Expanding Application Rate Guidance for Salt Brine Blends for Direct Liquid Application and Anti-icing

Final Report

CLEAR ROADS

research for winter highway maintenance

University of Wisconsin–Madison

Project 1036345/CR19-01
December 2021

Pooled Fund #TPF-5(353)
www.clearroads.org

Technical Report Documentation Page

1. Report No. CR 19-01	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Expanding Application Rate Guidance for Salt Brine Blends for Direct Liquid Application and Anti-icing		**5. Report Date** December 2021 **6. Performing Organization Code**
7. Authors Boris Claros, Madhav Chitturi, Andrea Bill, Wilfrid Nixon, and David A. Noyce		**8. Performing Organization Report No.** CR 19-01
9. Performing Organization Name & Address Traffic Operations and Safety (TOPS) Laboratory University of Wisconsin – Madison Engineering Hall 1415 Engineering Dr. Madison, WI 53706		**10. Purchase Order No.** **11. Contract or Grant No.** MnDOT No. 1036345 WO1
12. Sponsoring Agency Name & Address Clear Roads Pooled Fund Minnesota Department of Transportation 395 John Ireland Blvd. St. Paul, MN 55155-1899		**13. Type of Report & Period Covered** Final Report [June 2020 – December 2021] **14. Sponsoring Agency Code**

15. Supplementary Notes
Project completed for Clear Roads Pooled Fund program, TPF-5(353). See www.clearroads.org.

16. Abstract

As part of this research project, a literature review, a survey of practice, field data collection, and an analysis of application rates was conducted. The literature review covered application rates, performance measures, chemical products, environmental impacts, corrosion, impacts on concrete and asphalt, agro-based products, and benefit-cost analyses. A survey of practice was conducted to gather agencies' winter maintenance practices involving materials, predominant winter conditions, liquid application rates, experience, performance measures, and interest in serving as a study site. Agencies from different geographical regions of the United States were selected for field data collection to provide a wide range of winter conditions, road types, and resources. Data collected consisted of route information and field data in terms of weather, roadway conditions, materials, application rates, and performance measures. Seventeen agencies representing nine states submitted data from 31 routes resulting in field data for 167 storms. Ranges of application rates were identified according to pavement temperature, temperature trend, road surface condition, and materials used.

Guidance was developed exclusively from field data and practitioner feedback. Guidance was developed for liquid applications, blends, and "Shake and Bake" for light snow conditions (<1 in/hr., <4" in 24 hrs.). Shake and Bake is a combination of liquid and solid applications. Application rate ranges are provided in tables by material, pavement temperature, temperature trend, and supporting information regarding field data (agencies and number of storms observed).

17. Key Words Road Winter Maintenance, Salt Brine, Direct Liquid Application, Application Rate		**18. Distribution Statement** No restrictions. This document is available to the public through the Clear Roads pooled fund and the Minnesota Department of Transportation.	
19. Security Classification (this report) Unclassified	**20. Security Classification (this page)** Unclassified	**21. No. of pages** 41	**22. Price** -0-

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Expanding Application Rate Guidance for Salt Brine Blends for Direct Liquid Application and Anti-Icing

Project Number: TPF-5(353)

Final Report

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DISCLAIMER

EXECUTIVE SUMMARY

Previous Clear Roads research project 15-01 "Synthesis of Material Application Methodologies for Winter Operations" developed a companion document "Material Application Methodologies Guidebook" to provide recommendations for material liquid application rates. However, there is a gap in liquid application rate recommendations at low to moderate temperatures (0-15°F and 15-25°F) and diverse roadway surface conditions. Also, research studies performed in laboratory environments provide significant scientific knowledge. However, findings do not directly translate to the highly diverse and variable conditions in the field. The objective of this research project is to expand liquid application rate recommendations from previous research using field data and practitioner involvement.

As part of this research project, a literature review, a survey of practice, field data collection, and an analysis of application rates was conducted. The **literature review** covered application rates, performance measures, chemical products, environmental impacts, corrosion, impacts on concrete and asphalt, agro-based products, and benefit-cost analyses. A **survey of practice** was conducted to gather agencies' winter maintenance practices involving materials, predominant winter conditions, liquid application rates, experience, performance measures, and interest to serve as study site. Winter maintenance practices vary across regions with predominant winter conditions. Agencies from different geographical regions of the country were selected for **field data collection** to provide a wide range of winter conditions, road types, and resources. Data collected consisted of route information and field data in terms of weather, roadway conditions, materials, application rates, and performance measures. Seventeen agencies representing nine states submitted data from 31 routes resulting in field data of 167 storms. Ranges of **application rates** were identified according to pavement temperature, temperature trend, road surface condition, and materials used.

Guidance was developed exclusively from field data and practitioner feedback. Guidance was developed for liquid applications, blends, and "Shake and Bake" for light snow conditions (<1 in/hr., <4" in 24 hrs.). Shake and Bake is defined as the spraying of liquid and application of solid materials at the same time, liquid immediately followed by solid, or solid immediately followed by liquid. Application rate ranges are provided in tables by material, pavement temperature, temperature trend, and supporting information regarding field data (agencies and number of storms observed). Field based application rate guidance was shared with practitioners who have extensive experience using liquid applications. The intent of involving practitioners was to receive feedback, validate observed application rates, and raise awareness about specific conditions.

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1. INTRODUCTION

Guidance on application rates for liquid deicers at low to moderate temperatures and diverse roadway surface conditions are currently unavailable. The objective of this project is to expand liquid application rates guidance. Current guidance was developed using existing literature (mostly laboratory experiments), practitioners experience, and agency interviews. Laboratory tests may not directly translate to complex dynamics in the field. Thus, outcome-based performance measures from field observations are limited. As part of this project, commonly used liquid blends and applications rates from field data were identified to develop guidance. Field data was collected from different geographical regions in the United States. Observed field application rates and materials, feedback from winter maintenance experts, and Clear Road technical advisory committee oversight were considered for the development of application rates presented in this report.

2. LITERATURE REVIEW

The literature review covers application rates, performance measures, chemical products, environmental impacts, corrosion, impacts on concrete and asphalt, agro-based products, and cost/benefit.

2.1. Application Rates

There are several factors that influence decision-making for the implementation of chemical materials in winter maintenance. Although research studies performed mostly in laboratory environments provide significant scientific knowledge, findings do not directly translate to highly diverse and variable conditions in the field. It may seem simple to come up with a secret winter treatment strategy that outperforms all other strategies. However, rock salt is undoubtedly the most commonly used ice control material in winter maintenance. Level of service expectations have also played a significant role in winter maintenance because users have developed unreasonable expectations of well-maintained roads during winter conditions. With increasing costs, limited budgets, and environmental concerns, agencies are forced to adjust their practices to more sustainable and cost-effective winter maintenance operations. Changes to traditional winter practices may be challenging and staff training, education, and community involvement is crucial for implementing new practices.

Most application rate guidance was derived from practical, field-based experience. For instance, Iowa developed application rate guidance by creating first a matrix of pavement temperature and snow/precipitation type, and then getting operators to fill in the blanks (i.e., to specify the application rates) (Nixon 2011). Many of the application rate tables are closely derived from the 1996 FHWA report: Manual of Practice for an Effective Anti-Icing Program (Ketcham et al. 1996) since it was one of the first formal publications of application rate charts in the United States.

Selection of application rates depends on weather conditions, road type, level of service, cycle time, equipment, and material. Thus, the application rates found in the literature should serve as a starting point and agencies should adjust their practices to local conditions based on experience and performance. Recommended application rates found for anti-icing and deicing are a function of pavement temperature range, road surface condition, material, and winter event type. Appendix A provides application rates from existing literature. The following sections provides a breakdown of the parameters found in existence literature to provide guidance.

2.1.1. Precipitation

Existence guidance has different precipitation definitions and ranges to characterize various weather conditions. Precipitation parameters are presented in terms of intensity and type. The following terms are identified: light/medium/heavy snow, ice, frost, black ice, slush, sleet, and freezing rain.

Table 2.1. Precipitation Classifications.

References	Description
Shi et al. 2019	Light snow (<1 in/hr, <4 in. in 24 hrs)
	Moderate snow (1–2 in/hr, about 4–8 in. in 24 hrs)
	Heavy snow (>2 in/hr >8 in. in 24 hrs)
	Freezing rain
Blackburn and Associates 2014	Snow
	Frost/black ice
	Freezing rain
	Sleet
	Light snow
	Moderate snow
	Heavy snow
Porter 2018	Light snow (less than 0.5 in/hr)
	Medium snow (0.5 to 1.0 in/hr)
Ohio LTAP 2018	Light snow (less than 0.5 in/hr)
	Medium snow (0.5 to 1.0 in/hr)
	Heavy snow (more than 1 in/hr)
	Freezing rain
	Black ice
MnDOT 2012	Snow
	Freezing rain
	Frost
	Black ice
	Light snow
	Moderate snow
MoDOT 2019	Frost, flurries, freezing fog, blowing snow, refreeze
	Dusting to 1 in. of snow, sleet, or other frozen precipitation
	1 – 6 in. of snow/frozen precipitation in 24 hours or a trace to 1/2 in. of ice
	6 – 12 in. of snow in 24 hours or ½ to ¾ in. of ice
	More than 12 in. of snow in 24 hours or more than ¾ in. of ice
Nixon 2011	Heavy frost, mist, light snow
	Drizzle, medium, snow 1/2 in. per hour
	Light rain, heavy snow 1 in. per hour
ODOT 2002, WSDOT n.d.	Dry
	Wet, slush, light snow cover
ODOT 2017	Snow
	Freezing fog/black ice
	Freezing rain/sleet
	Light snow (1 in. per hour or less)
	Moderate – heavy snow (more than 1 in. per hour)
	Freezing fog/black ice
	Freezing rain/sleet
	Compacted/bonded snow

2.1.2. Pavement Temperature

Guidance is provided based on temperature ranges and trend.

Table 2.2. Pavement Temperature Ranges.

References	Description
Shi et al. 2019	32 °F steady or rising
	25-32 °F or below is imminent
	20-25 °F remaining in range
	15-20 °F remaining in range
	0-15 °F steady or falling
	Below 0 °F steady or falling
Blackburn and Associates 2014	Over 30 °F
	26-30 °F
	21-25 °F
	16-20 °F
	11-15 °F
	6-10 °F
	Below 15 °F
Ohio LTAP 2018	30-32 °F
	29-27 °F
	26-24 °F
	23-15 °F
Nixon 2011	32-30 °F
	29-27 °F
	26-24 °F
	23-21 °F
	20-18 °F
IDOT 2002	Above 32 °F steady or rising
	28-32 °F staying in range and equal to or below dew point
	20-28 °F staying in range and equal to or below dew point
	10-20 °F staying in range and equal to or below dew point
ODOT 2002	Above 32 °F steady or rising
	Above 32 °F below is imminent
	25-32 °F remaining in range
	20-25 °F remaining in range
	15-20 °F remaining in range
	Below 15 °F steady of falling
ODOT 2012	Over 30 °F
	26-30 °F
	21-25 °F
	15-20 °F
	Below 15 °F
WSDOT n.d.	Above 32 °F steady or rising
	32 °F or below is imminent
	20-32 °F remaining in range
	15-20 °F remaining in range
	Below 15 °F steady or falling

2.1.3. Roadway Surface Condition

Pavement roadway surface conditions usually refer to dry, wet, slush, ice, and snow cover.

Table 2.3. Roadway Surface Condition Categories.

References	Description
Shi et al. 2019	Dry
	Slush or light snow
	Dry (snow forecast)
	Light snow cover
	Ice patches
	Slush or ice
Ohio LTAP 2018	Dry pavement
	Wet pavement
MoDOT 2019, WSDOT	Dry
	Wet
	Slush
	Light snow cover

2.1.4. Materials

Form existing literature, Table 2.4 provides some of the recommendations provided based on material and chemical concentration.

Table 2.4. Guidance According to Type of Material.

References	Description	
Shi et al. 2019	Salt brine	
	Calcium Chloride	
	Magnesium Chloride	
	Dry salt	
	Pre-wet salt	
	Abrasives	
Blackburn and Associates 2014	**Liquid**	**Solid**
	23% NaCl	Solid NaCl
	32% $CaCl_2$	90-92% $CaCl_2$
	27% $MgCl_2$	100% $MgCl_2$
	50% Kac	100% Kac
	25% CMA	96% CMA
MoDOT 2019	Pre-wet salt	
	Salt brine	
IDOT 2002	Salt brine	
	Dry salt	
	Pre-wet salt	
ODOT 2002	23% Salt brine	
	Solid salt	
	Pre-wet	
ODOT 2017	Salt brine	
	Calcium Chloride	
	Magnesium Chloride	

2.1.5. Frequency

Recommendations of frequency of liquid application rates is limited. Porter 2018 provided guidance of liquid application for two hours or less and for three hours.

2.2. Performance Measures

According to the FHWA definition (FHWA 2020): "Performance measurement is the use of evidence to determine progress toward specific defined organizational objectives." Common performance measures include: safety, accessibility, mobility, environment, and operational efficiency. Basic definitions and classification of quantifiable performance in winter maintenance are input-, output-, and outcome-based performance measures. Similarly, there performance measures such as level of service (LOS) or uncontrollable factors that contribute to decreasing performance such as a natural hazard or emergency (Qiu and Nixon 2009).

Input measures are directly associated with agency spending, and outcome measures reflect how well operations meet organizational goals and customer expectations (Qiu and Nixon 2009). Most importantly, application of performance measures requires quantifiable data, sample size considerations, and frequency of measurements. Commonly used performance measures in winter maintenance include traveling speed, volume, and safety in terms of crashes. The following sections provide some references to the observed effects of winter weather on traveling speed, volume, and crashes.

2.2.1. Travelling Speed

Snow events and poor visibility were found to be associated with reductions in speed and increase of variation in speed. Brown and Baass (1997) found a 10% to 30% reduction in free flow speed. Liang (1998) found variations of three times larger in speed during a snow event. Studies evaluating travelling speed suggest that decrease in speed and increase in speed variation during snowstorms were influenced by road classification and vehicle type (Padget 2001, Liang 1998). To illustrate this trend, Hanbali (1994) found snowy/icy conditions are associated with an average 18% to 42% speed reduction on two-lane highways and 13% to 22% reduction on freeways.

