it required extra attention in preventing the wing from hanging over the centerline. Additionally, while the wings are easily interchangeable from the left to the right side of the vehicle, the change must be performed in the yard or shop, and cannot be done mid-route.

During the winter of 2009-2010, Wisconsin DOT implemented TowPlow. As detailed in Table 5, they estimated a 32%-43% operational cost savings for using a TowPlow to complete the same task as a regular plow truck (142).

Some other important snowplow technologies include: an improved displacement snowplow (143), an automated snow blower or rotary plow (144), driver assistive technologies such as the Minnesota's Intelligent Vehicle Lab Snowplow Driver Assistive System, California's Advanced Snowplow Driver Assistance System, and the emerging use of laser technology for collision avoidance (145), and virtual snowplow training (146). Limited published materials are available regarding the costs and benefits of lighting packages for winter maintenance vehicles (147,148,149). Vehicle guidance and collision avoidance systems have been used to assist snowplow drivers in low visibility conditions. This technology seems to be most beneficial on high volume roads that experience frequent road closures from winter weather (150).A Utah DOT study found that during a 6-month period following simulator training, a plow driver's odds of being in an accident were lower compared with an untrained group. Additionally, data indicated that fuel efficiency was greater for the simulator-trained drivers (151).

Dispensing Technologies

Material placement systems have been documented to various degrees and there are a few cost-benefit studies of them in the published domain (152,153,154,155). In the winter road maintenance context, "spreading operations are directed at achieving three specific goals…: anti-icing, deicing, and traction enhancement...the selection of the appropriate spreading operation is based on economics, environmental constraints, climate, level of service, material availability, and application equipment availability" (156). Hoppers configured to allow the snowplow to carry and spread both liquid and granular materials in different amounts are becoming popular, especially in areas sensitive to certain chemicals and materials.

Currently, the vast majority of road agencies use spreader systems that are adjustable as to amount of material applied per lane mile. Spread rates can be manually reset by in-cab controls. There is also application equipment that adjusts the application rate of snow and ice control materials based on real-time data from onboard sensors (157). An advanced version of such systems has been patented, which claims to enable "coordinated application of a plurality of materials to a surface simultaneously and in desired proportions and/or widths automatically and/or selectively" (158). Another patented technology is a surface condition sensing and treatment system, which includes an Electromagnetic Radiation (EMR) transmitter used to determine one or more characteristics of a road surface such as friction, ice or snow, and freezing point temperature as well as depth, density and composition of the road surface material. The system also comprises a geographic information system (GIS), material spreader control system and a temperature sensor. The system features manual or automatic material spreader control by using the information obtained from the sensing devices and weather forecasts. The system may be controlled both remotely and locally, and the data may be transmitted, received and processed. The researcher indicated that the entire system may also have a vehicle-mounted application (159).

Table 6: Cost of HMCV (in 2002 USD)

Equipment Item	*Cost*	*Vendor*
Chassis – International	$65,500	Monroe Snow & Ice Control
RDS Dump Box	5,500	Same
Front Plow	4,000	Same
Sander/Salter	2,600	Same
Underbody Blade	6,600	Same
On-board Pre-wetting	2,500	Same
Anti-icing Spray Bar System	14,000	Same
DCS 710 Ground Speed Controller	8,000	Raven Industries
Added Features for HMCV		
Surface Temp. Sensor	800	Sprague
AMS 200 Data Management	2,500	Raven Industries
Trakit AVL *	4,663	IDA Corp
DGPS Antennae	1,400	Communications Systems International
HID Plow Lights	1,100	Speaker
Frensor Mobile Freeze Point Detection	Provided**	Aero Tech-Telub
Total	**$119,163**	

*The Trakit AVL costs are hardware and software only. The HMCV incurred additional charges for testing and development of the communications system.
**The Mobile Frensor was provided by AeroTech-Telub for the field tests that were conducted. If purchased, the cost of the Mobile Frensor is approximately $10,500.

Starting in 1995, several state DOTs (Iowa, Pennsylvania, Wisconsin, etc.) have been developing a HMCV that incorporates some of the latest technologies, including: temperature sensors, friction sensors, freeze point sensors, high intensity lights, GPS/AVL, ground speed spreaders, pre-wetting equipment, liquid spreaders, power boosters, and underbody plows (160). The goal has been to re-engineer highway maintenance vehicles so as to address universal, ever-growing challenges in snow and ice control. The HMCV project discussed several anti-icing, deicing and pre-wetting systems/control methods used in the different prototypes (161). Minnesota, Iowa and Michigan prototypes all employed a V-box in the dump body and a 900 gallon liquid tank. The

Minnesota prototype systems were controlled by the vehicle operator who specified and maintained predetermined application rates. For the Iowa prototype, anti-icing and pre-wetting application rates were controlled by the vehicle operator, while a granular material controller automatically adjusted application rates based on vehicle speeds. For the Michigan prototype, anti-icing, deicing and pre-wetting were automatically controlled based on vehicle speeds and a targeted application rate range set by the operator. The presence of more than one material on-board the vehicle allowed operators to adjust strategies based on current road and weather conditions. No discussion of the effectiveness of the different spreader control strategies was provided by the report. In the third phase of the HMCV project, a decision matrix was prepared to automatically control the spreading of chemicals based on the information available (162). This prompted the fourth phase of the HMCV project that investigated the feasibility of integrating location data (GPS/AVL), on-board sensor devices, and friction measurements with an automatic material spreader system. A rule-based algorithm using the FHWA Manual of Practice for Snow and Ice Control guidelines was coded into an application capable of controlling the material distribution (163). It was concluded that a State agency using advanced technology with the concept vehicle would reduce material usage and operating time and hence result in a reasonable benefit/cost ratio. The cost of HMCV items is detailed in Table 6; however, the benefit-cost analysis was not conducted since not all technologies were deployed on the vehicles (164).

The Minnesota DOT developed a spreader control that used on-vehicle friction sensors to automatically adjust a zero-velocity spreader (165). The controller was found to adequately apply granular materials up to speeds of 25 mph. According to a recently completed Clear Roads study (166), "automatic control of material application rates is achieved with ground-speed-oriented controllers. This type of controller has been used in Europe since the 70s. …(in this study), actual salt, abrasive, and pre-wetting liquid chemical dispensing rates from spreader trucks with various types of manual and ground-speed-controller units were investigated and documented from both a yard study and in simulated field settings that would be used during winter storm events". Eight spreader/controller combination products were tested, and they were manufactured by Cirus Controls, Component Technology, Dickey-John, FORCE America, Muncie Power Products, and Pengwyn, respectively (167).

Snowplow Blades

There are limited studies on the relative performance and cost benefits of plow blade options (168,169,170,171,172). The key research is summarized in Table 7 (173). Much of the research has been focused on plow performance and blade wear; some of the research also has been focused on adverse impact of edges on surfaces and raised objects (manhole covers, expansion joints, etc.).

Table 7: Snowplow Cutting Edges for Improved Plowing Performance, Reduced Blade Wear, and Reduced Surface Impacts (173)

Subject	*Research*	*Year*	*Improved Plow Performance*	*Improved Blade Wear*	*Reduction of Impact to Surface, Markings, etc.*	*Overall Improvement*
Rubber-Encased Steel Blades	WisDOT Evaluation	2001	Yes	Yes	Yes	Yes
Rubber-Encased Steel Blades	Ohio DOT Evaluation	2008	Yes	Yes	Yes	Yes
Rubber-Encased Steel Blades	Clear Roads Product Experience Feedback (OH, MO, MN)	2008	Yes	Yes	Yes	Yes
Rubber-Encased Steel Blades	Mn/DOT Maintenance Research	2006	Yes	Yes on Bituminous	-	Yes on Bituminous
Rubber-Encased Steel Blades	Iowa DOT Evaluation	2001	Yes	Yes	Yes	Yes
Alternative Carbide Edge Snow Blades	Maine DOT Evaluation	2004	No	No	-	No
Solid Rubber Blades	Mn/DOT Evaluation	2008	No	No	-	No
Adjustable Blade System	Iowa DOT	2009	Research in progress			

A recent report summarized the experiences of Ohio DOT and other highway maintenance agencies with Joma plow blades (82). Benefits of the Joma blade include: no metal-to-metal contact between the blade and plow, vibration and noise reduction, and better conformation to the contour of the pavement. The Ohio DOT's Lake County has experienced four times longer blade life when using Joma blades, and their mechanics have spent seven times fewer labor hours repairing Joma blades relative to repairs made to steel blades. Other agencies have experienced similar increased blade life and reduced blade maintenance, including the Franklin County Engineer's Office and the Pennsylvania DOT. Additional research on Joma Plow blade may also be found from Iowa DOT (174), Wisconsin DOT (175), etc. A report from Minnesota DOT maintenance research (176) favors usage of Joma 6000 on bituminous snowplow routes, due to its lower cost on bituminous roads than conventional concrete roads when blade life is considered.