2.2.2. Traffic Volume

During rain fall, highway traffic volume decreases up to 2% depending on the precipitation rate. Variations during are also significant according to the time of the day (Keay 2005, Doherty et al. 1998, Colding 1974). During snow fall, Hanbali (1994) found that traffic volume decreases substantially from 7% to 56%. Similarly, Knapp (2001) obtained traffic volume reductions between 10% and 50%. In terms of likelihood to observe traffic volumes during snowstorms conditions, it is likely to observe very low traffic volumes, less high traffic volumes than conditions with rain or no precipitation (EIDessouki, 2004).

2.2.3. Crashes

Winter maintenance safety evaluations are usually associated with crash rates which account for crash counts and traffic. Exiting literature of crashes in relation to adverse weather conditions suggest that weather is associated with an increase in the number of minor injury and property damage only crashes, and only a minor influence on severe injury or fatal crashes (Andrey 2003). Snow and poor visibility were found to be associated with reductions in speed and increase of variation in speed (Idaho Transportation Department 2000, Liang 1998). Also, there are temporal variations such as 5.2% increase in crash rate observed during the night compared to 1.9% increase during the day with rain precipitation. The effect of inclement weather is more likely to reduce mobility by deterring traffic or reducing speeds than to increase crash occurrence (Andrey 2003, Qiu and Nixon 2009).

Eisenberg (2005) and Suggett (2002) found that the risk of fatalities is significantly higher on the first snowy day of the season compared to days during the same season. Single vehicle crashes, locations with traffic control, and roadway segments with posted speed limits of 60 kph (37.3 mph) are disproportionally associated with snow events and are less likely to involve normal driving involving turning maneuvers (Andrey 2003, Qiu and Nixon 2009). Lane (1995) found that driving maneuvers involving passing or lane change were especially hazardous during winter conditions and risk increased based on slush and snow build up between the right and left lanes and on the shoulders. An important factor in crashes observed during these weather conditions were excessive vehicle speed. Similarly, crash risk is particularly high during freezing rain and sleet events and low crash risk for drizzle or dry snow (Suggett 2002). Crash risk remains consistent even after precipitation ends which may be associated with accumulation of precipitation and remaining slippery roadway conditions.

In the NCHRP 889: Performance Measures in Snow and Ice Control Operations, several measures and indicators of performance were identified and were classified into the following categories (ICF et al. 2019):

- Storm characteristics/severity
- Material management
- Labor resource allocations
- Level of maintenance response
- Maintenance response outcomes
- Level of operational responses
- Traveler experience, mobility, and safety
- Cost, budget, and funding
- Transportation resilience
- Economic activity

Based on a categorization taxonomy and evaluation criteria, NCHRP 889 report identified core measures according to input-output-outcome-impact categories that fell under each category. As illustrated in Figure 2.1, a core set of measures were identified for safety, mobility, and sustainability. The term sustainability in the context of the research is defined from an agency's perspective of sustainable operations defined by their environmental stewardship, efficiency of response, and the public satisfaction (ICF et al. 2019).

Figure 2.1. Core set of performance measures (ICF et al. 2019).

Based on the core set of performance measures Figure 2.2 illustrates the application of performance measures as a function of the storm timeline.

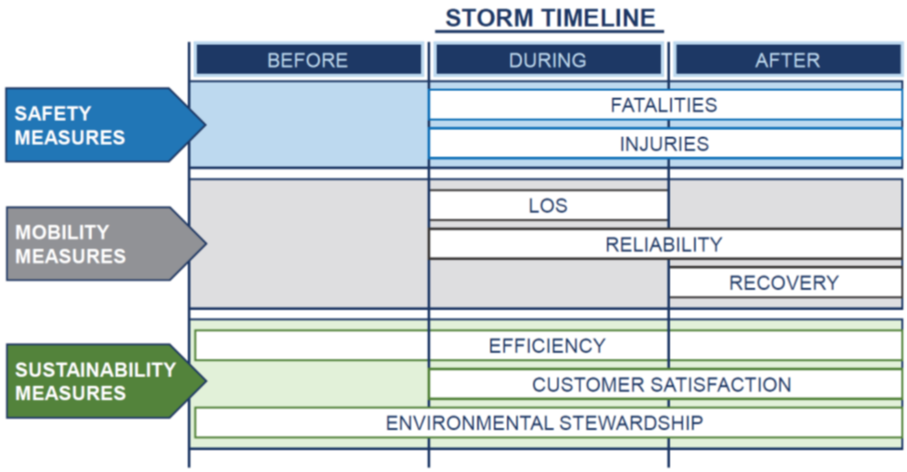

Figure 2.2. Applicability of performance measures with respect to the timeline of a storm. (ICF et al. 2019).

Table 2.5 summarizes some of the existing practices in performance measures of winter maintenance according to the performance measure and application.

Table 2.5. Current Practices of Performance Measurement (ICF et al. 2019, Xu et al. 2017).

References	Performance Measure	Application
Neimi (2006)	Post-storm bare lane regain time	The post-storm bare lane regain time targets are set per Average Daily Traffic (ADT) category.
Zwahlen et al. (2006)	Surface traffic speed levels during a storm	LOS is defined by comparing surface traffic speed levels during a storm with the average dry surface speed.
Caltrans (2009)	Snow and Ice Levels of Service (SNOW LOS)	To measure the effectiveness of the department's snow removal operations on high traffic volume routes.
Cuelho et al. (2010)	Effective temperature and application rate of chemicals	Based on these, guidelines were developed for optimal snow and ice removal operations.
Usman et al. (2010)	Traffic and safety	A model integrates weather, road surface conditions, traffic and maintenance, and relates those elements to accidents.
Kwon et al. (2012)	Traffic speed, flow rate, density data and speed-change patterns	Traffic flow data is associated with road condition recovery time and is incorporated into Traffic Information and Condition Analysis System.
Lee et al. (2004, 2008)	Automatic traffic recorder data	Speed recovery duration was identified as an appropriate performance measure for winter maintenance operations.
Adams et al. (2003)	Data collected by differential Global Positioning System on winter maintenance vehicle	LOS is defined by a set of performance measures for winter operations that are tied to business goals and objectives.
Murphy et al. (2012)	Winter performance index (WPI)	Idaho Transportation Department (ITD) use the WPI that measures the duration of ice per unit of storm severity.
Maze et al. 2007	Time to return to a reasonable near-normal condition, length of road closures, crash reduction, and customer satisfaction	Performance Measures for Snow and Ice Control Operations
Blackburn and Associates 2014	Pavement snow and ice condition (PSIC) index	Characterizes roadway conditions and used to assess during- and post-storm performance. PSIC is easy to use and low cost, but is subjective

References	Performance Measure	Application
Maze et al. 2007, Fay et al. 2013	Friction measurements	Indicator of road condition
Bandara (2015)	Relationship between visually observed pavement conditions and measured friction	Indication of how objective friction measurements are related to more subjective observations of pavement condition
Cao et al. (2013)	Vehicle speed	Impact of winter weather and road surface conditions on the average vehicle speed on rural highways
Qiu and Nixon (2009)	Average free-flow traffic drop, average vehicle speed, storm severity index (SSI)	Winter maintenance activity intended effect
Greenfield et al. (2012)	Real-time traffic speed reductions	During a winter storm using commonly reported and forecast road weather data
Kwon (2012)	Road condition recovery times	Traffic-flow data from existing Intelligent Transportation System (ITS) infrastructure
Levola and Pakkala (2014)	Customer satisfaction and safety targets	Road performance–based maintenance contracts
Mirtorabi and Fu (2013)	Severity indicators defined at disaggregate spatial and temporal levels	Resource, safety, and mobility impact
Usman et al. (2010)	Empirical relationship between safety and road surface conditions, road condition index	Quantify safety benefits of winter maintenance
Veneziano et al. (2010, 2013), Ye et al. (2012), Nordlof (2014)	Cost-benefit analysis	Winter maintenance materials, equipment, and operations

2.3. Performance of Chemical Materials for Winter Maintenance

Winter maintenance relies on plowing and application of chemical products to treat the roadway pavement surface to provide safe conditions for transportation of goods and people in the event of a winter storm. Chemicals may be used for anti-icing, pre-wetting, or deicing.

Anti-icing is a proactive approach which consists of applying liquid brine on the road surface to create a layer of chemical material to prevent snow or ice from freezing over the pavement surface. In order to maintain the anti-icing layer, subsequent applications may include liquid brine or solid salt. Anti-icing may significantly reduce costs and amount of material used during a storm. Pre-wetting is the addition of liquid brine to solid dry salt to provide a more reactive chemical material and prevent material from rolling to the ditch when it is applied on the road. Deicing consists of breaking the bond between the pavement surface and snow/ice as a chemical treatment or to aid mechanical removal (deicing chemical and plowing).

Chloride based chemicals are traditionally used, and there is a vast range of product variations that have been introduced into winter maintenance practices including agro-based products, urea, glycols, formates, and acetates. Since there is a wide range of chemical compositions and properties, the majority of research are based on laboratory tests. It is difficult to accurately quantify the effectiveness of these products on real field conditions. Available literature on performance measures (i.e., ice-melting capacity, eutectic temperature) of commonly used winter maintenance chemicals is covered in this section of the literature review.

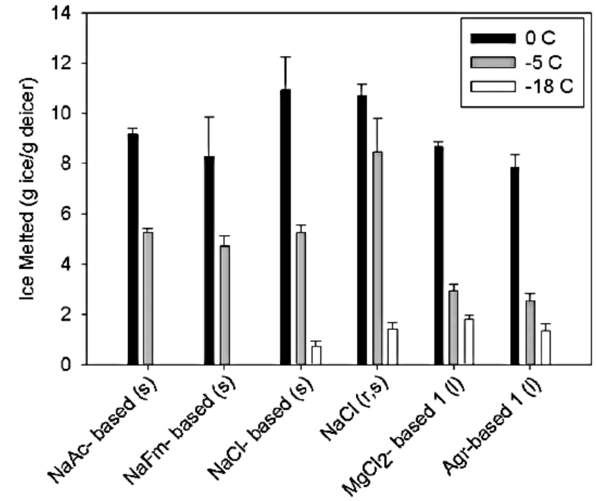

Figure 2.3. Ice-melting capacity after 60 minutes of application (Fay and Shi 2011).

2.3.1. Ice-Melting Capacity and Rate

Performance of several deicers were evaluated with laboratory tests by Fay and Shi (2011). Deicers and reagent-grade chemicals were used in granular and liquid forms. Some of the tests included ice-melting capacity, penetration, undercutting, and thermal properties.

In Figure 2.3, at 0°C (32°F), melting capacity of liquid and solid deicers was fairly similar after 60 minutes. At -5°C (23°F), solid deicers such as NaCl, NaFm, and NaAc based chemicals performed better that liquid deicers ($MgCl_2$ and agro-based chemicals). At -18°C (0°F), liquid deicers outperformed solid deicers, NaAc and NaFm failed to melt any ice (Fay and Shi 2011).

Penetration and undercutting tests are not recommended for solid deicers due to reproducibility issues. At 0°C (32°F), $MgCl_2$, KAc, and agro-based liquid based chemicals penetrated to the bottom within 30 minutes of the 60-minute test. Thermal properties in Figure 2.4 showed that NaCl based deicers consistently featured two distinct peaks in the warming cycle. The peaks represent endothermic phase transitions. The peak at lower temperatures represents the separation of ice from subcooled NaCl or the pseudoeutectic formation. The second peak represents the warmest temperature at which ice crystals begin to form. KAc based deicer had the coldest effective temperature followed by $MgCl_2$ based deicer (Fay and Shi 2011).

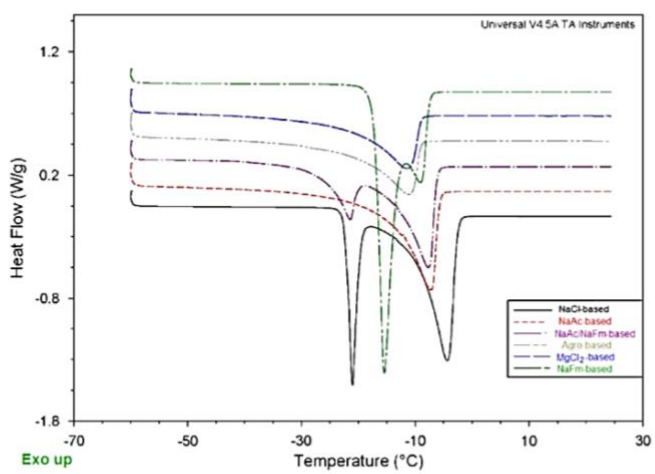

Figure 2.4. Thermogram of heating cycle (Fay and Shi 2011).

Commercially available snow and ice control products made of naturally sourced material were also tested by Jungwirth and Shi (2017). One control and four products were considered:

- Control: salt brine at 23% by weight of aqueous solution
- Naturally occurring minerals in the Great Salt Lake with $MgCl_2$ (30%)
- Saltwater containing naturally occurring Na (9%), Ca (9%), K (1%), and $MgCl_2$ (2.25%)
- Agro-based product derived from sugar beet processing
- Mixture of salt brine and sugar beet at volume ratio of 60/40

Laboratory tests included ice-melting capacity. Naturally occurring minerals in the Great Salt Lake with $MgCl_2$ (30%) had the highest ice melting capacity of all four products, outperforming the control salt brine at 15°F, and slightly lower capacity than control salt brine at 5°F. Products with sugar beet exhibited lower ice melting capacities suggesting that agro-based products are not suitable as liquid deicers at low temperatures (Jungwirth and Shi 2017).

A quantitative evaluation of commonly used snow and ice control chemicals was performed (Shi et al. 2014). The chemicals were commonly used in Idaho Transportation Department Districts which included rock salts, IceSlicer products, and salt brines. A total of 26 products were evaluated. Laboratory tests included differential scanning calorimetry (DSC) Thermograms, and ice-melting test at 15°F.

DSC Thermogram test measures the amount of thermal energy that flows into the deicer sample during the solid/liquid phase transition. Solid products were made into liquid at 23% by weight. Test temperature range was between 77 to -76°F with cooling/heating rate of 3.6°F. Two outlier brines and the liquid $MgCl_2$ exhibited significantly different characteristics than other brines. Ice melting capacity of several deicers were evaluated at 15°F and the results are presented in Figure 2.5 (Shi et al. 2014).

- Commercial 30% $MgCl_2$ liquid dicer exhibited significantly higher ice-melting capacity (may be attributed to compound effect of additional chemical additives)
- Solid rock salt produced considerably more ice-melting capacity than brines at 60 minutes of application at 15°F. Thus, solid salt can achieve its fullest potential with sufficient time
- $MgCl_2$ liquid deicer was more likely to continue to work (instead of refreeze) under cold temperatures
- Solid salts had higher melting capacity and friction values

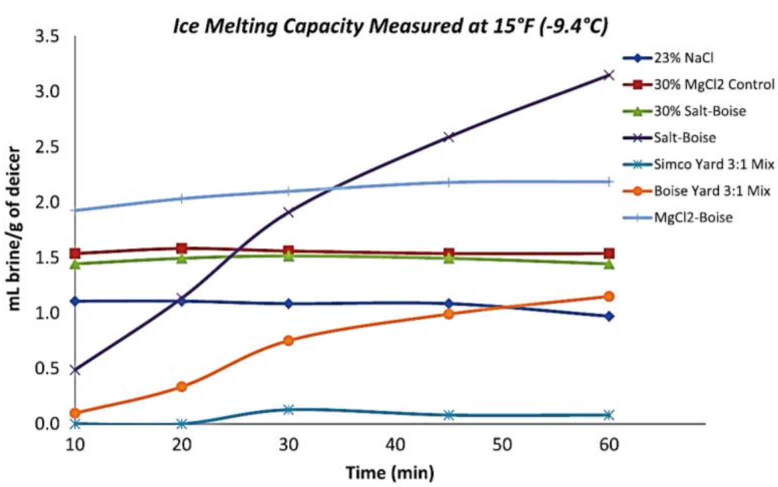

Figure 2.5. Ice-melting capacity of selected deicers at 15°F (Shi et al. 2014).

In a similar study, Shi et al (2013b) investigated the performance of commonly used chloride deicers by performing the Modified SHRP (Strategic Highway Research Program) ice-melting test of solid and liquid deicers at 30°F, 15°F, and 0°F. The results are presented in Figures 2.6-2.8. The findings indicate that NaCl and $CaCl_2$ $2H_2O$ had the highest performance at 30°F and 15°F (Figure 2.6 and 2.7). Calcium and Magnesium based deicers significantly outperformed NaCl in solid and liquid forms at 0°F (Figure 2.8). Solid NaCl achieved its fullest potential with sufficient time and at moderate temperatures (15-30°F). The difference of performance among deicers became apparent as temperature decreased. For instance, at 60 minutes, NaCl dramatically dropped its ice-melting capacity at colder temperatures as illustrated in Figure 2.8. In summary, ice-melting capacity of deicers is dynamic, time-sensitive, and highly dependent on deicer composition/properties and test temperature (Shi et al. 2013b).

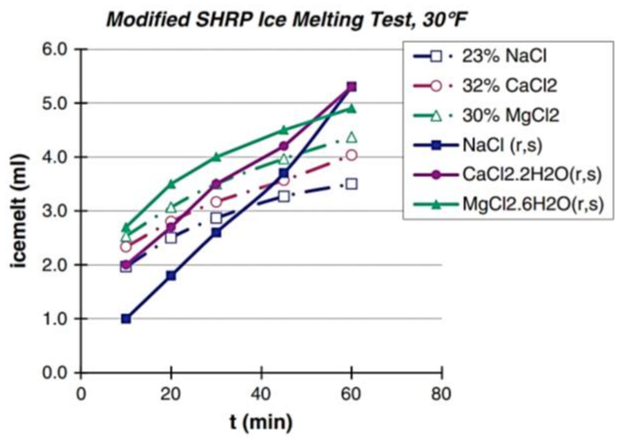

Figure 2.6. Ice-melting capacity of solid and liquid deicers at 30°F (Shi et al. 2013b). Notes: (r,s) for reagent-grade solid.

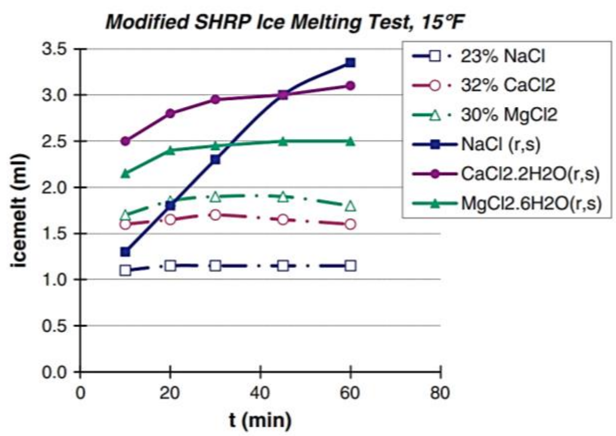

Figure 2.7. Ice-melting capacity of solid and liquid deicers at 15°F (Shi et al. 2013b). Notes: (r,s) for reagent-grade solid.

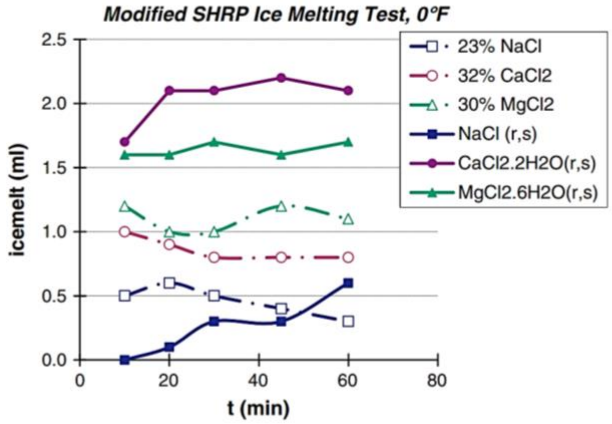

Figure 2.8. Ice-melting capacity of solid and liquid deicers at 0°F (Shi et al. 2013b). Notes: (r,s) for reagent-grade solid.

Effectiveness of deicers is commonly evaluated in terms of ice-melting capacity which conventionally consists of measuring ice melted over a relatively short period of time (1 hour). Although it is of interest to know the ice-melting capacity of deicers in a short period of time, it is important to evaluate deicers' total ice-melting capacity and rate over longer periods of time. Koefod et al. (2015c) evaluated the effect of pre-wetted brines ice-melting rate at very cold temperatures over prolonged periods of time. The results in Figure 2.9 illustrate ice-melting rate of solid NaCl, $MgCl_2$ flake, and $CaCl_2$ flake at -4°F. If the analysis would focus on a 1-hour time period, it would be concluded that NaCl is an ineffective deicer at cold temperatures compared to $MgCl_2$ and $CaCl_2$. When looking at a prolonged period of time, ice melting rate is more relevant. Thus, NaCl may not be effective after 1 hour, but after 24 hours, the amount of ice melted was not significantly different than $MgCl_2$ or $CaCl_2$, and after 48 hours, NaCl produced more ice melt than either $MgCl_2$ or $CaCl_2$. NaCl does have a substantial ice-melting capacity, but the ice-melting rate is very slow (Koefod et al. 2015c).

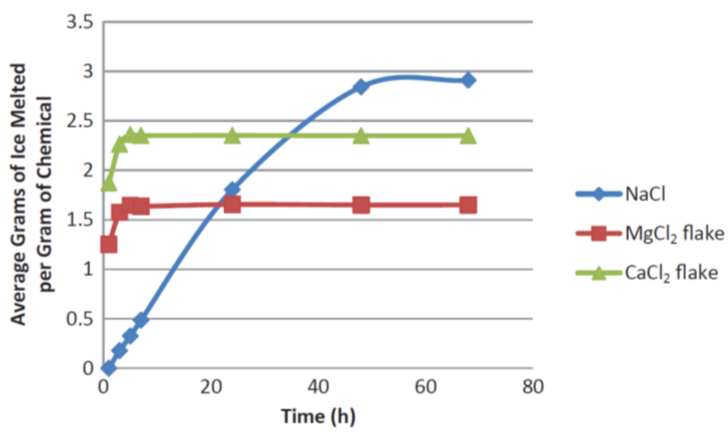

Figure 2.9. Ice-melting rates of solid deicers at -4°F (Koefod et al. 2015c).

Similarly, Koefod et al. (2015c) evaluated the effect of brine additives on ice-melting rate of solid salt (pre-wet). Figure 2.10 shows the results of ice-melting rate of five different pre-wetted salt variations. The results showed that salt pre-wetted with $MgCl_2$ melted ice 7.1 times faster after 3 hours, 3.5 times faster after 7 hours, and 1.7 times faster than dry salt after 24 hours at an average temperature of −4.4°F. Pre-wetted salt with NaCl brine melted ice 2.9 times faster after 3 hours, 2.0 times faster after 7 hours, and 1.6 times faster than dry salt after 24 hours at an average temperature of −4.4°F (Koefod et al. 2015c).

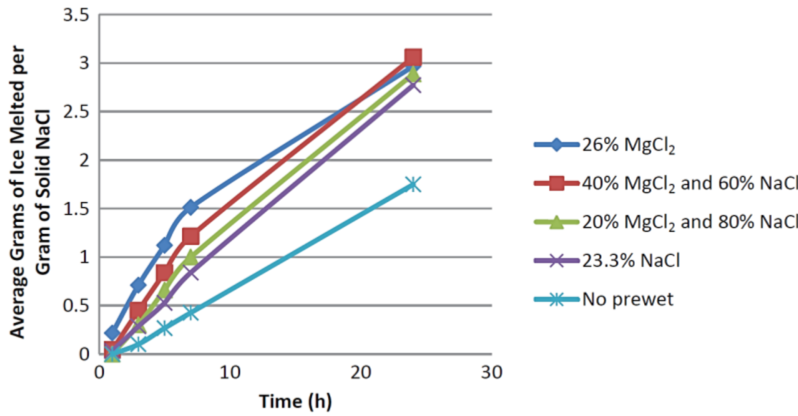

Figure 2.10. Ice-melting rates of pre-wetted salt with different brines (Koefod et al. 2015c).

Koefod (2017) expanded upon previous research to evaluate the effect of pre-wetting and mixing at cold temperatures. With laboratory tests, measurements of ice-melting rate were determined for pre-wetted salt. Brines used for pre-wetting salt in the study were:

- 30.29% $MgCl_2$
- 30.26% $CaCl_2$
- 23.30% NaCl brine spiked with 0.50% calcium sulfate
- Commercial deicer consisted of 17.53% $MgCl_2$ and enhancer (undisclosed concentration)
- 30/70 $MgCl_2$/NaCl hot mix
- 30/70 commercial $MgCl_2$/NaCl hot mix
- 30/70 $CaCl_2$/NaCl hot mix

In a laboratory environment, ice-melting rates were measured with the new Tracer Dilution Method which consists of measuring the change in concentration of chloride, magnesium, or calcium cations in the ice melt as tracers. Tests were conducted under mixing and no mixing conditions at a temperature of -2.7 °F. Although mixing in laboratory tests increases precision, the same mixing conditions might not be representative in the field. Traffic action may provide some mixing, but low traffic may resemble relative static conditions. Results are illustrated in Figures 2.11 and 2.12. Koefod (2017) indicated that:

- Chemical composition of pre-wetting brine influenced the rate at which solid salt melts ice
- $CaCl_2$ brine caused solid salt to melt ice substantially faster than NaCl brine
- NaCl and $MgCl_2$ brines ice melting rate difference decreased overtime
- Ice melting rate of a “hotmix” was higher than just NaCl brine
- Greater solubility of NaCl in the brines, further it is from saturation, and additional NaCl can dissolve and melt more ice
- Salt in plain NaCl brine is an ineffective deicer at cold temperatures, but with good mixing between ice and deicer, ice melting rate of pre-wetted salt increased by 27.1% with NaCl brine and 50.5% with $CaCl_2$ brine after 60 minutes of surface being treated
- Mixing produced 5 times more ice melt than static conditions
- $CaCl_2$ and $MgCl_2$ were similarly effective at enhancing ice melting rate of salt
- $CaCl_2$ brine was less dependent on mixing than salt with NaCl brine

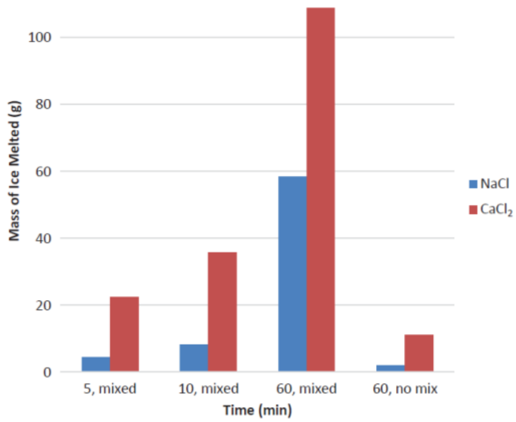

Figure 2.11. Average ice melted of pre-wetted salt with NaCl and $CaCl_2$ brines at -2.7°F (Koefod 2017).

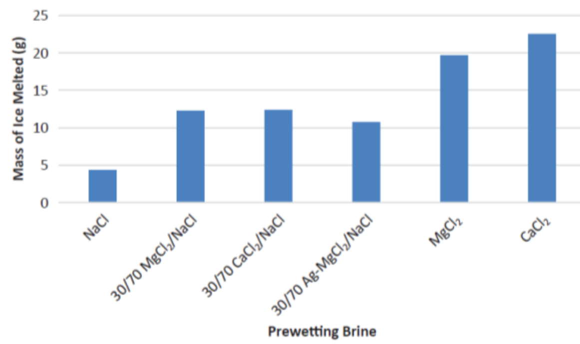

Figure 2.12. Average ice melted of salt and pre-wetted salt at -2.7°F after 5 minutes of mixing (Koefod 2017)

Michigan DOT conducted a series of studies to quantify loss material of dry salt applications. The results showed that losses significantly increased with higher spread speeds (> 35 mph). Overall, it was estimated that around 30% of dry salt ended up outside the three-lane roadway (i.e. in the ditch) while with pre-wet salt, only 4% was lost. MDOT recommends 7-10 gallons of liquid additive to dry salt with truck speed between 20-25 mph, with the exception of high-speed roads or specialized spreader technologies at speeds of 35 mph or higher (MDOT 2012). From a survey conducted by Fay et al. (2015), application with pre-wetted salt were between 5.0-17.8 gal/ton (or 10% to 20%) of brine and typical applications considered 8-20 gal/ton of brine.