Iowa, Indiana, Iowa, Minnesota, Ohio and Wisconsin DOTs participated in the Clear Roads Multiple-Blade Snowplow project initiated in April 2008. A multiple plow blade system was designed to work as an alternative to the traditional front-mounted snowplow blade. This allows operators to apply the most appropriate blade based on roadway conditions—snowy, slushy, ice-covered or hardpack—to clear the roadway with a single pass, without swapping out blades or plows. Participating states discovered that factors such as climactic conditions and the capabilities of existing winter maintenance fleets would affect how a multiple blade plow is used. Areas with milder temperatures that receive wet, heavy snow will likely make more frequent use of a squeegee blade. As some of the participating states concluded, a two-blade rather than a three-blade solution may be best suited to an agency's winter maintenance fleet and the winter conditions it faces. Scarifying or ice chipping blades were studied as part of the project (177).

Recent work has quantified visibility improvements from deflectors placed over snowplow blades (178). Additionally, previous work investigating the development of moldboards indicated that energy consumption could be reduced through the effective use of such attachments (143).

MDSS

New and emerging technologies, such as maintenance decision support systems (MDSS) (22), laser guidance and driving simulators may shed light on the future of winter highway maintenance operations. In the U.S., MDSS is a tool developed under the leadership of Federal Highway Administration (FHWA) and several national laboratories with the support of three dozen State DOTs. It is a software application that integrates information from a variety of sources, such as fixed RWIS and weather service forecasts, to provide recommendations for road treatment under the given constraints. This system will make more appropriate recommendations as the quality of information (inputs) improves. The Meterologix/DTN MDSS deployed by the Maine DOT in the winter of 2006-2007 offered the DOT and the Scarborough road maintenance crew a useful winter storm planning tool, in terms of start time, precipitation type, anticipated amount of precipitation, and duration (179). A recent cost-benefit study revealed that the tangible benefits of Pooled Fund MDSS significantly outweigh its costs, and relevant data for three case-study states are provided in Table 8 (180). There are also many intangible benefits of MDSS implementation, such as improved documentation of actual maintenance activities, reduced response time and clearance time, reduced labor and equipment costs, reduced corrosion and environmental impacts, and establishment of a platform for future technology implementation. In Japan, Makino et al. (2012) reported the development of a system similar to MDSS coupled with AVL, which "enables flexible shifting of snow removal sections" (181). Such flexibility can be valuable in fighting extremely severe winter storms.

Table 8: Summary of cost-benefit analysis of implementing Pooled Fund MDSS (180)

Case State	Scenario*	Benefits	Percent of User Savings (%)	Percent of Agency Savings (%)	Costs	Actual Resource Usage (ton)	Simulated Resource Usage # (ton)	Benefit/ Cost Ratio
New Hampshire	Same Condition	$2,367,409	50	50	$332,879	152,653	149,980	7.11
	Same Resources	$2,884,904	99	1				8.67
Minnesota	Same Condition	$3,179,828	51	49	$496,952	234,629	222,968	6.40
	Same Resources	$1,369,035	187	-87				2.75
Colorado	Same Condition	$3,367,810	49	51	$1,497,985	111,622	107,091	2.25
	Same Resources	$1,985,069	90	10				1.33

General Trends

The use of advanced winter maintenance technologies has increased throughout the United States and Canada since the time the Strategic Highway Research Program (SHRP) began funding research in new areas of winter maintenance technology (SHRP Project H-207 and SHRP Project H-208) and the International Winter Maintenance Technology Scanning Review was completed in 1998. Transportation agencies have been under increasing pressure to conduct timely and environmentally responsible snow removal operations, generally without a corresponding increase in staffing or fiscal resources. Fortunately, there appears to be significant possibilities for technology to address these challenges. A variety of vehicle-based sensor technologies have been used to optimize material usage, reduce associated annual spending, and ensure the safety of the personnel responsible for maintaining winter roadways. Moreover, there is considerable interest among transportation agencies and the vendor community to use technology, including vehicle-based solutions, to improve winter maintenance efficiency and safety. Synergies between winter maintenance applications and those among other markets will likely result in future enhancements to winter maintenance operations.

Integration was an underlying goal in several U.S. winter maintenance vehicle-based technology projects, including RoadView, Mn/DOT's Advanced Snow Plow, and the HMCV. There is continued support in the winter maintenance community for similar vehicles that use integrated technologies to improve operations and safety. Agency snowplow specifications are increasingly requiring vendors to allow greater levels of technology integration with road condition sensors, spreader controllers, and other vehicle equipment. AVL is the one most integrated with other technologies, especially surface temperature sensors, freezing point and ice presence sensors, salinity sensors, snowplow blade position sensors and application rate sensors. If these sensors work properly, then both vehicle operators and maintenance managers can have more precise information on current roadway conditions, resulting in better winter maintenance decisions and optimized usage of resources. Integration is also a key consideration with the MDSS. With many mobile data collection technologies integrated into an AVL platform, there is the potential for far more comprehensive data that will ultimately enable best possible winter maintenance strategies and tactics. There are also considerations related to the integration of various technologies with the maintenance vehicle's basic structure. From the users' standpoint, it would be desirable to have standardized instruments' interfaces and software that adapt to the needs of each customer without extensive modifications (20).

Currently, there is a trend toward increased automation of snowplow operations. This trend recognizes the complexity associated with executing winter maintenance tasks during storm events, when such tasks are most critical. For example, collision avoidance and vision enhancement sensors are designed to relieve some of the burden from vehicle operators, allowing them to shift their focus from aspects of vehicle operations to aspects of winter maintenance, such as chemical application. In the future, two-way AVL could offer the potential for a maintenance manager to select application rates without needing to involve the vehicle operator. This trend toward more automation has appeal for transportation agencies as a way to improve winter maintenance efficiency, protect the safety of agency staff and road users, and reduce maintenance costs. Nonetheless, two-way AVL would require a level of communications reliability that has only been demonstrated in limited applications.

Pavement Treatments

This section describes various pavement treatments designed to reduce the bond of ice or compacted snow to pavement or to prevent or treat winter precipitation. Such pavement treatments present a desirable alternative or supplement to chemical and abrasives usage for snow and ice control, as they would reduce the amount of winter traction materials needed for a given LOS. They become particularly attractive at extremely cold temperatures (e.g., below 15°F or -9.4°C), where most of the chemical deicers lose their effectiveness and the use of conventional methods (abrasives and snowplowing) become very costly and inefficient. Pavement treatments can range from anti-freezing pavements that rely on physical action, to high-friction *in situ* anti-icing polymer overlays, to asphalt pavements containing anti-icing additives, to heated pavements using energy transfer systems. Pavement treatments may be used alone or in combination with other strategies for winter highway maintenance operations. In light of cost considerations, they are most suitable for critical highway locations such as bridge decks, mountain passes, sections prone to frost and/or sensitive to chemicals, and locations featuring sharp change in road conditions. Relative to the fixed anti-icing spray technology (20), pavement treatments may exhibit higher reliability and incur less capital and maintenance costs.

Rough Surfaces and Physical Bending Pavements

Zhang et al. (182) reported that asphalt pavement can be modified to feature rough surfaces that provide improved skid resistance in icy conditions. The roughening can be achieved through the use of open-graded or half open-graded asphalt concrete overlay and coarse aggregate (e.g., recycled ceramics particles). Such designs also aim to facilitate the breaking and abrasion of ice layer on pavement. In addition, ordinary asphalt pavement can be modified after construction, by pressing or engraving elastic materials (rubber particles or other polymers) into the pavement surface. Such designs aim to alter the contact between roadway surface and vehicular tires, so as to facilitate the breaking of ice bond to pavement while enhancing surface friction. They have been reported to be plagued by durability issues. Takeichi et al. (183) evaluated three types of pavement that provide anti-freezing effect through rough surface texture and another eight types through pavement bending. The study found that "the pavement in which grooves were cut and filled with urethane resin…and the pavement with cylindrical or doughnut-shaped rubber embedded at regular intervals in the surface…had particularly high anti-freezing effectiveness". These two types of pavement were installed at intersections and exhibited positive performance for pedestrians and automobiles.