Klein-Paste Wåhlin (2013) conducted a research study focused exclusively on wet pavements subjected to freezing temperatures. Anti-icing practices have commonly used the freezing point depression to explain the anti-icing mechanism. The freezing point depression can be experimentally determined and provided in a phase diagram (freezing temperatures as a function of NaCl concentration). It appears that the required NaCl concentration predicted with the use of phase diagrams can be unrealistically high (Klein-Paste Wåhlin 2013). Other studies have also suggested that less salt was required in comparison to the estimates with phase diagrams (Murakuni 1997, Haavasoja et al. 2012).

Not only does less salt provide acceptable pavement friction coefficient but also makes the ice structure softer and ice disintegrates into small particles with traffic. Thus, it is apparent that salt weakens ice that is formed when a wet pavement freezes. Through laboratory testing and field studies in Norway and Finland, ice films and anti-icing chemicals were evaluated considering the physical mechanism of ice melting and chemical concentration to ensure sufficient pavement friction (Klein-Paste Wåhlin 2013). The authors concluded that anti-icing chemicals not only depress the freezing point but also control the mechanical properties of ice formed when a wet pavement freezes. Minimum salt concentration was proposed based on minimum brine fraction of a conservative 0.4 (ice is sufficiently weakened). The brine fraction is the ratio between the initial concentration in the water film prior to freezing over the concentration where equilibrium is reached. Thus, with the minimum brine fraction of 0.4, it implies that 60% less salt is required compared to the concentration predicted by using phase diagrams (freezing point depression theory). The authors emphasized that the results do not directly translate to field application rates. Several other factors such as salt loss, dilution and temperature drop, weather forecast reliability, capability of measuring amount of water present, and cycle times influence the selection of application rates (Klein-Paste Wåhlin 2013).

2.4. Environmental Impacts

Driven by higher driver expectations of level of service and costs, diverse chemicals have been implemented in winter maintenance practices. There is a growing concern over the impact of winter maintenance practices in the environment including soil, flora, fauna, surface/ground water, and human health. Conclusive evidence shows that chloride salts have a negative effect on the environment (Ramakrishna and Viraraghavan 2005, Fay and Shi 2012, Dugan 2017a, Vignisdottir et al. 2019). Although the effects of other chemicals have been less investigated (i.e. urea, glycols, acetates, agro-based products), there are still environmental concerns with impacts on aquatic ecosystems (Fay and Shi 2012). Ecosystems such as surface waters have physical, biological, and chemical seasonal cycles that adapt to changes at a slow pace (Mayer et al. 1999). Short events such as spring snowmelt and storm water runoff can lead to pulse discharges of deicers and abrasives into surface waters (Fay and Shi 2012). Table 2.6 provides a summary of exiting literature about environmental effects of abrasives, chlorides, acetates/formats, glycols, and agro-based products (Fay and Shi 2012).

Table 2.6. Summary of Environmental Effects of Deicers (Fay and Shi 2012).

	Abrasives	Chlorides	Acetates/formates	Glycols	Urea & agro-based
Soil	Will accumulate.	Cl, Ca, and K can mobilize heavy metals. Na can accumulate in soil and reduce soil permeability, leading to increased soil density. Ca can increase soil permeability and aeration. Mg can increase soil stability and permeability. NaCl can decrease soil fertility, leading to reduced plant growth and increase erosion.	Ca and Mg can mobilize heavy metals, increase soil stability, and permeability. CMA degradation may increase soil pH.	Readily biodegrades. Propylene glycol degradation may reduce hydraulic conductivity in anaerobic soils.	Use of urea can lead to increased nitrate concentrations. Little data are available on agrobased deicers.
Flora	Can accumulate on foliage and in adjacent soils that contact the roots, potentially causing stress.	Few effects have been observed. At low concentrations, acts as a fertilizer and, at elevated concentration, reduces seed germination, causing low biomass yield, leaf browning, and senescence.	Few effects have been observed. At low concentrations, acts as a fertilizer and, at elevated concentration, reduces seed germination, causing low biomass yield, leaf browning, and senescence.	Can inhibit plant growth.	Little data are available on agrobased deicers.
Surface & ground waters	Can increase turbidity and decrease gravel and rock pore space, leading to limited oxygen supply.	Cl, Na, Ca, and K ions easily go into solution, migrate, and can harden the water. Can cause density stratification in small receiving waters, potentially causing anoxic conditions at depth. K and Ca can mobilize heavy metals in water. K can cause eutrophication of water.	Can leach heavy metals from soil that can transport into water. Has a high BOD and can cause oxygen depletion. Can increase turbidity and hardness of water.	Can increase BOD to a greater extent than any other deicer. Degrades in water faster than additives which can be toxic. Readily biodegrades.	Use of urea can lead to increased nitrate concentrations. Urea additives can be toxic.
Fauna	Can reduce oxygen in stream beds and cause increased turbidity.	Little to no impact when ingested unless extremely elevated concentrations are reached. Direct ingestion of salts by mammals and birds have caused behavior changes and toxicity. Concentrations of 250 mg/L have been shown to cause changes in community structures. Use on roadways may lead to increased wildlife– vehicle collisions.	Can exert a high BOD which may cause anoxic conditions in aquatic environments. KAc and NaAc appear to be more toxic than CMA. Can promote bacteria and algae growth.	Ingestion of concentrated fluid can lead to death. A known endocrine disrupter.	Little data are available on agrobased deicers.
Human	Can cause increased PM-10 and can lead to air quality nonattainment issues. Can reduce stream visibility, alter stream and roadside habitat, and decrease aesthetics.	Skin and eye irritant. Drinking water with sodium concentrations >20 mg/L can lead to hypertension. Can increase Cl, Ca, K, and Na concentrations above recommendations. Anti-caking agents may contain cyanide, a known carcinogen.	Skin and eye irritant. Ca and Mg can increase water hardness.	Ingestion of concentrated fluid can lead to death. A known endocrine disrupter.	Use of urea can increase nitrate levels in water. Little data are available on agrobased deicers.

Limited information is available on the degree of toxicity of liquid deicer chemicals/additives and the potential effect on aquatic ecosystems. Pilgrim (2013a) tested acute and chronic toxicity of a variety of chemicals used in winter maintenance. Chemicals were ranked based on the level of toxicity. Two thresholds were considered in terms of acute survival and chronic growth or reproduction. Test species were Ceriodaphnia Dubia (crustacean), Pimephales Promelas (fish), and Selenastrum Capricornutum (algae). The results of the study conducted by Pilgrim (2013b) are provided in Table 2.7 in which LC50 is product concentration at which there is 50% mortality for the test organisms and IC50 is the product concentration at which there is a 50% reduction in growth or reproduction (Pilgrim 2013b). The results showed that deicing products relative toxicity was in the following order from high to low: K-Acetate, $MgCl_2$, $CaCl_2$, and NaCl. When comparing products with corrosion inhibitors (i.e. Beet 55) and just salt brine (Watershed CI), the inhibitor added can significantly increase toxicity. Ingredients or composition of corrosion inhibitors in the products tested were not available and were not studied independently.

Table 2.7. Relative Toxicity of Deicing Products (Pilgrim 2013b).

Product	Relative Toxicity	*C. dubia*		Fathead Minnow		*S.Caprico-rnutum*
		Acute	Chronic	Acute	Chronic	Chronic
		LC50[1]	IC50[2]	LC50[1]	IC50[3]	IC50[4]
Watershed Cl(NaCl)	0.00	13.00	2.70	23.00	26.00	19.00
Boost ($CaCl_2$)	2.90	6.00	2.20	3.70	3.20	5.00
Road Guard Plus ($CaCl_2$)	3.64	6.50	2.70	2.10	2.50	4.00
Beet 55(NaCl)	6.02	12.00	0.29	2.50	2.50	5.10
FreezGard CI Plus ($MgCl_2$)	6.02	14.00	0.15	1.70	3.30	6.60
Apogee (Glycerol)	6.36	>8.0	1.20	>16	0.31	0.08
Meltdown Apex ($MgCl_2$)	6.88	5.80	0.05	3.30	7.00	3.10
CF-7 (K-Acetate)	10.00	1.00	0.00	1.30	2.10	0.44

Notes: All toxicological endpoints as mL of product per liter of diluent. Values rounded to two significant digits, [1]endpoint is survival, [2]endpoint is reproduction, [3]endpoint is growth, [4]endpoint is cell growth.

More recently, Vignisdottir et al. (2019) reviewed 35 peer-reviewed research articles (between 2000 and 2018) that reported winter maintenance environmental impacts. The authors focused on reviewing global and local environmental effects. The results of the literature review found that global environmental impacts of winter maintenance were mainly on climate change and ozone depletion due to fossil fuel winter maintenance operations in cold climate regions. Local impacts were related to soil, water, air, vegetation, and biodiversity. With the implementation of chemicals, there is a considerable impact on soil pH caused by deicers and some road dust, increase in water salinity up to toxic levels, increased emissions of particulate matter, damage to vegetation, and alteration of biodiversity (defects, slow adaptation, death) (Vignisdottir et al. 2019).

Since there is a predominant use of chlorides in winter maintenance, much of the material ends up in nearby water bodies. Dugan et al. (2017a) studied long term chloride trends in 371 freshwater lakes in North America. Lakes selected for the study had at least 10 years of chloride records, mean chloride concentration less than or equal to 1 g/l, and surface area equal or greater than 9.88 ac (4 ha). The study evaluated land cover metrics of road density and percentage of impervious land cover within 328-4,921 ft (100-1500 m) buffer surrounding each lake. Using regression trees (ANOVA) and Random Forest statistical methods, predictive models were developed. Dugan et al. (2017a) reported that 44% of the freshwater lakes studied had undergone long-term salinization. Road density and other impervious surfaces surrounding lakes where road salt is used for winter maintenance should be of high concern. In lakes with surrounding impervious land cover greater than 1% within 1,640 ft (500 m), 94 out of 134 lakes had increasing chloride trends. Extrapolating results to all existing freshwater lakes in the North American Lakes Region (CT, MA, ME, MI, NH, NY, RI, VT, and WI), approximately 7,700 lakes may be experiencing high chloride concentrations which may be attributed to road salt run off. From lakes studied, 26 out of 284 in the North American Lakes Region already have chloride concentrations higher than 100 mg/l in the most recent sampling (24.8% impervious surface in 1,640 ft buffer). Extrapolating the results, 47 lakes are on track to reach chloride concentrations of 100 mg/l and 14 are expected to surpass 230 mg/l (EPA's aquatic life criterion concentration) by year 2050. Concentration level at which drinking water deterioration is perceptible (Dugan et al. 2017a). Figure 2.13 illustrates long term chloride trends at eight lakes in Wisconsin (Dugan et al. 2017a). Three lakes in the City of Madison, surrounded by a significant urban land cover showed long-term increase in chloride concentrations. From five lakes in Northern Wisconsin situated in a forested landscape, only two lakes bordering a major highway showed long-term increase in chloride concentrations.

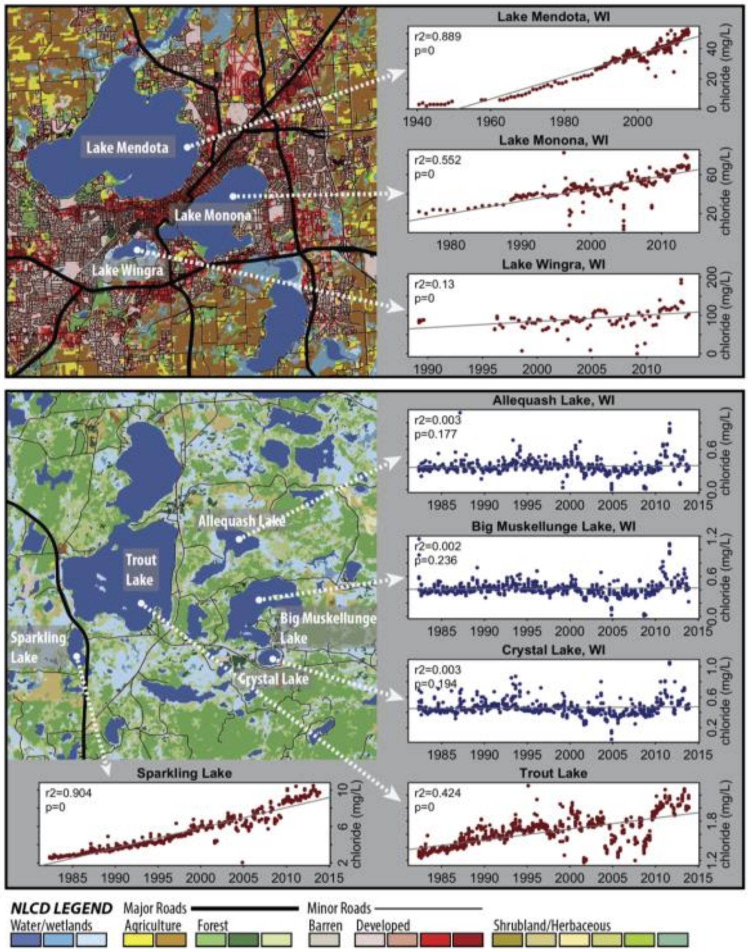

Figure 2.13. Chloride concentrations of eight lakes in Wisconsin (Dugan et al. 2017a).

Dugan et al. (2017b) further evaluated the effect of road salt application on shallow water bodies. The results of the study suggested that shallow water bodies were at much higher risk of elevated chloride concentrations than deeper water bodies during the process of ice cover thickening (Dugan et al. 2017b).

2.5. Corrosion

Corrosion is the deterioration of metals as a result of chemical or electrochemical reaction with its environment (Revie 2008). Corrosion can cause damage to automobiles, home appliances, drinking water systems, bridges, and public buildings. Metals have different properties, so the type and extend of corrosion depends on their environment. According to a study on corrosion in the United Sates, the direct cost of metallic corrosion is $276 billion per year (Koch et al. 2002). Cost of corrosion by industry indicates that transportation and infrastructure account for 21.5% and 16.4%, respectively. From the cost of corrosion in infrastructure, 37% of the cost were from highway bridges. Koch et al. (2002) determined that the increase in cost of vehicles manufacturing corrosion resistant materials was $2.56 billion, corrosion repairs and maintenance was $6.45 billion, and corrosion related depreciation was $14.46 billion, totaling a corrosion-related cost to motor vehicles of approximately $23.4 billion per year. In a recent survey conducted by AAA (2017), 15% of drivers living in cold climate regions had their vehicle repaired at least once because of rust damage caused by chemicals used in winter maintenance. Rust-related damage on vehicles was estimated to cost drivers more than $3 billion a year (average of $490 per repair), and 51% of the people surveyed in cold climate regions were concerned that winter maintenance chemicals may cause damage to their vehicles. Corrosion is a natural process and ºtakes many forms, its occurrence and associated costs cannot be completely eliminated. However, it was estimated that 25-30% annual corrosion costs could be reduced with optimal management and engineering practices (Koch et al. 2002).

Winter maintenance practices predominantly rely on chlorides. Since large quantities are required, chlorides are the most affordable alternative. Shi et al. (2009a) consulted several highway maintenance agencies which indicated that sodium chloride (NaCl) was the most commonly used deicer, followed by magnesium chloride ($MgCl_2$), agro-based products, calcium chloride ($CaCl_2$), and other chemicals (acetates, formates, Clearlane, IceSlicer). Since it is difficult to quantify the hidden costs associated with corrosion due to winter maintenance practices, it is important to determine the degree of corrosivity of materials before their use on roads that may be more susceptible to corrosive chemicals (Shi et al. 2009a).

This section presents a review of commonly used deicers and their impact on metals present in infrastructure, motor vehicles, and winter maintenance vehicles and equipment. Also, performance of corrosion inhibitors is covered.

In recent years, the implementation of $MgCl_2$ has increased in conditions with pavement temperatures below 10 °F, in which NaCl may not be effective. Shi et al. (2017) conducted field and laboratory studies to determine the corrosion effect and tensile stress of 25% $MgCl_2$. Materials tested were stainless steel (SS 304, unstressed and externally tensile stressed), aluminum (Al 1100), and low carbon steel (C1010). The results of the study determined that carbon steel (C1010) suffered the most corrosion (% rust area and weight loss), and aluminum (A1 1100) suffered the most loss in tensile strength. Tensile stressed stainless steel suffered more corrosion than unstressed stainless steel in both the field and laboratory tests. The ability of $MgCl_2$ to penetrate deep into the matrix of aluminum alloy poses a great risk to A1 1100 structural material (Shi et al. 2017).

Corrosion may decrease the service life of structural materials. Mends and Carter (2002) conducted a study in Montana evaluating the impact of $MgCl_2$ on concrete and reinforced steel. The authors concluded that $MgCl_2$ increased the potential of corrosion by facilitating chloride ion penetration into concrete. It was estimated that remaining service life of a bridge could be decreased by 20-30%.

Premature deterioration of several bridge decks (reinforced steel concrete) in Iowa were identified due to chloride ion penetration. Callahan (1989) evaluated additives and alternative deicing chemicals that could inhibit corrosion of steel. Chemicals tested were calcium magnesium acetate (CMA), CMA and NaCl (1:2, CMA:NaCl by weight), Quicksalt and Polymeric Corrosion Inhibitor (PCI) (70-80% NaCl, 5-7% $MgC1_2$ $6H_20$, and 15-20 percent Lignosulfonate derivative), and Cargill CG-90 (90-95% NaCl and 5-10% Polyphosphate corrosion inhibitor). The results of laboratory tests showed that all deicers tested were less corrosive than NaCl, and pure CMA was the only deicer tested that significantly inhibited corrosion of reinforced steel concrete (Callahan 1989).

Motor vehicles are also susceptible to deicer chemicals. Xi and Xie (2002) investigated corrosiveness of $MgCl_2$ and NaCl on several automobile components. Materials tested included stainless steel (410 and 304L), aluminum (2024 and 5086), coated automobile body sheets, copper wires, and mild steels. Standard laboratory test procedures were implemented, and the results showed that the degree of corrosion of both $MgCl_2$ and NaCl depends on service conditions experienced by automobile components. Thus, $MgCl_2$ was more corrosive in humid environments, and NaCl was more corrosive under immersion and arid environments. Since solutions with $MgCl_2$ are higher in viscosity, attracted to water, and water soluble; $MgCl_2$ solutions easily stick and crystalize on metal surfaces under dry conditions and quickly become a solution on metal surfaces under wet conditions (Xi and Xie 2002).

McKenzie et al. (2015) conducted a study evaluating performance of several commercial deicer products. As part of the performance measures, rate of corrosion was considered. Standard laboratory tests were conducted on rock salt, salt brine, Magic Minus Zero, Beet Heet, GreenBlast, and AquaSalina. Corrosion analysis resulted in high variability among corrosion testing rounds, attributed to variability in ambient temperature and humidity. Overall, GreenBlast and AquaSalina were the least corrosive, rock salt and Beet Heet had similar corrosion rates. Salt brine level of corrosion was very variable and difficult to compare with the rest of deicers (McKenzie et al. 2015).

Adding corrosion inhibitors to deicer blends has become a popular alternative to winter maintenance practice to decrease the corrosive effects of chlorides. However, little is known about their effectiveness. Relative corrosivity of deicers depends on several factors including metal/deicer properties, interactions (cation Na^+, $Ca^{2+,}$ or Mg^{2+}), corrosion inhibitor with Cl^- influences the pH of the electrolyte, and chloride diffusion in concrete (Shi et al. 2010a). Shi et al. (2010a) determined the benefits of corrosion-inhibited deicers to mitigate corrosion of rebar or dowel bars in concrete in comparison to conventional NaCl. Materials tested were salt brine (23% aqueous solution) as control, $MgCl_2$ brine with Shield GZT, Freezgard CI Plus (~30% of $MgCl_2$ by weight), and Geomelt CT (~ 30% CaCl2 by weight, $MgCl_2$, NaCl and KC1). The methodology consisted of Arterial Neural Networks (ANN) modeling to determine cause and effect relationships among deicer, concrete, and steel bar. Modeling results showed that corrosion inhibitor added to $CaCl_2$ and $MgCl_2$ did slow down the process of penetration of chloride into concrete. The risk of corrosion to reinforced concrete was in the following order from high to low: non-inhibited NaCl, inhibited NaCl, inhibited $CaCl_2$ deicer, and inhibited $MgCl_2$ deicer. Once active corrosion of bars was initiated, corrosion inhibitors showed little benefits in slowing down corrosion and propagation (Shi et al. 2010a).

Transportation agencies have reported corrosion as a major issue since there is a higher risk of corrosion in winter maintenance equipment. Li et al. (2013) determined that on average, transportation agencies cost of corrosion management accounted for $1.06 million per year and the cost for corrosion related deicer exposure was $14.05 million per year. Equipment more susceptible to corrosion were dump trucks, followed by liquid deicer applicators, hoppers, front end loaders, and supervisor trucks or crew pickups. Products used to reduce the effect of corrosion on winter maintenance equipment identified in the study were anticorrosion coatings (Zero Rust Red, Zero Rust Black, Rust Bullet, and Lubra-Seal), spray-on corrosion inhibitors (Krown, Ship-2-Shore, Vegetable Oil, and Rust-Oleum), and salt removers (MR 35, HoldTight, ChlorRid, SaltAway, Soap Water, and Neutro-Wash). The level of corrosion protection of the different products was tested through Electrochemical Impedance Spectroscopy (EIS). Based on their performance with EIS, Rust Bullet was the best coating, Krown was the best spray-on corrosion inhibitor, and effective salt removers were HoldTight and ChlorRid. Identified products had optimal corrosion protection to carbon steel substrate against $MgCl_2$ solutions (Li et al. 2013, Shi et al. 2013a).

There is an increase of winter treatment applications with liquid brines because of their proven cost benefit, reduced amounts of chemicals released in the environment, and decrease damage to infrastructure. There are several anecdotal reports that claim that liquid brines generate more corrosion damage to motor vehicles than conventional rock salt. However, there is no conclusive evidence that liquid brines are more corrosive than rock salt (Koefod 2016). Essentially, salt brine is a diluted salt in water solution in which salt concentration is usually 23%. When rock salt is applied on roads and is melting ice, it will get diluted and turn into brine. Thus, there is no difference in corrosion of rock salt and salt brine per pound of actual salt. On the other hand, increased signs of corrosion on maintenance trucks due to salt brine have been reported. In these cases, increased corrosion would be expected since winter maintenance equipment are more exposed to the salt brine mist and spray compared to regular traffic (Koefod, 2016).

2.6. Deicer Impact on Concrete

A vast amount of research has been conducted on the damaging effects of deicers on concrete. There are three mechanisms in which deicers may cause damage to concrete: 1) freeze-thaw scaling, 2) chemical attack, and 3) steel rebar corrosion. For more specific information, the reader is referred to the references cited in this section and the study conducted by Xiao et al. (2018), who evaluated the use of different deicing/anti-icing chemicals and their effect on concrete durability in Wisconsin.

2.6.1. Freeze/thaw Scaling

Freeze/thaw scaling is a direct physical attack on the structure of concrete. Since concrete is a porous material, water generally is present in the pores of the surface of concrete. Thus, when water freezes, it expands by approximately 9% of its volume and generates pressure in the surrounding concrete surface. Concrete can manage the stress generated by just water freezing. When deicer chemicals are dissolved in water present in the porous concrete surface, it increases the amount of stress on concrete when the water with deicer solution freezes. Cumulative effect of successive freeze-thaw cycles can eventually cause cracking, scaling, exposure of the aggregate, and crumbling of concrete. Conventionally used chemicals in deicers increase freeze-thaw damage including sodium chloride (NaCl), calcium chloride ($CaCl_2$), acetates, formats, urea, and glycols. The only exception is Magnesium based deicers such as magnesium chloride ($MgCl_2$) and calcium magnesium acetate (CMA) which cause less freeze-thaw damage than other deicers. However, Magnesium based deicers cause the most damage from chemical attack which is discussed in the next section. Overall, concrete is very resistant to freeze/thaw scaling when properly produced (air entrainment), cured, and finished even in the presence of deicers (Santagata et al. 2000, Lee et al. 2000, Sutter et al. 2006, Wang et al. 2006, Sutter et al. 2008, Shi et al. 2009b, Cutler et al. 2010, Shi et al. 2010c, Fay and Shi 2011, Ma et al. 2011, Jain et al. 2012, Sumsion and Guthrie 2013, Dang et al. 2014, Shi et al. 2014, Koefod 2015a, Jungwirth and Shi 2017, PCA 2018).

2.6.2. Chemical Attack

Deicer chemical attack has a direct effect on concrete. All chemicals used in deicers cause chemical reactions with concrete which has the potential of damaging the concrete structure over time. In terms of the degree of damage caused by chemical attack, the least damaging chemical is sodium chloride (NaCl), followed by calcium chloride ($CaCl_2$). On the other hand, magnesium chloride ($MgCl_2$) is the most damaging chemical to concrete. Most studies were conducted in laboratory environments in which accelerated and aggressive conditions were tested. Results from studies resembling real conditions (with field samples), suggested that the detrimental effects of chemical deicers such as calcium chloride ($CaCl_2$) may have negligible effects on concrete durability and magnesium chloride ($MgCl_2$) effects were slow over time (Cody et al. 1994, Cody et al. 1996, Lee eta al. 2000, Mussato et al. 2004, Wang et al. 2006, Sutter et al. 2006, Darwin et al. 2008, Sutter et al. 2008, Glasser et al. 2008, Shi et al. 2009b, Giebson et al. 2010, Truschke et al. 2011, Shi et al. 2011, Sumsion and Guthrie 2013, Shi et al. 2014, Farnam et al. 2015, Koefod 2015b, Farnam et al. 2016, Althoey et al 2018, Qiao et al. 2018).

2.6.3. Steel Rebar Corrosion

Corrosion is considered to have an indirect effect on concrete (a section in the literature review covered the details of corrosion effect of deicers). Corrosion of rebar in concrete occurs when the rebar is exposed to the environment and reacts to water and deicer chemicals. Corrosion results from reaction of iron in the steel rebar which converts into iron oxide (Fe_2O_3) and creates a film on the surface of the rebar, expanding inside the concrete-steel binding. This expansion generates stress to the concrete structure and ultimately breaks or cracks concrete over time (Sutter et al. 2008, Shi et al. 2010b, Shi et al. 2014, Wang et al. 2014).

In summary, deicer chemicals do not pose a significant threat to the durability of properly produced, cured, and finished concrete. Although Magnesium based deicers appeared to have less freeze-thaw damage compared to most deicers, magnesium chloride ($MgCl_2$) had the most detrimental chemical effect on concrete. Deicers should be of concern with marginal quality concrete. Laboratory tests expose concrete samples to accelerated and aggressive conditions which may not translate to real field conditions and the effects of deicers may be negligible in the durability of properly produced, cured, and finished concrete (Koefod 2015a, 2015b).

2.7. Deicer Impact on Asphalt Pavement

Asphalt is less sensitive to deicer damage. Similar to concrete, asphalt may be impacted by freeze-thaw and chemical reaction damage. Most of the studies conducted on asphalt pavements were on airports in which the effects of urea, formates, and acetates were evaluated. Results of those studies suggested that using acetate and formate-based deicers in airport winter operations caused some chemical reactions that softened the asphalt binder properties which could lead to aggregate separation. Chlorides were found to have less chemical reaction with asphalt binder. Overall, deicers have a relatively small detrimental effect on asphalt pavement durability (Hassan et al. 2002, Pan et al. 2008, Shi et al. 2009b, Wei Goh et al. 2011, Koefod 2016).

2.8. Agro-Based Products

Agro-based products are increasingly being used for anti-icing and deicing winter maintenance activities. Several agro-based chemical formulations have been proposed in recent years and products include desugared beet molasses, corn by-products, cheese brewing by-products, beer/wine brewing by-products, succinate salts, urea, and starch. Agro-based products are being used alone or in combination with other chemicals. Commercial agro-based formulations claim to reduce corrosiveness and environmental impacts; and improve effectiveness at lower temperatures, pavement friction, and material adherence. The performance of agro-based products has mostly been documented from anecdotal field observations. Despite reported advantages, there are still concerns regarding their toxicity to aquatic ecosystems, attraction of wild animals, increased cost of winter maintenance, effectiveness, and quality control (consistency of product). Little is known about the mechanisms that may lead to the observed benefits. Commercial agro-based products may contain additional chemicals which may be attributed for enhanced product performance. This section focuses on providing the results of laboratory and field studies evaluating the performance of agro-based products.