Another type of design for physical bending pavements features the admixing of rubber particles into asphalt pavement during construction, partially replacing aggregate. The admixing of rubber particles makes it difficult for the asphalt to reach sufficient level of compaction (182). PlusRide® features the use of 3-4% granulated tire rubber (1.6-6.4 mm particles) by weight of the mixture, along with some buffings and chopped fibers in the top course of hot-mix asphalt pavements. It is intended to increase skid resistance and provide "elastic aggregates which flex on the pavement surface under traffic" so as to facilitate the breaking of bond of ice to pavement (184). The technology was originally invented in Sweden in late 1960s and later marketed and field tested in the U.S. It generally doubles the cost of the asphalt mixture. Laboratory testing showed that PlusRide "increased the resistance (of asphalt pavement) to low temperature cracking and decreased the resistance to rutting" and "had a variable effect on (its) moisture susceptibility". Nonetheless, most field PlusRide pavements surveyed under a FHWA study exhibited "no difference in performance (rutting, cracking, and raveling", relative to control sections. Field test of PlusRide by Alaska and New Jersey DOTs reported significant benefits in reducing vehicle stopping distances during ice conditions and in improving skid resistance of pavement, relative to control sections (184). In the northern cold regions of China, the use of crumb rubber asphalt mixture for snow and ice control was evaluated. Adaptability of gradation type, anti-freezing performance, ice-breaking performance, and anti-wearing performance were assessed. It was found that the field performance of asphalt mixture could be improved by crumb rubber, if appropriate amount of admixture was added. The crumb rubber asphalt mixture was paved in high-grade highway in China and exhibited excellent field performance. The method was effective at temperatures above -12°C (10.4°F) and with the ice thickness no more than 9 mm, but no cost-benefit analysis was conducted (185). In contrast, a survey response by Alaska DOT in 1998 (186) reported experimenting with rubber asphaltic mixes to produce a pliable mix that would flex and break the ice as the temperature changes. However, the experimental results were not satisfactory and little benefit was obtained, which seems to contradict their earlier success with PlusRide.

High Friction Anti-icing Polymer Overlays

Textured seal coats for pavements or bridge decks have the potential to prevent dangerous icy or slippery conditions and there are products available on the market (e.g., Cargill's SafeLane®). SafeLane is a surface overlay in which epoxy is applied to the paved surface and an aggregate is broadcast over the surface. The aggregate acts like a rigid sponge, serving as a slow-release mechanism for the applied liquid deicers. As such, the overlay can provide residual anti-icing benefits between applications. The technology was patented and commercialized after laboratory tests showed a medium-porosity limestone aggregate and CMA deicer provided impressive residual anti-icing performance. One experiment was conducted at 25°F with repeated applications of compressed snow. The results showed that reduced force was needed to shear the snow for a significantly greater number of snow reapplications, relative to a granite aggregate and NaCl deicer (187). A frost experiment conducted at 34°F with aggregate samples cooled to

20°F showed the limestone–CMA combination prevented frost growth (188). Field observations during the 2005–06 winter season indicated that: SafeLane was generally superior to control sections with 1) reduced snow and ice accumulation, 2) lower chemical applications were needed, and 3) better snow removal when plowing was needed (189). However, no pavement temperatures below 15°F were observed during that winter season. During the 2006–07 winter season there were still some instances of SafeLane performing better than control sections, but other instances showed performance was either worse or no different. Again, most pavement temperatures observations were above 15°F. However, during December 7, 2006 when the Mitchell Bridge in Hibbing, MN was -3°F, the SafeLane section was 50 percent frost-covered while the control section was clear (190). More information and documentation are needed to determine the benefits of SafeLane during extreme cold scenarios. Meanwhile, continued research is warranted to advance the technology in high friction anti-icing polymer overlays, so as to ensure their long-term durability and anti-icing effectiveness.

Asphalt Pavement with Anti-icing Additives

Verglimit® features an additive of anti-icing chemicals (0.1-5 mm flake particles of 95% $CaCl_2$ and 5% sodium hydroxide) encapsulated in linseed oil or polyvinyl acetate and admixed generally at 5-6% by weight of the mixture in the top course of hot-mix asphalt pavements. It is intended to provide anti-icing benefits throughout the life of the pavement and works best for bridge decks, steep grades, sharp curves, heavily shaded roads, and roads adjacent to water. Laboratory testing showed that Verglimit increased the resistance of asphalt pavement to rutting at high temperatures, slightly reduced its temperature susceptibility, and decreased its resistance to moisture damage (184). Verglimit has been used in Europe, North America and Japan since 1970s. There are several reports available on the field performance of Verglimit pavements and, in general, the data were somewhat inconclusive (191,192,193,194,195). Specifically regarding its performance at extremely cold temperatures, the following are notable:

- Observations by the New York State DOT on a test section installed in Albany, NY in 1978 suggested the overlay performs better during temperatures above 20°F. At lower temperatures, “few or no apparent differences can be discerned” relative to an adjacent control section (191).
- “Areas such as Western Europe, New York State, and Pennsylvania with relatively warm, wet winters have had positive deicing results; however, areas with colder, drier winters such as Minnesota, Mannitoba, and Illinois have not seen deicing benefits” (194).
- In Colorado Verglimit projects, “the deicing action was so slow the effects were often masked by normal salting and sanding operations” (184).

Stuart and Mogawer (184) concluded that “Verglimit generally triples the cost of the mixture and thus is used in selected problem areas. The additional cost is not offset by reductions in sanding and salting operations but may be offset if accidents are reduced”. In the field, some Verglimit pavements exhibited raveling problems and others did not, which highlights the need for better quality control at the hot-mix plant and during pavement construction (especially compaction). Due to their ability to absorb moisture from air, Verglimit pavements may become slippery after construction, which can be mitigated by sand application or water flushing (184). An article from the Michigan DOT (196) concluded that Verglimit achieves its effectiveness when the temperature is over 27°F (-3°C). Heavy traffic (at least 5,000 ADT) is a must for Verglimit to reach its full deicing potential. Its main advantages include: little environmental risk and significant reduction in salt usage. However, the cost of Verglimit is high ($109-145 per ton), approximately 33 times the cost of asphalt.

Other anti-icing additives that need to be considered include Mafilon® (Japan), IceBane® (China), WinterPave/ECO-S among others (197), all of which aim to reduce the usage of chemical deicers and improve the efficiency of mechanical removal. For this technology, the challenge is to balance the need to control-release the encapsulated anti-icing chemical with the risk of degrading the durability performance of the pavement.

Heated Pavement Technologies

The last category under pavement treatments for snow and ice control features heated pavement technologies, aimed to prevent ice formation or to facilitate snow and ice removal. Depending on the relative location of heating source to the pavement, they can be classified as internal heating [e.g., geothermal heat pumps (198) and electrical resistive heating (199,200,201,202)] and external heating (e.g., microwave and infrared heating). Infrared heat lamps and insulating bridge deck with urethane foam were attempted but found to be ineffective (203, 204). Table 9 presents cost estimates by the Iowa DOT for various heating systems (56).

Table 9: Cost Estimates for Various Heating Systems for Snow and Ice Control

Heating	Approximate Capital Cost	Power Consumption	Operating Cost
Infrared Heat Lamp	$96/m^2$ ($8.9/ft^2$)	75 W/m^2 (7 W/ft^2)	Not available
Electric Heating Cable	$54/m^2$ ($5/ft^2$)	323–430 W/m^2 (30–40 W/ft^2)	$4.8/m^2$ ($0.45/ft^2$)
Hot Water	$161/m^2$ ($15/ft^2$)	473 W/m^2 (44 W/ft^2)	$250/Storm, 3-inch snow
Heated Gas	$378/m^2 ($35/ft^2)	Not available	$2.1/m^2$ ($0.2/ft^2$)
Conductive Concrete Overlay	$48/m^2$ ($4.5/ft^2$)	516 W/m^2 (48 W/ft^2)	$5.4/m^2$ ($0.5 ft^2$)

Geothermal Heating

Geothermal energy has been used to melt ice and snow on roads, sidewalks, bridges and other paved surfaces for years in locations around the world. Either heat pipe technologies or direct geothermal hot water can be used to heat the pavement. Heating airport runways with geothermal heat was claimed to be able to pay for itself in 2-5 years (205). The design was described as "either transfer the heat through pipes in the pavement by a flow of warm liquids or from direct geothermal water or through the use of heat exchanger systems or hot runoff liquids from local industry or power plants". According to a presentation by Hellstöm (206), there were plans to use a Borehole Thermal Energy Storage system to heat the runway at Kallax airport in Lulea, Sweden. The system aimed to utilize waste heat from a local steel plant by "pumping the water down into boreholes that are 65 m (210 ft) deep where it can be stored at an average temperature of 50°C with only approximately 10% heat loss in a volume of one million cubic meters". As the cost of mechanical snow removal was around $3 million, it was estimated that the system would pay for itself in 1-2 years if only the runway is heated, and in 5-10 years if the entire surface area is heated. In 2000, Lund (207) examined several methods of pavement snow melting using geothermal hot water and steam.