Jungwirth and Shi (2017) conducted a laboratory investigation of several naturally sourced deicers. Laboratory tests consisted of quantifying ice melting capacity, corrosion effect, and impact on concrete. One control and four commercially available products were considered. Salt brine (23% by weight of aqueous solution) was used as control to test the following naturally sourced deicers (Jungwirth and Shi 2017).

The results of the study conducted by Jungwirth and Shi (2017) showed that the four liquid deicers reached or approached their maximum ice melting capacity approximately at 30 minutes (at 15 °F and 5 °F). The product with $MgCl_2$ (30% by weight) had the highest ice melting capacity compared to the control salt brine and other tested solutions. Products with sugar beet exhibited lower ice melting capacities suggesting that agro-based products are not suitable as liquid deicers at low temperatures. In terms of corrosion, all four solutions tested showed significantly lower corrosion rates (in mm/year) than the control salt brine. Natural sourced liquid deicers had lower risk to the integrity of carbon steel which might be attributed to adsorption of an organic layer on the surface of steel providing protection against corrosion. Tests on the impact of naturally sourced deicers on concrete showed that all four liquid deicers led to increased chemical attacks and reduction of strength on Portland cement concrete samples. Reduction of concrete strength can be attributed to chemical degradation of the cementitious phases in concrete samples (Jungwirth and Shi 2017).

Muthumani and Shi (2016) also evaluated the performance of four agro-based liquid deicers. Products consisted of concentrates with 23.3% NaCl aqueous solution at either 70/30 or 80/20 volume ratio. Agro-based deicers tested contained beet sugar, and likely had certain amounts of $MgCl_2$ or $CaCl_2$. Rock salt or regent-grade NaCl were used as control samples. Performance of deicers were tested in terms of thermal properties, ice melting capacity, and corrosion. Muthumani and Shi (2016) found that agro-based products appear to lower the freezing point of 23% NaCl brine, but do not increase ice melting capacity at 25 °F or 15 °F. Also, agro-based products had significant benefits in reducing corrosion with 23% NaCl brine which may be attributed to the anodic-type inhibitor and not beet based additives. Agro-based deicers did not exhibit lower temperature characteristics than regent-grade.

By-products from agricultural processes were evaluated for deicing applications in Iowa (Talor et al. 2010). Naturally sourced and commercial patented products were considered. Table 2.8 provides the list of products included for evaluation.

Table 2.8. List of Agricultural Based Products Evaluated (Talor et al. 2010)

I.D.	Combination
A	100% glycerol
B	90% glycerol + 10% $MgCl_2$
C	80% glycerol + 20% NaCl
D	90% Geomelt® + 10% $MgCl_2$
E	80% Geomelt® + 20% NaCl
F	90% Ice B Gone® + 10% $MgCl_2$
G	80% Ice B Gone® + 20% NaCl
H	5% solution of NaCl in water
I	50 % E310 + 50% glycerol
J	100% NaCl
K	40% E310 + 40% glycerol + 20% NaCl
L	50% glycerol + 50% $MgCl_2$

As part of the research project, the use of Glycerol in deicing formulations was proposed (Talor et al. 2010). Glycerol is a colorless, odorless, and viscous liquid obtained as by-product of the process of conversion of animal fat into soap. Also, Glycerol is obtained as a by-product of the production of biodiesel. Since Glycerol has low toxicity, it is widely used in the pharmaceutical industry, personal care, and food formulations. Laboratory test conducted for the evaluation of product performance included: freezing point with eutectic temperature, ice melting capacity, skid resistance, and viscosity. Overall performance from the products with regards to the different tests was considered, and the formulation of 80% Glycerol with 20% NaCl showed the most promising results. There were some concerns with the viscosity of the formulation, so viscosity of the product was measured with different concentrations in water. The results suggested practical applications in the field with Iowa DOT deicer spray truck configurations at a reasonable concentration-to-flow ratio (Talor et al. 2010).

Agro-based products were also used in pilot routes in the Southeast Region in Michigan during the winters of 1999-2002 (Kahl 2002). The region experiences heavy lake effect precipitation. Performance of $MgCl_2$ with agro-based products (Mountain Products M50 Road Deicer, Caliber M-2000) were evaluated for pre-wetting, anti-icing, and deicing winter operations. Kahl (2002) evaluated cost effectiveness, performance, and crash frequency. Initial anti-icing application rates were 35 gal/lane-mile and followed by rock salt. Dark color appearance was observed on the road and was mistaken by black ice. Adjustments were made during the period of analysis, anti-icing application rates were reduced to 25 gal/lane-mile and clear color agro-based product was used. Results of the study suggested that agro-based products decreased overall material costs (anti-icing, pre-wet), reduced the use of abrasives for traction control, agricultural by-products should be used for anti-icing only, and crash frequency of winter events decreased in comparison to previous years with similar number of winter events (Kahl 2002). Crash estimates should be interpreted with caution since linear regression was used, short period of analysis, and regression to the mean or storm intensities were not accounted for.

On a field study conducted by Fu et al. (2012), performance of salt brine and two beet juice organic deicers were compared on a 7.5-mile corridor in Ontario, Canada. Performance measures consisted of road friction, high resolution images, and meteorological data during nine winter events (approx. 100 hours). Traffic was between 16,000-18,000 vpd. The corridor was divided into six zones where different combination of applications and material were implemented. Treatments consisted of pre-wetting (adding liquid chemical before granular salt is applied to road) and direct liquid application (applying deicing liquid directly to road surface, initiated ahead of storm). Materials used were salt brine (23% NaCl), 30% beet juice M1 and 70% salt brine, and 30% beet juice M2 and 70% salt brine. Beet juice M1 and M2 were from different providers and had similar constituents. Fu et al. (2012) found mixed performance with pre-wetting (small differences among the three materials). For direct liquid applications, organic materials showed better performance in comparison to just salt brine in terms of higher average pavement friction. Also, direct liquid applications showed significantly better results than sections with pre-wetted salt. Limited data was available to evaluate performance of materials at low temperatures since there was only one storm with temperature below 14°F. The findings were limited to the application rates selected, performance measures, and winter events observed.

Another agricultural by-product is steep water which is the main waterborne waste from the process of corn wet milling. Janke and Johnson (1997) proposed the use of steep water for anti-icing, deicing, and corrosion inhibitor. Steep water was found to have higher melting capacity than salt/sand mixture. It was active at temperatures as low as 7.5°F, whereas salt/sand mixture stopped around 20°F (Janke and Johnson 1997). Yang and Montgomery (2003) attempted to improve the deicing properties of steep water by treatment with alkali in the presence of glucose. The new steep water formulations were compared to other conventional deicers. Laboratory test included freezing temperature, viscosity, specific gravity, and ice meting capacity. The results showed that steep water alone was not an effective deicer. Monovalent metal hydroxides were more efficient in producing deicer solutions than the divalent metal hydroxides, but treating with alkali monovalent metal hydroxides (NaOH or KOH) can provide more efficient deicer solutions (Yang and Montgomery 2003).

Minnesota DOT anti-icing guide provides commonly used chemicals and corresponding application temperature, benefits, and treatment recommendations. As part of the chemical's recommendations, it was noted that organic products like liquid corn salt provide some freezing point depression and in order to improve adherence of material, blends should have at least 10% of organic product (Peterson et al. 2010).

There are still some concerns that have not yet been thoroughly studied with the use of agricultural by-products for winter maintenance (Muthumani et al. 2015). There is some anecdotal evidence of roadway slickness which may be possible with excessive or over-application of agricultural by-products. Viscosity of blends is also of significant concern since it may clog the equipment used to spray material. Also, storage over prolonged periods of time and higher temperatures can promote the growth of bacteria in organic products. Finally, the smell and taste of agricultural by-products on rural roadways may attract wild animals and increase the risk of wildlife-vehicle collisions. Although there are anecdotal reports, there is not clear conclusive evidence that agro-based products on the road attract wild animals or increase wildlife-vehicle collisions (Muthumani et al. 2015).

2.9. Benefit-Cost of Deicers

Selection of deicer products directly influences the cost of winter maintenance operations. Direct cost of winter maintenance includes cost of material (chemicals, number of storms, and severity of storms), equipment (brine maker, storage, operating hours, fuel, maintenance, etc.), and staffing (wages, benefits, overtime, standby, training, etc.). Indirect costs may be associated with negative impacts on motor vehicles, transportation infrastructure, and the environment (Shi et al. 2014). It is a complex task to estimate the overall cost of winter maintenance—type, amount, and cost of material.

Liquid applications have become more common in winter maintenance and in-house production is practical. In the case of salt brine, true cost of in-house salt brine must include capital costs (brine maker, storage, and entire system components). Costs of brine per gallon were reported as low as $0.05; however, little information on equipment, labor, and material costs were considered. Crow et al. (2019) conducted a case study in Ohio to estimate the true cost of salt brine. Table 2.9 illustrates the costs that were considered in the analysis.

Table 2.9. Costs Used for the Calculation of the Cost of Liquid Brine (Crow et al. 2019).

Variables	Average	Standard Deviation	Source
Capital Cost of 3,000 gph Brine Maker	46,900	4,000	ODOT
Life Span of Brine Maker (yr)	13	2	ODOT
Annualized Factor (i)	0.04	0.02	ODOT
Labor Efficiency for Brine Maker	0.25	0.05	ODOT
Electric Rate Cost ($/kwh)	0.0947	0.04	electricitylocal.com & www.neo.ne.gov
Kilowatt - Hour at Summit (Two Pumps)	15	2	County
Salt Cost - High ($/ton)	82.72	17.33	Refill 2014-2015 Salt Cost
Salt Cost - Medium ($/ton)	51.22	6.89	Years Averaging> $50/ton
Salt Cost - Low ($/ton)	45.3	6.95	Years Averaging < $50/ton
Water Cost ($/gallon)	0.07	0.027	OEPA
Summit County Brine Usage per Year	578,000	141,000	ODOT
Variables	**Upper Limit**	**Lower Limit**	**Source**
Gallons Produced with 1-Ton of Salt	1,000	900	ODOT
Production Rate of Bri.ne Maker (gph)	3,000	2,000	ODOT
Labor Rate ($/hr)	75	15	ODOT

Using Monte Carlo simulation, equations of brine, salt, electric, and capital cost were simulated one million times to find the average cost of brine and range of variation. Since the cost is highly dependent on the cost of salt per ton, three costs were estimated. Thus, the true cost of salt brine was between $0.13-0.17 per gallon (for $45.3-82.72 per ton of salt). Cost of storage was not accounted for in the calculations (Crow et al. 2019).

Table 2.10. Costs Used for the Estimation of the True Cost of Sal Brine (Keep 2018).

Labor	$$$
Brine Maker/ Hr.	$18.00
Loader With Operator	$15.00
Cleanout Cost	$2.00
Labor Cost Per Gallon at 830 Gallons Production Per Ton of Salt	**$0.04**
Equipment	**$$$**
Brine Maker Complete System New	$60,000.00
Repairs & Maintenance -10 Years	$10,000.00
Residual Value	($5,000.00)
Indirect Cost or Facility	$18,000.00
Annual Total	$8,300.00
Equipment Cost Per Gallon at 100,000 Gallons Annual Production Rate	**$0.08**
Material	**$$$**
Salt Per Ton	$75.00
Contamination Factor	5%
Useable Salt Weight Per Ton	1,900
Gallons of Salt Brine Produced	830
Water Cost Per Gallon	$0.001
Electricity Cost Per Gallon	$0.001
Cost Per Gallon - Salt Only	$0.09
Real Cost Per Gallon	**$0.22**

As mentioned previously, calculation of the true cost of salt brine is complex and varies based on the production capacity and storage, assumptions, and unit

costs considered. For instance, Keep (2015) argued that estimated true costs of salt brine in the range of $0.08-0.10 per gallon omit and underestimate in-house costs associated with labor, equipment, and material. For instance, Keep (2018) considered that a brine maker and complete new system is approximately $60,000, and repairs and maintenance over 10 years is $10,000. Table 2.10 provides additional information of costs considered in the estimation of the true cost of salt brine per gallon. Keep (2018) estimated that the true cost of salt brine per gallon was $0.22.

Estimating the cost of material used in winter maintenance is just one aspect of the complex process of decision making for effective operations. It is important to consider the most effective treatment at a reasonable cost. Fitch et al. (2013) reported that the cost of winter maintenance with solid salts was $3,149 and with salt brine $3,343 per typical 100 lane miles (insignificant difference of cost per storm basis). From a survey conducted by Ye et al. (2013), the weighted average application rate of 28 gallons per lane mile with salt brine (23% NaCl) was estimated to be $0.14 per gallon and for $MgCl_2$ liquid deicer $0.72 per gallon, indicating a considerable difference in cost per gallon. Ye et al. (2013) also estimated average annual direct costs (material, equipment, and staffing) in lanes per mile of $123 (solid salt), $121 (salt brine), and $263 ($MgCl_2$). The use of salt brine was slightly more cost effective than solid salt. $MgCl_2$ based products had higher cost likely due to the inclusion of corrosion inhibitor. Sand is relatively inexpensive, but environmental impacts and cleanup activities can make it less cost-effective (Shi et al. 2014).

A comprehensive benefit/cost analysis of several winter maintenance strategies was conducted by Fay et al. (2015). The scope of the study included a literature review, surveys, and interviews with practitioners to develop a benefit-cost matrix. Information considered to assemble the benefit-cost matrix included reported costs, benefits, effectiveness of achieving LOS, performance, pros and cons, and environmental impacts. The analysis was divided into winter activities and strategies, and a summary of the cost estimates are presented in Table 2.11.

Table 2.11. Cost of Winter Maintenance by Activity (Fay et al. 2015).