In Japan, Marita (208) introduced and evaluated the Gaia Snow-melting System for melting snow. Gaia Snow-Melting System utilizes the geothermal heat from the shallow ground and its auxiliary solar heat in the summer. The first system installed in Ninohe, Iwate Prefecture in 1996 has shown that even under very low temperatures for the month of January (averaging -8.3°C), the system was effective in snow and ice melting and environmentally benign. However, modifications would be needed to guarantee its proper operations in very cold days and recommendations on future improvements were proposed to achieve higher performance. In 2006, Yasukawa summarized the advantages of geothermal heat pump application of "Gaia System" (209). These include: reduced consumption of fossil fuels (and thus less CO_2 emission), reduced consumption of electricity with higher coefficient of performance, and reduced urban heat island effect with heat exhaust into underground. Hiroshi et al. (210) reported the use of a snow melting technology utilizing tunnel spring water and hot spring water on a highway through the Abo Pass, where average minimum temperature is around -18°C during past 5 years with average annual accumulated snow fall depth of 500 cm. They concluded that the snow melting system using tunnel spring water and hot spring water are practical ways to melt snow where such thermal energy and large site are available. This is based on their higher construction costs (1.15 to 1.24 times the cost of conventional, electric-powered road heating) and lower operating costs (22 to 46 percent of the conventional systems).

Table 10: Pavement Heating System Costs per Season, in 1972 USD

System Type	Installation Cost (per sq. ft.)	Operating Cost (per sq. ft.)
Fluid Circulation		
Earth Heat Exchanging	Not established	Less than $.01
Fuel Burning	(Estimated $6-$12) $4	$.10-$.15
Electric		
Cable or Mat	$2-$4	$.32-$.45
Electrically Conductive	$1-$3	$.32-$.45

Table 11: Cost Data of a Geothermal Heating System in Virginia, in 2000 USD

Item	Cost
Construction	\$323/m^2 (deck area); \$181,500 total
Retrofit	\$18.73/m^2
Operating	\$18/h (gas); \$312/year (electricity)
Maintenance	\$500/year

In the U.S., geothermal heating technology has also been widely used in bridges and airports as an alternative to traditional methods of snow and ice control. Due to the limited number of geographical locations with geothermal fluids above 100°F, the heat pipe technologies are used more commonly in the U.S. As early as 1972, Murray (211) briefly reviewed some alternative snow ice control methods which include pavement heating system, with their estimated costs in Table 10. The costs of different geothermal heating technologies are in ascending order as follows: geothermal snow melting without heat pump (around \$20/ft^2), ground source heat pumps (\$35/ft^2 for typical highway bridge deck systems), and "hydronic" geothermal heating system. Total cost for the deck and heating system will run \$100 to \$150/ft^2. This high cost has limited its usage to only critical areas such as bridge decks and airports (212). In New Jersey, a heat pipes system circulated an ethylene glycol-water mixture between pipes embedded 2 inches below the pavement surface and a horizontal grid buried 3 to 13 feet below the pavement on 2-foot levels. The performance of this ground system was compared to that of a companion 68 Btu/h/ft^2 electric pavement heating system. The high cost of excavation to place the ground pipes was noticeable in considering its cost-effectiveness. (207). Virginia has chosen a two-lane bridge on Route 60 over the Buffalo River in Amherst County to conduct field evaluation of a heat pipe system using Freon HCFC 123 as the working fluid. The evaluation has shown that applying heat pipe technology to heat bridge decks is feasible and the effectiveness of heating depends largely on the proper working fluid. No construction problem was found for installing the heat pipe system. The cost data of this system are summarized in Table 11 (213). Operating costs for the heat pipe system are lower than those for an electrical or hydronic system. The heating system does not seem to have any adverse effects on the durability of the bridge deck.

Electrical Resistive Heating

Electric heating cables can be embedded below the pavement surface. The heating is activated by surface mounted sensors or cameras when they detect snow or frost on the pavement. Electrical heating cables were installed as early as 1960s in Newark, New Jersey. It was abandoned later because of problems with unreliable sensing to activate the heating unit and with electrical cables being pulled out of the overlay by the traffic. The Ladd Canyon Heating Project by the Oregon DOT tested this method at a one-mile section on Interstate Highway I-84 in 2006 (214). Similar problems were observed: two heating cables were dysfunctional due to damage by traffic. The sensors buried in the pavement were unreliable and resulted in wasted energy. The operating temperatures should be over 19°F (-7.2°C) as the system lost its effectiveness when temperature was too low. There were no system failures serious enough to impact the function of the system in keeping the structure and road safe. The low reliability and high operating cost can be two of the major disadvantages of electric heating cable approach.

Table 12: Costs of Conductive Concrete versus Conventional Concrete, in 1998 USD

Material	**Cost/lb**	**Conductive Concrete** Cost/yard[3]	**Conventional Concrete** Cost/yard[3]
Steel fiber	$0.40	$80.0	0
Conductive material (Coke breeze, steel shaving, etc.)	$0.10	$70.0	0
Sand	$0.0024	$2.6[a]	$2.4
½ in. Limestone	$0.0024	$3.9[a]	$4.7
Cement	$4/(sac of 94 lb.)	$35[a]	$32
Total		$191.5	$39.1

[a] Due to the use of conductive materials, more sand and cement and less limestone were used than in conventional concrete **(**215**).**

Electrically conductive concrete is made by adding electrically conductive components to a regular concrete mix to attain stable electrical conductivity of the concrete. A thin layer of conductive concrete can generate enough heat due to its electrical resistance. This can be utilized to prevent ice formation on the pavement surface when connected to a power source. The conductive concrete includes two types: 1) conductive fiber-reinforced concrete, and 2) concrete containing conductive aggregates. The two types have both advantages and limitations. Recent advances in this field include electric roadway deicing systems featuring the use of carbon nanofiber paper (216) or carbon/glass fiber hybrid textile (217). These new materials are yet to be field evaluated but claim to offer enhanced electrical conductivity, improved heating capacity at low voltage, uniform and rapid heating, reliable performance, low cost, and/or improved service life.

In 1998, Yehia and Tuan (218) investigated the feasibility of using a conductive concrete overlay for bridge deck deicing through small-scale experiments. They used conductive concrete mixes for heating concrete decks for Nebraska Department of Roads. Table 12 gives material costs of conductive concrete versus conventional cement concrete. The method was found easy to maintain at a lower operating cost relative to the embedded electrical/thermal heating and was a cost- effective method for bridge deck snow and ice control. Following the small-scale experimental study (215), a concrete mix containing 1.5 percent of steel fibers and 25 percent of steel shavings by volume was developed specifically for concrete bridge deck deicing for the Roca Spur Bridge in Roca, Nebraska. The average energy cost was about $0.8/m^2 per snow storm. A comparison of conductive concrete technology against other deicing technologies in the literature revealed its potential to become the most cost-effective deicing technology in the future (215).

Table 13: Comparison of Different Deicing Systems

Deicing System	Initial cost*	Annual operating cost*	Power consumption
Automated Spray System, 2004	$600,000	$12,000	Not applicable
Electric heating cable, 1961	$54/m^2	$4.8/m^2	323 - 430 W/m^2
Hot water, 1993	$161/m^2	$250/storm [76 mm snow]	473 W/m^2
Heated gas, 1996	$378/m^2	$2.1/m^2	Not available
Conductive concrete, 2003	$635/m^2	$0.80/m^2/storm	350 W/m^2

*Cost figures were quoted directly from the literature, and conversion to present worth was not attempted.

As a follow-up, the Roca Bridge deicing system implemented with conductive concrete deck was under evaluation from 2003 to 2008. In light of certain drawbacks of the steel shavings used in the previous study, carbon and graphite products were used to replace steel shavings in the conductive concrete mix design. In the storm events, an average of 500 W/m^2 (46 W/ft^2) was used to raise the slab temperature 16°F above the ambient temperature by the conductive concrete. The total construction cost of the Roca Spur Bridge deicing system was $193,175. The cost per unit surface area of the conductive concrete inlay was $59/ft^2. The construction costs of the various deicing systems are compared in Table 13. The operating cost of the Roca Bridge deicing system was about $250 per major snow storm (219). The author stated that “the most challenging task in the mix design was to achieve the long-term stability of the electrical conductivity… The use of high voltage and high current causes a safety concern”.

The conductive concrete pavement technology has also found its application to airport runways. One such example is the Snowfree® system installed and operated at O’Hare International Airport (220). Snowfree® electrically conductive asphalt pavement uses a unique blend of graphite, asphalt and electricity to heat the runway surface and break the ice bond to pavement. It was installed and operated at O’Hare International Airport for four years since November 1994. The installation costs were at $15 per square foot. The conductive asphalt showed similar durability as regular asphalt concrete and “consistently melted snow in all but the most severe conditions”. It was able to increase the pavement temperature 3 to 5°F per hour as designed. A cost/benefit analysis was conducted, which showed that the system on high-speed exits could have a payback in 3 years. In severe snow storms, Snowfree would expedite the runway reopening after the shutdown, leading to cost savings for airlines and airports and safety benefits. The system was effective even when temperatures went down to -10°F in one of the winter seasons. Its ability to increase the pavement temperature 22°F confirmed its effectiveness in the extremely cold weather.

Alternative Heating (Solar, Wind, Microwave and Infrared)

To further reduce the energy consumption by snow removal equipment and to overcome the problems associate with other methods, snow melting systems using natural energy have been under development in Japan. Many renewable heat sources can be used to heat the pavement such as solar energy and wind energy. Hiroshi et al. (210) outlined a number of snow melting systems using natural heat sources in Japan. The approaches include utilizing underground water sources or steam, storing heat underground and circulating it under pavements, and using electricity produced by wind power. Relative to electrical resistive heating systems, such systems entail relatively high capital cost, the savings are expected from reduced maintenance cost (energy savings) as well as environmental conservation.

For microwave and infrared heating, very limited technical information was found during the literature research. The knowledge is still lacking on their performances and cost-effectiveness (221, 222). The infrared heaters can be mounted on a truck or on the bridge-side structures to provide heat from the lamps to melt the snow and ice on the bridge deck. In 2001, Switzenbaum et al. (223) described its application on aircraft. Microwave heating shares the similarities in the installation of infrared heaters and can be mounted on a truck or on the bridge-side structures (224).

Concluding Remarks

Successfully implementing a highway winter maintenance program requires appropriate selection of chemicals or pavement treatments for snow and ice control, obtaining the right equipment, having well-trained staff, making informed decisions, and proper execution of strategies and tactics. There is a substantial amount of knowledge in the published domain, regarding best practices of winter maintenance in the following categories respectively: *chemical usage*; *operational strategies*; *weather forecasting*; *winter maintenance equipment*; and *pavement treatments*. However, most of these best practices are versatile and there are limited research dedicated to best practices of snow and ice control at extremely low temperatures, which highlights the need for more research in this field.

Conventional practices for fighting winter storms at extremely low temperatures focus on the use of abrasives and plowing. Chemical usage still holds great promise in improving the effectiveness and efficiency of snow and ice control under such conditions, as new cost-effective chemical anti-icers or deicers emerge on the market. There is still room in improving operating strategies, weather forecasting, and equipment, so as to optimize the timing of winter maintenance operations and to maximize the outcome (level of service) and resilience of winter maintenance with the limited resources at hand. Pavement treatments generally bear higher cost per lane mile than the use of chemicals for snow and ice control, and thus should be targeted for problem locations where the best return on investment can be expected. Pavement treatments offer the benefit of reducing chemical usage and associated environmental toll, enhancing agency preparedness, and quicker recovery to bare pavement. Despite the limited reports, certain technologies (geothermal heating, conductive concrete layer heating, etc.) seem to indicate positive performance at cold temperatures (15°F or lower).

Continued research and development can be expected in all these enabling technologies, while efforts are made to advance the knowledge base underlying the key interactions and processes between the pavement, snow/ice, and chemicals.

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Appendix B: Detailed Survey Results

A survey was distributed to learn how various transportation agencies maintain roads during extremely cold winter storms. The survey was distributed on June 5 and responses were collected until July 11.

Q1. Please provide your contact information

The distribution of survey responses in the United States is shown in Figure 3.

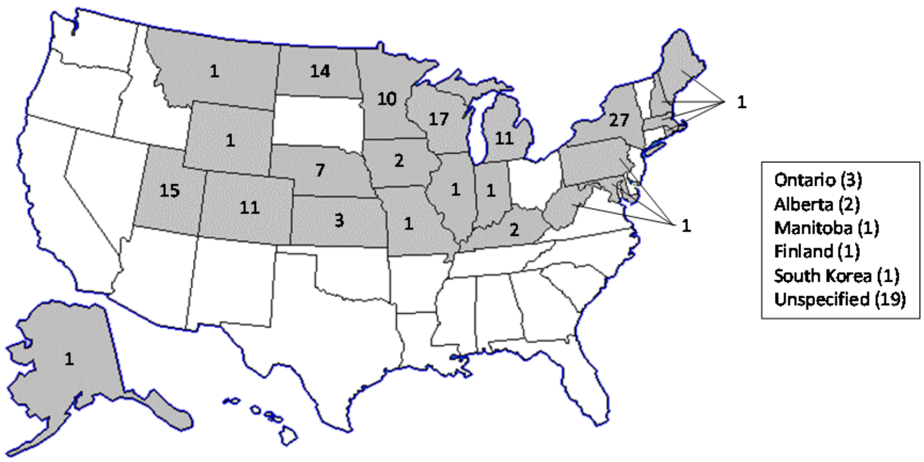

Figure 3: Location of survey respondents.

Q2. Please indicate the group that you belong to.

Most respondents work for the DOT, either at the headquarter level or district/region/station level (Table 14). Several other respondents were responsible for county or city roads. There were a few other representatives as well.

Table 14: Number of responses for each group

Group	No. of Responses
DOT winter maintenance manager (headquarter level)	45
DOT winter maintenance manager (district/region/station level)	64
County winter maintenance manager	25
City winter maintenance manager	7
Contractor	2
Research	5
Vendor/Manufacturer	2
Other*	6*
Skipped question	10

* Other includes county commissioner, bureau director, engineer, fleet manager, continuing education, and overlap between state, county and city winter maintenance

Q3. Did your region experience any winter storms with extremely cold temperatures (below 15°F or 9.4°C) in the last 5 to 10 years, or do you have information on best practices for winter maintenance under such temperatures? If yes, what percentage of storms typically has extremely cold temperatures?

There were 159 responses to this question and only 14 (about 9 percent) indicated "No" and exited the survey. There were 117 responses that answered the follow-on question that showed the frequency of extremely cold winter storms is not negligible (Figure 4).

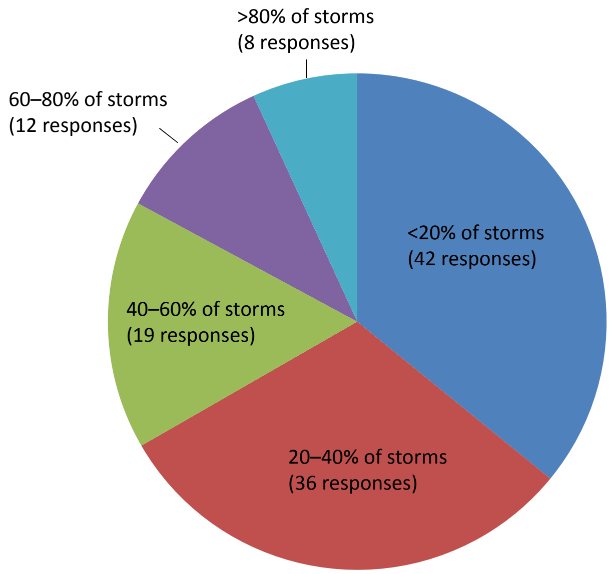

Figure 4: Percent of winter storms with extremely cold temperatures and the number of responses that fall into each category.

Q4. How many lane miles must your state/region clear of snow and ice per year? What percentage do you consider high volume versus low volume roads?

There were only 94 responses to this question, but they represented a wide range of road surface responsibility, from only 10 lane miles to nearly 100,000 lane miles (Figure 5). The respondents indicated responsibility for both high-volume and low-volume roads, with the split on average about 50 percent. No guidance was given based on average daily traffic levels, thus the responses likely reflect significant differences between what is considered high volume versus low volume based on local definitions.