Activity	Average Cost	Cost Range
Plowing		
Annual average cost / lane mile	$1,335.00	-
State DOTs	$1,353.00	-
Counties	$882.00	-
Municipalities	$251.00	-
Solid Salt (NaCl)		
Average cost / ton	$71.04	$48.63 - $120.00
Average cost of anti-icing / lane mile	$68.41[1]	$39.47 - $100.00
Salt Brine		
Average cost / gallon	$0.16	$0.05 - $0.35
Average cost production and application / lane mile	$37.92	$5.91 - $78.94
Average cost anti-icing / lane mile	$68.41[1]	$39.47 - $100.00
Average brine-making equipment cost	$89,273.00	$7,000.00 - $250,000.00
Magnesium Chloride ($MgCl_2$)		
Inhibited solid cost / ton	$150.00	-
Inhibited liquid cost / gallon	-	$1.00 - $1.50
Uninhibited liquid cost / gallon	$1.20	-
Calcium Chloride ($CaCl_2$)		
Inhibited liquid cost / gallon	-	$1.00 - $2.80
Uninhibited liquid cost / gallon	-	$0.40 - $1.09
Uninhibited solid cost / ton	-	$340.00-$450.00
Inhibited solid cost / ton	$963.50	
Corrosion Inhibitors		

Activity	Average Cost	Cost Range
Average cost / gallon	$1.18	$0.78 - $1.50
Cost / ton	$650.00	-
Cost / lane mile	-	$695.55 - $1,652.93
Liquid storage setup for stockpile pre-wetting	$3,000.00	-
Inhibited Salt		
Average cost / gallon	$0.31	$0.12 - $0.50
Blended Products		
Inhibited liquid cost / gallon	-	$0.50 - $2.80
Abrasives		
Average cost / ton	$9.32	$4.00 - $16.00
Average cost / ton of abrasive-salt mixtures	$20.86	$15.00 - $35.00
Average cleanup cost / mile	$85.66	$62.95 - $120.00

Notes: [1] The average cost of inti-icing for salt and salt brine was the same due to limited information from survey respondents.

Calculated benefit-cost ratios by winter activity and maintenance strategy are provided in Table 2.12. Overall, the most cost-effective activities for basic and intermediate winter activities were plowing and salt brine. In more advanced winter activities, all maintenance activities proved to be cost-effective alternatives such as the use of corrosion inhibitors, $MgCl_2$, or $CaCl_2$. When comparing maintenance strategies of solid salt and liquid salt brine applications, liquid salt brine was 1.58 times more cost effective than solid salt (Fay et al. 2015).

Table 2.12. Calculated Benefit-Cost Ratios by Winter Activity and Strategy (Fay et al. 2015).

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

Notes: * Shi et al. 2013a, Nazari et al. 2015.

3. SURVEY OF PRACTICE

A survey of practice was conducted to gather agencies' liquid application guidance, practices, and to identify potential sites for field data collection. Information gathered from the literature review was considered in preparing the survey questions. Clear Roads technical advisory committee reviewed and approved the survey questions. The online survey was distributed to winter maintenance practitioners at the state and local level to ensure the survey captures a wide range of experiences and contributes to the overall research plan. The survey emphasized on agencies' practices involving materials, predominant winter conditions, liquid application rates, experience, performance measures, and interest to serve as a test site.

3.1. Survey Design

The survey was developed and supported in the online Qualtrics software, Version XM of Qualtrics. Copyright © 2020 Qualtrics. Qualtrics and all other Qualtrics product or service names are registered trademarks or trademarks of Qualtrics, Provo, UT, USA. https://www.qualtrics.com.

Based on the responses to the survey, personal follow-up telephone calls were employed to expand the pool of responses, as well as to clarify agencies' experiences and recommended practice in more detail. For instance, agencies interested in participating in the study were contacted with telephone calls. The survey focused on liquid application practices and effectiveness. The survey introduction and questions are included in Appendix B.

3.2. Survey Distribution

Personal connections with vast experience in winter maintenance operations across the United States were considered to facilitate survey participation. Additionally, the research team worked with Clear Road technical advisory committee to expand and augment the list of survey recipients. The list of contacts that the survey was sent out to is also included in Appendix B.

3.3. Overview of Survey Results

A total of 33 responses were received (two responses were incomplete and did not have contact information). Respondents were from different local and state agencies. Six out of the 33 respondents were from one state agency. Ten agencies that have experience with liquid applications indicated their willingness to participate in the study and collect field data. A summary of the survey responses is provided in Table 3.1.

From the section ***"A. Liquid Application Guidance and Practices"*** of the survey, 31 (94%) agencies use liquid applications and 22 (67%) have a guidance document for when to use liquids. Eleven respondents submitted the guidance documents used at their agencies. From one of the most important questions of this survey, 23 (70%) respondents indicated that their agencies use liquid applications at pavement temperatures below 20°F. It is also of interest to know commonly used materials and blends by the different agencies. Coincidentally, 22% of all selected materials in the survey were for salt brine followed by selections of 18% for solid salt, 17% for prewet salt, and 13% of Magnesium Chloride. Other chemical materials used include Biomelt AG-64, Boost, Geomelt 55, beet juice, AquaSalina+ and other agricultural byproducts. In terms of pavement temperatures ranges and surface conditions, as expected, most agencies expressed that liquid applications were commonly used at pavement temperature ranges between 20-32°F, but most agencies would avoid using liquid applications at pavement temperatures below 20°F. However, four agencies indicated that they commonly used liquid applications at pavement temperatures below 15°F. Forty seven percent of respondents used liquid in combination of solid applications (Shake and Bake) and 39% of respondents used extremely heavy pre-wetting at up to 70 gallons a ton (Slurries).

Responses in the section ***"B. Performance Measures,"*** showed that the main performance measure used in winter maintenance was the amount of salt used (28%) followed by time to bare/wet (21%) and cost of material used (17%). It is worth mentioning that friction testing was also used as performance measure by 16% of respondents. Friction testing may be overrepresented. From the 12 (16%) agencies that selected friction as a performance measure, four responses were from the same agency. Other performance measures used included cycle times, level of service, and traffic volumes. Tools commonly used in winter maintenance include AVL (43%), video feed (16%) and other such as RWIS (19%).

In section ***"C. Project Data Collection,"*** ten agencies that already had experience with liquid applications indicated their willingness to participate in the study, collect, and provide data.

Table 3.1. Summary of Survey Responses

A.	**Liquid Application Guidance and Practices**						
Q1	**Does your agency use liquid applications for winter maintenance?**	Count			Percentage		
		Yes	No		Yes	No	
		31	2		94%	6%	
Q2	**Do you have a guidance document for when to use liquids, at what application rates, and what frequency?**	Yes	No	Blank	Yes	No	Blank
		22	9	2	67%	27%	6%
	Please upload guidance document or provide URL (Submitted)	11		22	33%		67%
Q3	**Is your agency willing to share internal or commonly used application rates in a follow-up call?**	Yes	No	Blank	Yes	No	Blank
		7	2	24	21%	6%	73%
Q4	**Does your agency use liquid applications at pavement temperatures below 20°F?**	Yes	No	Blank	Yes	No	Blank
		23	8	2	70%	24%	6%
Q5	**What chemical materials does your agency use at pavement temperatures below 20°F?**	Choice Count			Choice Percentage		
		82			100%		
	Liquid	**46**			**56%**		
	Salt Brine (23% NaCl)	18			22%		
	Calcium Chloride (32% $CaCl_2$)	6			7%		
	Magnesium Chloride (27% $MgCl_2$)	11			13%		
	Potassium Acetate (50% KAc)	3			4%		
	Calcium Magnesium Acetate (25% CMA)	0			0%		
	Other liquid chemical material	8			10%		
	Solid	**36**			**44%**		
	Solid Salt (NaCl)	15			18%		
	Prewet Salt	14			17%		
	Calcium Chloride (90-92% $CaCl_2$)	3			4%		
	Magnesium Chloride (100% $MgCl_2$)	3			4%		
	Potassium Acetate (100% KAc)	0			0%		
	Calcium Magnesium Acetate (96% CMA)	0			0%		
	Other solid chemical material	1			1%		
Q6	**If Q5 Other is selected. Please, describe OTHER liquid/solid chemical materials used**						
	Biomelt Supreme						
	Beet Heet and AquaSalina+						
	Blended brine (see recipe below)						
	Geomelt 55 - Beet juice 10-20%						
	Agricultural by products blended with Salt Brine Beet Juice						
	We have boost which we can add to Salt Brine at 20% for benefit at colder temps.						
	Boost at a rate of 25 Gallons Per Lane Mile.						
	Biomelt AG -64 from SNI Solutions						
Q7	**What blends are commonly used at your agency? For example: 90% Salt Brine and 10% Calcium Chloride**						
	90% Brine 10% AG-64, 85% of the time 85% Brine 15% AG-64, 10% of the time 80% Brine 20% AG-64, 5% of the time						

	90% Salt Brine for general application and 10% Boost for Cold Weather Application
	Not blending with our current $MgCl_2$ liquid.
	I believe 80 salt 20 calcium
	100% salt brine
	75% Salt Brine 24% Magnesium Chloride 1% Potassium Acetate
	We blend solar salt with mined salt at a 2:1 ratio.
	80% Salt Brine and 20% Calcium Chloride 70% Salt Brine and 30% Calcium Chloride
	80/20 and 90/10 mix of salt brine and beet juice
	80% Brine - 20% Beet 85% Brine - 15% Beet 80% Brine - 10% Beet-10% Calcium (32%) 85% Brine -10% Beet-5% Calcium (32%)
	85% (of 23% NaCl) with 15% (of 28.5% $MgCl_2$)
	90% Salt Brine and 10% Calcium Chloride, 90% Salt Brine and 10% Beet Heet, 90% Salt Brine and 10% AquaSalina+ and 90% Salt Brine and 10% AquaSalina + IceBite
	85% NaCl brine: 15% $MgCl_2$ brine
	We have started adding organic sugar additives to our brine during colder temperatures such as 80% Beet Heat to 20% Salt Brine and 80% Ice B Gone to 20% Salt Brine
	90 salt brine/10 carbohydrate or 95 salt brine/5 carbohydrate

Q8 **In which weather conditions does your agency COMMONLY USE liquid applications?**

Pavement Temperature and Surface Condition	Snow		Frost/Black Ice		Freezing Rain		Sleet		Total
20-32°F DRY	20	33.90%	23	38.98%	7	11.86%	9	15.25%	59
20-32°F WET	18	33.96%	20	37.74%	7	13.21%	8	15.09%	53
15-20°F DRY	13	30.95%	16	38.10%	7	16.67%	6	14.29%	42
15-20°F WET	12	30.00%	14	35.00%	7	17.50%	7	17.50%	40
Below 15°F DRY	6	30.00%	7	35.00%	4	20.00%	3	15.00%	20
Below 15°F WET	8	34.78%	7	30.43%	4	17.39%	4	17.39%	23

Q9 **What conditions would your agency AVOID using liquid applications?**

Pavement Temperature and Surface Condition	Snow		Frost/Black Ice		Freezing Rain		Sleet		Total
20-32°F DRY	4	16.00%	2	8.00%	11	44.00%	8	32.00%	25
20-32°F WET	10	21.74%	7	15.22%	15	32.61%	14	30.43%	46
15-20°F DRY	10	22.73%	7	15.91%	14	31.82%	13	29.55%	44
15-20°F WET	12	23.08%	10	19.23%	15	28.85%	15	28.85%	52
Below 15°F DRY	17	23.94%	15	21.13%	20	28.17%	19	26.76%	71
Below 15°F WET	16	23.53%	15	22.06%	19	27.94%	18	26.47%	68

Q10	**If Q1. response is No. In which conditions would your agency consider using liquid applications?**
	Not enough responses

Q11	**Are liquid applications used in combination with solids at pavement temperatures below 20°F?**	Choice Count	Choice Percentage

	Yes: Shake and Bake When liquid salt application is immediately followed by solid application	18	47%
	Yes: Slurries Extremely heavy pre-wetting at up to 70 gallons a ton	8	39%
	No	5	24%
B.	**Performance Measures**		
Q12	**What performance measures are used in your jurisdiction?**	Choice Count	Choice Percentage
	Amount of material used	21	28%
	Cost of material used	13	17%
	Time to bare/wet	16	21%
	Speed measurements	7	9%
	Pavement friction	12	16%
	Other	6	8%
Q13	**If Q12 Other is selected. Please, describe OTHER performance measures**		
	Total cost of labor, material and equipment. We look a speed recovery after the storm event has stopped against the amount of cost put into meeting our recovery goals.		
	Cycle times		
	Level of serviced or decreased …		
	Performance measures have not been stablished		
	None		
	Traffic volumes		
Q14	**What tools does your agency use for winter maintenance?**	Choice Count	Choice Percentage
	MDSS	9	16%
	AVL	25	43%
	CLARIS	0	0%
	Video feed	9	16%
	Friction testing	4	7%
	Other	11	19%
Q15	**If Q14 Other is selected. Please, describe OTHER tools for winter maintenance**		
	Reid sites that have a camera and roadway info		
	Visala and RWIS locations as well as AVL		
	RWIS sites		
	Roadway Weather Information System		
	RWIS		
	DTN weather forecast		
	RWIS		
	One RWIS site that MDOT provides logins too. BP		
	RWIS, Weather contract, traffic cameras		
	RWIS/Grip Sensors, Spreader Systems/Ground Speed Control, Pavement Temperature Sensors,		
	Paid weather forecasting service, US Weather Service, RWIS, MARWIS, Mini-RWIS (High Sierra Ice Sights)		
	Reid sites that have a camera and roadway info		

		Count		Percentage	
Q16	**Does your agency utilize performance-based testing in procuring deicers?**	Yes	No	Yes	No
		6	27	18%	82%

Q17	**If Q16 Yes is selected. Please, explain the performance-based testing procedure to procure deicers**
	Mechanical rocker test for ice-melting capacity.
	Certain solids on our Geo Melt 55, check our 32% calcium and salt brine with a refractometer by "MISCO" for quality
	After a vendor has submitted a sample and the sample has been reviewed and went through lab testing and environmental assessments, MnDOT will complete field testing. The chemical will then be evaluated in a field test for one winter season. Products that perform well, will be added to the Mn/DOT approved winter chemical list.
	If the deicer has any ice melting capabilities or dry material enhancement.
	We turn in numbers to explain cost and get more material if needed
	We send out our blends and purchased products for independent testing analysis.
C.	**Project Data Collection**

		Count			Percentage		
Q18	**Is your agency willing to provide data for the development of application rate guidelines with liquid applications?**	Yes	No	Blank	Yes	No	Blank
		10	20	3	30%	61%	9%

Q19	**If Q18. Yes is selected. Please, provide potential routes for data collection in your jurisdiction**
	Route information will be revised and follow up calls will be conducted

		Count	
Q20	**If Q18 No is selected. Is your agency planning to implement liquid applications in the upcoming 2020-2021 winter season and would your agency be willing to provide data for the development of application rate guidelines with liquid applications?**	Yes	No
		0	2