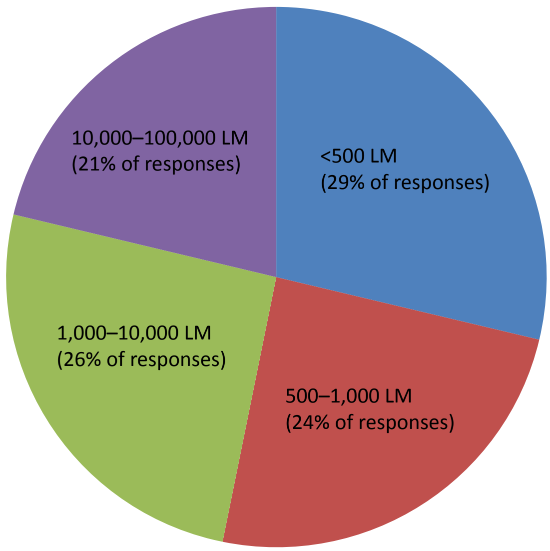

Figure 5: Total lane miles (LM) of roadway under winter maintenance responsibility.

Q5. Please estimate the snow/ice control cost in a typical season for fighting extremely cold winter storms and what percentage this was of your total winter maintenance budget?

Only 57 responses were collected for this question. Almost half of the respondents spend less than $500,000 for their region while a third typically spends between $1 and 10 million. Seven respondents indicated expenses for extremely cold temperature winter maintenance at over $10million.

The percentage this represents of the total regional/state winter maintenance budget averaged 32 percent, and was closely related with the frequency of winter storms that have extremely cold temperatures. This similarity suggests that perhaps treating extremely cold winter storms does not cost a disproportionate amount of the budget. This was unexpected.

Q6. Which set of practices work most cost-effectively in managing winter maintenance under extremely cold temperatures? Please rank on a scale of 1 to 5, with 1 being least cost-effective and 5 being most cost-effective. (*Categories were Operation Strategies, Chemicals and/or Abrasives, Winter Maintenance Equipment, Innovative Pavement Technologies, Weather Forecasting/Snow Storage, Other*).

More than 90 respondents provided rankings, with the general consensus indicating pavement technologies are the least cost-effective and operational strategies are the most cost-effective for extremely cold winter storms (Table 15).

Table 15: Number of responses for each ranking for each category

Set of Practices	No. of Responses for Each Ranking					Average Rating
	1	2	3	4	5	
Operational Strategies	4	4	13	32	43	4.1
Equipment	2	4	28	41	20	3.8
Weather Forecasting/Snow Storage	4	7	21	38	22	3.7
Chemicals and/or Abrasives	8	16	18	36	17	3.4
Other*	2	1	1	2	2	3.1
Innovative Pavement Technologies	33	29	15	11	3	2.1

* Other includes MDSS, AVL/MDC, and a combination of all options based on each unique storm

Q7. Which of the following strategies do you use during extremely cold winter storms: (*Choices were Chemicals, Abrasives/Sand, Plowing, Snow Fences, Snow Storage*).

Just over 100 respondents answered with plowing, chemicals, and abrasives being the strategies used by most (Figure 6).

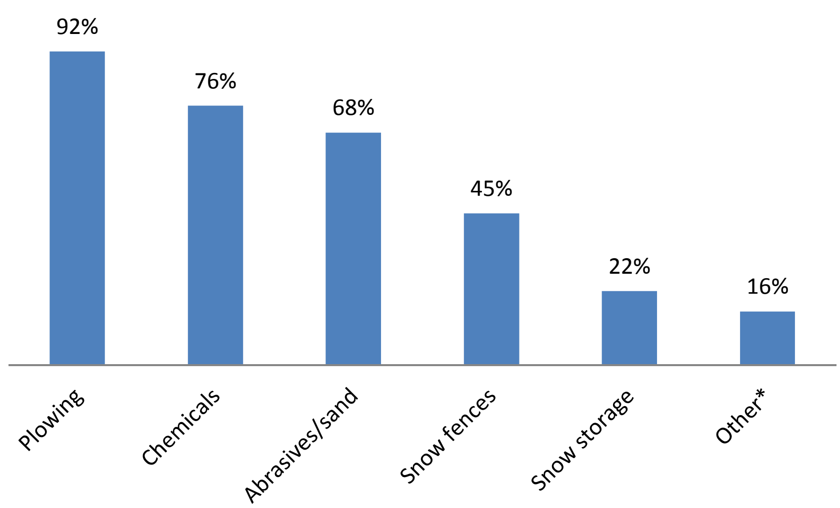

Figure 6: Frequency of strategy used by respondents. *Other includes blading; underbody, extended wing & tow plows; reduced level of service; allow snow to blow off road if possible; start with a dry road; a combination; also specific chemicals were listed (includes salt brine, beet juice, Ice B'Gone II, Ice Slicer).

Q8. Do you have a decision tree with certain strategies for extremely cold storms? If Yes, are your strategies different for 1) high-volume vs. low-volume roads or 2) for storms with heavy snowfall vs. shorter, lighter storms?

There were 98 responses to this question; 32 answered Yes and 66 answered No. Most of the comments indicated higher volume roads receive faster and more aggressive treatment.

- Higher volume roadways have shorter cycle time for plowing and get heavier applications of chemicals, whereas low volume roadways may only get abrasives applied in critical areas (stop areas, hills, curves, etc.)
- High Volume vs. Low Volume - Use Department guideline and adjust application rates as needed. Storms with heavier snow require timely response and application to prevent hard pack on the roads. Shorter lighter storms normal application rates are typically adequate. Monitor drifting snow that can re-freeze on the wet road surface.
- More aggressive on high volume roads
- Yes, high volume get more effort with resources, heavy storms get less chemical during the storm and more after the storm than lighter storms
- High volume is usually high chemical applications. Low volume is usually winter sand treatments.
- We utilize MDSS to aid in our strategies. No formal documents

Q9. Considering only extremely cold winter storms, which chemicals do you use for these various strategies?

A total of 89 respondents answered this question with the number of checkmarks distributed as shown in Table 16, indicating sodium chloride is the most commonly used chemical, although there was significant use of magnesium and calcium chloride.

Table 16: Number of respondents for each chemical for each strategy.

	NaCl	$MgCl_2$	$CaCl_2$	KAc	CMA	Urea	Agro-based products	Other
Anti-Icing								
chemicals you use	45	33	19	4	1	0	12	15
the most cost-effective	32	18	5	2	0	0	6	14
Deicing								
chemicals you use	62	43	31	5	0	0	15	16
the most cost-effective	43	24	13	1	0	0	9	11
Pre-wetting Salt								
chemicals you use	37	36	23	0	1	0	11	13
the most cost-effective	28	18	13	0	0	0	9	13
Pre-wetting Sand								
chemicals you use	22	23	13	1	0	0	6	10
the most cost-effective	17	12	7	1	0	0	4	10

Eleven of the 32 comments for this section indicated “Other” refers to salt brine. Three mentioned Ice Slicer. Other comments include:

- Pre-wet sand with hot water occasionally.
- 15% beet juice & 5% calcium chloride
- Treated salt with MgCl2
- Granular products are all prewet using 80% brine and 20% Potassium acetate. Salt is the primary granular with sand used sparingly.
- Natural brine (primarily calcium chloride)
- We only use a small amount of sand throughout the whole winter, so pre-wetting is minimal
- Anti-icing: salt brine with ag product; De-icing: salt brine and salt; Combination Route: prewet salt brine
- 50/50 sand/salt mix in towns and stop and go areas. Try to keep roads dry.
- Sodium chloride brine enhanced with ag by-product (de-sugared beet molasses). We also use Ice Slicer (Envirotech) alone or mixed with salt for deicing at low temperatures.
- We only use Mag chloride in major metro areas
- We use no salt or sand at all, just mag on large parking lots & private roads
- Mixture of sodium chloride and calcium chloride (50/50)
- We only have salt brine treated with GeoMelt
- Ice Slicer has worked for us down to -5°F. Any liquid use below 16°F is cold temp modified mag. In one region we also use prewet sand with cold temp modified mag or sand mixed with 7% Ice Slicer which we may prewet during applications.
- We use Ice B' Gone and also blend it with salt brine, which makes it very cost-effective. We have used $CaCl_2$, but presently do not.

Q10. Under what conditions are these strategies most effective during extremely cold winter storms? (*Strategies were Anti-icing, Deicing, Prewetting*)

Anti-Icing Responses (grouped according to similarity, number of repeated answers noted in parentheses).

- Possibility of ice or frost (3)
- Urban areas/high traffic/bridges (3)
- No wind (5)
- During daylight hours (3)
- Before snow starts (3)
- Temperatures above freezing (1), below 25°F (1), above 20°F (1), above 15°F (2), above 5°F (1)
- Do not recommend for severe cold (3)
- All storms between Nov 1 and April 30
- You still will end up using a bunch of chemical to maintain during extremely cold conditions

- limited usage due to potential for sticking snow

Deicing Responses (grouped according to similarity)

- After the storm (7), During the storm (3), As recommended by MDSS (2)
- Little to no wind (3)
- During daylight hours or rising temperatures (9)
- Hardpack, ice, or when snow/ice is bonded to the pavement (9)
- Temperatures between 14 and 32°F (1), above 10°F (2), above 15°F (1)
- Plow at lower temperatures (2)
- Not very effective, do not deice (3)
- Products mentioned: $MgCl_2$, $CaCl_2$, IceSlicer, salt brine, Geo Melt, salt

Prewetting Responses (grouped according to similarity)

- During the storm (6)
- Standard practice to prewet all dry material (17)
- At all temperatures (3), above 20°F (1), above 15°F (1), 14 to 32°F (1), normal to cool temperatures (1), rising temperatures (1)
- Little to no wind (3)
- For extremely cold temperatures, recommended: $MgCl_2$ with agro-based product (3), $CaCl_2$ (3)

Q11. Have you had any problems with chemical storage during extremely cold temperatures?

Only 21 of the 91 answers to this was were "Yes." A list of comments indicated most of the problems were salt caking, chunking, clumping and freezing (11 responses) and salt brine freezing/crystallizing in lines (6 responses). Solutions mentioned were: covered/inside storage or wind protection, testing salt deliveries for moisture content, anti-caking agents, using mixers, and adding additives to salt brine (e.g., Ice B'Gone).

Q12. Have you had any problems with chemicals or abrasives not working during extremely cold storms?

There were 88 answers and most (63) were "Yes."

- Salt doesn't work at lower temperatures (16)
- Chemicals in general don't work well at extremely cold temperatures (8)
- Refreeze issues on the road (9) or chemicals freezing in lines (2)
- Chemicals not as effective at night (6) or with light traffic (3)
- Use abrasives or sand/salt mix (8)
- Problems with sand blowing off road (3)

- Generally just plow at extremely cold temperatures since chemicals don't work (4)

Despite the reported lack of effectiveness, some noted that not applying salt was politically not acceptable so they had to use it even when they knew it was ineffective. Also, if the temperature drops, but they started with chemical treatment, they needed to continue applying chemicals anyway. Some noted MDSS was helpful in suggesting chemicals appropriate for the different temperatures. Finally, two mentioned chemicals will work, but much higher application rates are needed.

Q13. During extremely cold temperatures, what sources do you use to gather weather information?

There were 91 responses to this question and most indicated multiple sources were used for weather information (Figure 7). Twelve respondents specified MDSS as the "Other." A few mentioned getting information from neighboring cities.

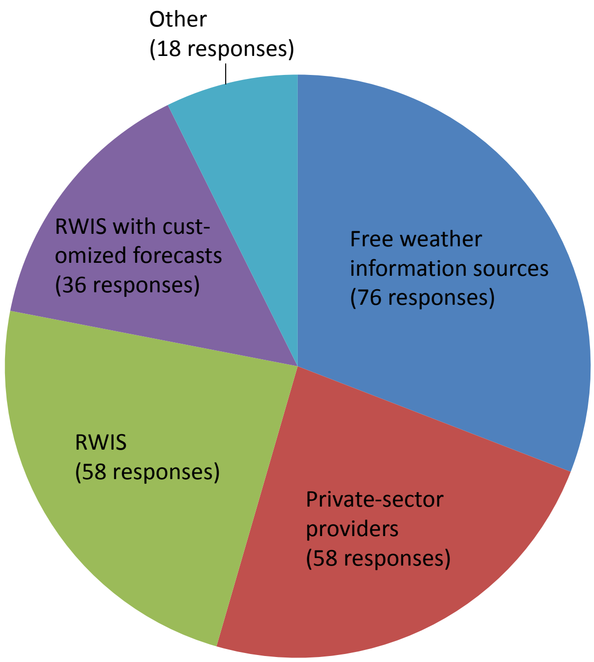

Figure 7: Sources of weather information

Q14. What are the most important parameters of real-time and forecasted weather conditions for snow and ice control at extremely cold temperatures?

There were 92 responses to this question and 91 percent indicated pavement temperature was the most important weather parameter. Timing of the storm and weather trend after the storm were mentioned several times in the comment section.

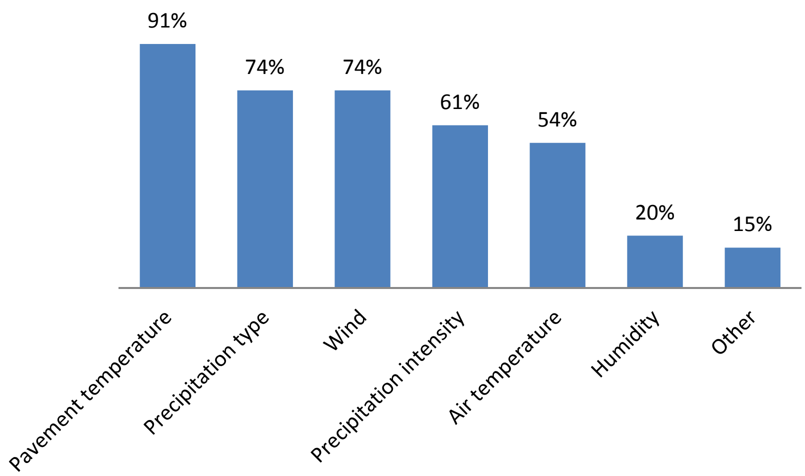

Figure 8: Importance of weather parameters

Q15. Do you have any issues with snow storage during extremely cold temperatures or winter storms?

There were 89 responses to this question and most (74) indicated snow storage is not a problem. Those that answered yes had the following comments:

- Snow piles may become frozen making it difficult to push them back and out of the way.
- Snow removal in town becomes a storage issue and you need to plan for snow hauls to suitable storage site
- Very infrequently in some smaller villages, snow blowers were utilized to clear snow.
- Snow blows around from the lack of moisture.
- Not usually during a storm, but post storm
- On narrow roadways in the Snow Belt areas storage can be an issue.
- Keeping snow pushed back with the use of blowers/loaders
- Just where we have some high back slopes and a few tree areas.
- Around structures
- It depends on the season. Ditches will fill up during a prolonged winter
- Most of the time we have had enough storms that our ditches are full before we go subzero.
- We have to keep storage areas open so that we can cast new snow. We use rotary snow blowers to mill deep snow and drifts and to clear storage areas after storms. Rotary plows are stationed near the locations of highest use. Loader-mounted snow blowers are used for avalanche removal and widening storage areas. We also use Sno-Cat grooming machines to move snow from storage areas and reduce drift tops so that rotaries can work.

Q16. Do you have any problems with equipment (plows, spreaders, etc.) during extremely cold winter storms?

There were 89 responses to this question and over half indicated vehicle/equipment break down and freezing/clogging of spread equipment was a problem. 32 percent indicated driver fatigue problems and 20 percent had corrosion issues with spreader equipment. 18 percent of respondents indicated they had no problems. The following comments were received,

- Same as other storms - pretty much any of those things can occur.
- Generally only have difficulty when it is below -10°F.
- Driver in-attention to equipment and chemical preparation before and during storm.
- Drive fatigue mainly during events with low visibility (heavy drifting/blowing snow and wind)
- Problems with windshield and windows being defrosted - lack of heat in cab - uncomfortable for operators
- Drivers are the hardest to train on cold weather applications. The more is better mentality is extremely difficult to break
- Sometimes chemicals (salt) freeze in hoppers
- Trucks may not start if left outside in cold weather
- Normal wear and tear , cold is hard on all equipment and people
- Hydraulics and other misc. parts seem to have issues. More shop time than we really should see.
- Sprayer motor can be finicky to start when very cold

Q17. Have you tried any innovative equipment/technologies for extremely cold winter storm maintenance?

There were 85 responses to this question and most (54) said they had not tried anything innovative specifically for extremely cold storms. The following comments were received:

- Different types of spray nozzles for deicing and pre-wetting.
- New cutting edges for plows, wings, and underbody scrapers
- Serrated cutting edges on underbodies
- MDSS
- Joma blades, TowPlows, MDSS, alternative deicers
- We have experimented with using rubber mounted carbide cutting edges on our plows, and MDSS/AVL units have been installed in most of our newer trucks, give operators real time storm information and recommendations
- Slurry spreaders with high strength chemicals
- Sno-cat storage area management - Prewetting salt and deslicking grit with calcium chloride. - This works very well
- Heated windshields
- Heated pre-wet tanks
- Different chemicals and solid products.
- Pre wetting work well (Mag Chloride)

- The use of Calcium Chloride for pre-wetting, and trying the blending of chemicals.
- Different liquids as explained before
- We have been using a blend of chemicals to lower the effective range where deicing chemicals work
- Several....best is flake chloride applied directly to salt.
- If wheel tracks ice up and salt isn't working we will us a combination of 2 trucks to keep the salt on the road and give it a chance to work. The first truck will salt heavy and the second truck which is right behind the first will sand heavy. The sand gives the traffic some abrasion and holds the salt on the pavement allowing it time to work.
- Chemical treatment of moving parts
- First Response Spreader
- Anti-ice roads with brine, 15% beet juice, 5% cal. chloride
- Some would say using mag blend only is innovative
- Oil field production water
- Redmond salt works for us
- Extensive liquid use testing
- Liquid
- 1/4 minus vs gravel, heavily prewet. Blast application at intersections which ice up very quickly due to exhaust and spinning tires.

Q18. Does your region use special pavement surfaces to reduce ice formation or improve chemical or plowing performance under extremely cold conditions?

There were 87 responses to this question and most (77) marked "No." Seven respondents checked Safelane and one checked IceBane. For Other, one mentioned FAST bridge deck systems and one said 3/8-inch chip seals was common throughout the state.

Q19. If you have special pavement treatments for snow/ice control, where are they located?

While only eight respondents indicated they had special pavement surfaces, there were 29 responses to this question, of which 25 selected "bridge decks." "Shaded areas" and "intersections" received 8 and 9 checks, respectively. In the "Other" section, one mentioned tunnels, one mentioned roundabout, and two mentioned FAST.

Q20. On the special pavement treatments for snow/ice control, do you have any information on their performance and cost?

Of the 55 responses to this question, 53 answered "No." Two that answered "No" said they were working on it. One that answered "Yes" said salt brine is cheap and effective for frost warnings and specific areas (that respondent indicated bridge decks, shaded areas, and intersections were all critical in the previous question).

Q21. Do you have any Best Practices, or have your strategies/techniques changed recently, to specifically address extremely cold winter storms?

There were 85 responses to this question and 30 marked "Yes." The following comments were received:

- Salt Management Plan, Salt Smart Training and Levels of Service documents
- Snow and Ice Guidelines are used.
- In lower volume roads we plow only, spread salt at first light for daytime heating
- Potassium Acetate and sand are our two main chemicals used in cold weather conditions.
- MDSS/AVL is a valuable winter maintenance tool.
- Timing of chemical applications, especially being aware of month of winter because of sun/UV and best strategy along with storm ending times, pavement temperatures.
- People and equipment need to be in place and active to control the situation. Good communication between drivers and decision makers is important
- Pavement temps and available sun light in post storm deicing treatments are crucial. The use of magnesium chloride and sodium chloride considering the amount of moisture present.
- Limit chemical treatment until after storm, keeps snow mat from building on road, More the roads are dry, less snow/ice mat builds. if temps are extremely cold, snow is dryer and does not stick to road compared to a wet heavy snow.
- Slower plow speeds; use of treated or pre-wetted salt with MgCl or CaCl.
- We have changed to a preventative department instead of a reactive department. We always try to be ahead of the system with liquid anti-icing
- Keep them dry if possible below 0 degree F.
- Restrict the use of straight salt, use more sand and where it absolutely needs to be addressed use the flake chloride.
- We used to stop spreading salt at 20 degrees, we changed that to 15 degrees.
- Yes, we typically do not apply any chemicals during extreme cold unless there are intersection or curve issues.
- The use of more Redmond salt in place of pre-mix.
- Setting up a temperature and humidity based system for chemical use and rate of application helps drivers utilize proper materials and quantities
- anti vibration cutting edges, more salt less sand, more man made salt water.
- as mentioned before, try not to apply chemicals which will turn pavements wet and encourage snow to stick and compact, then turn icy.
- Greater use of liquids, MgCl2 in particular. Use of Ice Slicer (fine graded complex chloride that is mostly NaCl with small amounts of MgCl2 and CaCl2)
- Updated weather stations and subscribed weather networks. We also run 24 hr patrols.
- We utilize flake calcium chloride mixed with salt and or salt/anti-skid to make a hot load. Normal mix is 100 lbs of $CaCl_2$ to 1000 lbs of salt.
- I have been using a product called Iceslicer during extremely cold storms for 4 years with good results compared to salt only.
- changed mag blend product a couple years ago- using Apex. slightly more economical.

- Our best strategy is to get to early in the storm, and always give the chemicals and abrasives time to work, often times when extremely cold winter storms hit with a lot of wind we look to close our low volume high elevation route.
- Prewet sand as a product and more prewetting of materials

Q22. Have you recently implemented any innovative strategies for extremely cold winter storms?

Twelve of the 85 responses to this question were “Yes.” The following comments were received:

- Under belly scrapers during heavy snowfall
- Special snow fencing on National park managed land
- Introducing MDSS this coming winter
- A system of recognizing and not reapplying materials until needed
- Pre-treat and reduce trigger depth if 0 or below.
- More preventative winter storm maintenance.
- We are trying beat juice sprayed on straight salt
- Different chemical blends and additives
- Prewet sand as a material and prewetting of materials
- We started using Redmond salt

Q23. Are you aware of any innovative methods, equipment, or technologies for winter road maintenance that you would like to try for extremely cold temperature scenarios?

Twelve of the 83 responses to this question were “Yes.” The following comments were received:

- Triple edged plow blade one of which is a serrated blade to cut ice or hard pack.
- Idaho Giant Hay bale snow fences
- MDSS and IWAPI
- Good pavement/air sensors
- Different chemicals and additives to NaCl
- Anti-ice
- Salt Brine
- Full heated pre-wet tanks and ice slicer
- High liquid + granular test
- I would like to become more economical in pre-treatment of the salt and do more stockpile treatment with the right product and use a conveyor to stockpile/mix it.
- Production salt water from oil wells

Q24. Do you have any ongoing experimental evaluation of methods, equipment, or technologies in treating snow and ice at extremely cold temperatures?

Only nine of the 82 responses to this question were "Yes.". The following comments were received:

- More or less trials and tribulations, nothing documented. We did have a best practices audit performed by an outside consultant that worked well.
- Utilizing various materials and chemical for past 6 years and tracking costs and road conditions
- The use of beet juice
- Use of straight salt
- Developing ice control spray system for contractors
- Pavement/air sensors (Vaisala Surface Patrol)
- We bought a tow plow.

Q25. Do you have any additional thoughts or comments for the research team?

Two people commented that the survey was confusing. Most The following comments were received:

- Use a little common sense
- We do not experience long term extremely cold conditions in NYS. It will be difficult to calculate cost proportions for extremely cold weather operations as asked for near beginning of the survey.
- Very few storms impact us with extreme cold temperatures. We are interested in the findings so we can better prepare for the times when our weather turns extremely cold.
- Being so close to the ocean our temperatures for most part are very moderate with most winter events staying within the range of 25F - 35F, and very rarely going below 25F. However in the past 2-3 seasons, we have experienced heavy snowfall rates with air temperatures as cold as 12F, which is extremely uncommon.
- We only get an occasional cold storm so we modify operations to use more high strength Chemicals, plow more.
- We are always interested in the data associated with cold weather applications. We strive to be good stewards of our environment.
- Lots of places out west do not use any salt and many do not use any sand either.
- In past years we have used salt pre-treated with mag chloride and agricultural byproducts. One you start anti-icing with these materials you are committed which can be very costly. We have been successful in not spreading below 15 degrees and plowing only.
- In Alberta, most of our 'normal' winter is what you've called extremely cold weather. We use the normal de-icing chemicals at temperatures that are lower than normal in more southern jurisdictions, just because we have to "do something" even though we know that we aren't necessarily being the most effective. We use a lot of abrasives (mixed ~5% salt

for freeze-proofing) with liquid de-icer pre-wet, which is effective even at what we consider low temperatures (below -30°C, -22°F). On the other hand, we are in a cold-dry climate that typically has low intensity snowstorms—a 15 cm (6 in) accumulation is unusual here. Most of our winter maintenance is geared at treating a 1 or 2 cm (0.4 to 0.8 in) total snowfall over a 24 hour period -- lots of thin packed snow & ice, that we treat by plowing then salting.

- Every storm is unique and a one size fits all theory cannot be depended upon to solve all of the problems the storms bring. Also depending on geographical location, road sections contain micro climates that need to be addressed not only by the Managers and Supervisors but also by the plow drivers themselves. The more information we can get up front the better we are able to prepare for the upcoming storm.
- There are so many different strategies, products, chemicals that it would be nice to have a definitive answer of what to use for different situations.
- Let me know what works best

CLEAR ROADS

research for winter highway maintenance

Lead state:
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