D. **Contact Information**

No.	Q21 Contact Information	Q22 Position	Q23 Agency	Q24 Email	Q25 Phone Number
1	Alastair Probert	District Engineer	Delaware DOT	alastair.probert@delaware.gov	(302) 853-1300
2	Marc Valenti	Manager of Operations	Town of Lexington	mvalenti@lexintonma.gov	(781) 274-8350
3	George Shutes	TOTL	Idaho Transportation Department	george.shutes@itd.idaho.gov	(208) 661-9028
4	Joe McGuire	Maintenance Foreman	Idaho Transportation Department	joe.mcguire@itd.idaho.gov	(208) 201-3307
5	Todd Law	Director of Maintenance	Vermont Agency of Transportation	todd.law@vermont.gov	(802) 828-7260
6	Jamie miller	Forman	Idaho transportation dept	Jamie.miller@itd.idaho.gov	(208) 699-2356
7	Dave palmer	Road foreman	Idaho transportation	Dave.palmer@itd.idaho.gov	(208) 772-1267
8	Troy Despain	Blackfoot maintenance supervisor (TOTL)	Idaho Transportation Department	troy.despain@itd.idaho.gov	(208) 604-0829
9	Ty Winther	Ops foreman	Idaho Transportation Dept	ty.winther@itd.idaho.gov	(208) 596-6090
10	Bob Cloninger	Maintenance Review Supervisor	Montana Department of Transportation	bcloninger@mt.gov	(406) 444-6035

11	William Davenport	Manager	PennDOT	wildavenpo@pa.gov	(717) 783-1199
12	Jacob Bumgarner	Director, Operations Division	WVDOT	jacob.m.bumgarner@wv.gov	(304) 414-8931
13	Rhett Arnell	Winter Maintenance Engineer	UDOT	rarnell@utah.gov	(435) 979-7083
14	Shannon McIntyre	Salt Sustainability Coordinator	MnDOT	shannon.mcintyre@state.mn.us	(612) 849-1757
15	Clay Adams	Bureau Chief of Maintenance	Kansas DOT	clay.adams@ks.gov	(785) 296-3233
16	Scott Rattay	Winter Maintenance Program Coordinator	Oregon Department of Transportation	scott.j.rattay@odot.state.or.us	(971) 701-1772
17	Bryan Pickworth	Road Maint. Supervisor	City of Farmington Hills - DPW	bpickworth@fhgov.com	(248) 231-8565
18	John DeCastro	Trans. Maintenance Manager	CTDOT	john.decastro@ct.gov	(860) 594-2614
19	Brian Burne	Highway Maintenance Engineer	MaineDOT	brian.burne@maine.gov	(207) 624-3571
20	Larry Gangl	District Engineer	ND Dept of Transportation	lgangl@nd.gov	(701) 590-4116
21	Mark Goldstein	Lead State Snow & Ice Engineer	MassDOT	mark.a.goldstein@state.ma.us	(617) 352-1892
22	Matthew Heinze	Assistant Emergency Management	TxDOT	Matthew.Heinze@txdot.gov	(512) 658-1220
23	Scott Lucas	Assistant Administrator	ODOT	scott.lucas@dot.ohio.gov	(614) 644-6603
24	Timothy Moran	Assistant Director - Operations Division	WVDOH	timothy.j.moran@wv.gov	(304) 550-0209
25	Ty Barger		Nebraska Department of Transportation	ty200402@yahoo.com	(402) 479-4787
26	Joe Thompson	S&I Program Manager	NYSDOT	joe.thompson@dot.ny.gov	(518) 222-9072
27	justin droste	regino support engineer	MDOT	drostej@mi.gov	(517) 636-0518
28	Dan Varilek	Winter Maintenance Engineer	South Dakota Department of Transportation	daniel.varilek@state.sd.us	(605) 773-2153
29	Clifford Spoonemore	Maintenance Staff Engineer	WYDOT	cliff.spoonemore@wyo.gov	(307) 630-8234
30	Jamie Yount	Winter Operations	private residence	jamie.yount@state.co.us	(307) 690-1895
31	Kevin Hensley	Superintendent of Public Services	City of West Des Moines	kevin.hensley@wdm.iowa.gov	(515) 273-0637

3.4. Follow-up Calls

The research team reached out to agencies willing to share internal information of commonly used application rates. Agencies that have provided potential routes were also contacted to gather more information and coordinate efforts for site visits and data collection.

4. FIELD DATA COLLECTION

Winter maintenance practices vary across regions with predominant winter conditions. Agencies from different geographical regions of the country were selected for field data collection to provide a wide range of winter conditions, road types, and resources. Survey of practice results were combined with the literature review to identify:

- Commonly used liquid application practices including commonly used blends for different combinations of pavement temperature, precipitation type, and weather
- Agencies currently using liquid applications for a wide range of pavement temperatures
- Blends that can be tested at low pavement temperatures
- Candidate agencies willing to test liquids at low pavement temperatures

Based on the information gathered from the literature review and survey of practice, the study design consisted of collecting storm, material, application rate, frequency of application, and performance data at study routes. Study routes consisted of sites managed by agencies that have experience and regularly implement liquid applications for a wide range of pavement temperatures. Study routes served to document performance of liquids at low pavement temperatures. The field data collection consisted of the following steps:

4.1. Route Selection

In the selection of segments, homogeneity, accessibility, and availability of data collection stations were considered. Homogeneity refers to sections of road that have consistent functional classification, operations, and geometry. Accessibility refers to the proximity and ability of winter maintenance equipment to reach the road segment without any difficulty and the ability to monitor and perform frequent liquid applications. Although not required, it was desired that segments had traffic and speed data collection stations at any point of the route. Similarly, it was desired to have MDSS and friction testing data if available. Routes selected consisted of segments:

- Ranging from five to 25 miles long with one to three lanes by direction
- With varied functional classifications, geometry, traffic conditions, and speed limits
- From different geographical regions

Study routes were selected in regions where storm events with cold pavement temperatures are frequently observed, and agencies with experience implementing liquid applications under those conditions.

4.2. Data Collection Forms

The research team provided templates of online forms to collect route information, equipment, and winter storm data. Based on agencies feedback, forms were customized according to each agency and expand upon the findings of the literature review and survey. The following forms for data collection were developed:

4.2.1. Segment Information

The form was used for one-time submission to collect details of segments. Data collected included name, location, designation, length, number of lanes, geometric features, and presence of bridges. Follow-up questions were required, as necessary.

4.2.2. Storm Data

Storm data was collected through an online form (Qualtrics). From previous experience of the team, an existing online form was expanded to accommodate project needs and facilitate data submission. The form included the following information:

- Time of beginning/end events

- Weather conditions before, during, and after the storm (air and pavement temperatures, temperature trends, type of precipitation, roadway condition, total snowfall, wind speed)
- Materials
- Blends
- Amounts used
- Application rates
- Frequency of application
- Timestamp of treatments
- Performance measures

4.3. Performance Measures

From the literature review and survey of practice, consistent, practical, and obtainable performance measures for liquid applications were identified:

- Time to bare/wet
- Amount of material used
- Speed drop from normal conditions
- Measures of pavement friction

Proposed performance measures are in line with guidance from the guide: "Performance Measures in Snow and Ice Control Operations" (ICF et al. 2019), which describes safety, mobility, and sustainability as the core structure of performance measures for greater consistency in data collection and analysis.

5. FIELD DATA ANALYSIS

Data collected consisted of route information and field data in terms of weather, roadway conditions, materials, application rates, and performance measures. Seventeen agencies representing nine states submitted data from 31 routes resulting in field data for 167 storms. Table 5.1 provides route and storm data submitted by state and agency.

Table 5.1. Number of Storms Collected by State and Agency

State	Agency	Routes	Storms
Michigan	Farmington Hills	1	14
Idaho	DOT	4	0
Minnesota	DOT	7	9
Nebraska	DOT	1	1
Ohio	DOT	4	0
Oregon	DOT	2	5
Utah	DOT	1	4
West Virginia	DOT	1	0
Wisconsin	Brown County	1	10
	Jefferson County	1	20
	Marathon County	1	14
	Marquette County	1	13
	Outagamie County	1	16
	Price County	1	2
	Shawano County	1	15
	Washington County	1	18
	Wood County	2	26
Total		**31**	**167**

Data was first reviewed for completeness and consistency. Unfortunately, some of the agencies submitted route information, but did not submit storm data (Idaho, Ohio, West Virginia). Also, materials or application rates information was not submitted for some of the storms (24 storms). Available storm field data was used for analysis.

5.1. Existing Guidance

The objective of this research was to expand liquid application rate guidance available in the Clear Roads Material Application Methodologies Guidebook 15-01. (Shi et al. 2019). Application rates in the Clear Roads guidebook were derived from guidelines and experiences from state DOTs. Guidance is provided in four tables according to intensity of snowfall and freezing rain:

- Light Snow (< 1 in/hr., < 4" in 24 hrs.)
- Moderate Snow (1–2 in/hr., about 4–8" in 24 hrs.)
- Heavy Snow (> 2 in/hr. > 8" in 24 hrs.)
- Freezing Rain

5.2. Field Data Characteristics

Available field data collected as part of this study was classified by pavement temperature range and snowfall precipitation. Results are provided in Table 5.2.

Table 5.2. Number of Storms by Temperature Range and Snowfall

Pavement Temperature	Snowfall (in/hr)		
	0.0-0.5	**0.5-1.0**	**2.5-3.0**
> 32°F	21		
25-32°F	81	3	1
20-25°F	27		
15-20°F	12		
0-15°F	16		
< 0°F	6		
All	**163**	**3**	**1**

Distributions of field data based on pavement temperature and snowfall indicated that most data available were for conditions with a snowfall rate of less than one inch per hour, which specifically covers existing guidance for light snow of the Clear Roads guidebook. Therefore, liquid application guidance was expanded for light snow conditions, especially for missing guidance below 20°F, which are highlighted in yellow in Table 5.3. (NR = Not Recommended).

Table 5.3. Clear Roads 15-01. Guidebook Application Rate Guidelines for Light Snow (< 1 in/hr., < 4” in 24 hrs.) (Shi et al. 2019)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)			Solid (lb/ln-mi)	
			NaCl	$MgCl_2$	$CaCl_2$	Dry Salt	Pre-wet salt
32°F	Steady or rising	Dry	NR			NR	
		Icy patches	20-40	15-35	15-35	120-160	110-150
32°F	Below is imminent	Dry (snow forecast)	20-40	15-35	15-35	NR	75-125
		Slush or light snow	30-40	15-30	15-30	140-180	100-150
25-32°F	Remaining in range	Dry (snow forecast)	30-50	20-40	20-40	NR	100-125
		Light snow cover	40-60	20-40	20-40	160-200	125-175
20-25°F	Remaining in range	Dry (snow forecast)	40-60	30-50	30-50	NR	125-175
		Light snow cover	50-80	20-40	20-40	200-250	175-225
15-20°F	Remaining in range	Dry (snow forecast)	NR	40-60	45-65	NR	175-225
		Light snow cover	NR	45-65	45-65	250-300	200-250
0-15°F	Steady or falling	Dry (snow forecast)	NR			NR	200-250
		Light snow cover	NR			NR	200-250
Below 0°F	Steady or falling	Light snow cover	NR			NR	NR

5.3. Guidance Based on Field Data and Practitioner Feedback

Ranges of application rates were identified according to pavement temperature range, pavement temperature trend, road surface condition, and materials used. Guidance is provided exclusively from field data and practitioner feedback. Therefore, application rates provided are supported by field evidence from agencies successfully implementing liquid material under conditions not previously documented. Guidance was developed for liquid applications only and “Shake and Bake.” Shake and Bake is defined as the spraying of liquid and application of solid materials at the same time, liquid immediately followed by solid, or solid immediately followed by liquid. Guidance for liquid application only was developed using field data and confirmed (not adjusted) through practitioners’ feedback. Guidance for Shake and Bake was also developed with field data, but guidance was adjusted based on practioners’ feedback and recommendations. Field based application rate guidance was shared with practitioners who have extensive experience using direct liquid applications. The intent of involving practitioners was to receive feedback, validate observed application rates, and raise awareness about specific conditions. Separate meetings were scheduled with different practitioners to discuss the results of the application rate guidance. The following practitioners participated in these discussions:

Name	**Position**	**Agency**
Bret Hodne	Public Services Director	West Des Moines, Iowa
Kevin Hensley	Director of Public Works	City of Grimes, Iowa
Larry Schneider	Streets Director	City of Fort Collings, Colorado
Scott Rattay	Winter Maintenance Program Coordinator	Oregon DOT
Beth Skowronski	Assistant Maintenance Superintendent	McHenry County, Illinois
Bill Kern	Highway Commissioner	Jefferson County, Wisconsin
Sean Heaslip	Superintendent	Jefferson County, Wisconsin
Michael Piacenti	Operations Manager	Brown County, Wisconsin
Jim Griesbach	Highway Commissioner	Marathon County, Wisconsin
Brandon Dammann	Patrol Superintendent	Wood County, Wisconsin
Brian Trebiatowski	Highway Commissioner	Marquette County, Wisconsin
Vance Pollitt	Patrol Superintendent	Price County, Wisconsin

Generally speaking, all practitioners were in concurrence with the guidance developed for liquid applications and adjustments were made only to Shake and Bake guidance. Comments from practitioners are summarized by topic in section 4.

5.4. Application Rates

Application rates are provided for liquid applications and Shake and Bake. Guidance in Tables 4 to 8 (liquid applications) were developed from field observations only. Table 9 (Shake and Bake) was also developed using field data, but the guidance was adjusted based on practioners' feedback. Tables 4 to 9 provide the range of application rates and corresponding number of storms and agencies from which the data was available.

5.4.1. Liquid Applications without Blending

Liquid applications without blending were observed with salt brine and Magnesium Chloride. In the case of salt brine, field data and practitioner feedback indicated that there is strong confidence with application of salt brine above 20°F. However, when temperatures get colder than 20°F, agencies and practioners would start blending or consider other chemical materials based on temperature trend, roadway condition, type of precipitation, and storm intensity. Magnesium Chloride applications were only observed at one location during four storms. Guidance was developed based on field data only and are provided in Tables 4 and 5.

5.4.2. Liquid Applications with Blending

Blending consists of incorporating chemical materials with more effective deicing or sticking properties to salt brine. Guidance was developed based on field data only. Chemical material used for blending were Calcium Chloride and Geomelt. Observed blends were 90/10, 80/20, and 80/10/10 of salt brine with Calcium Chloride and/or Geomelt. Tables 6-8 provide guidance using blended chemical materials.

5.4.3. Shake and Bake

Shake and Bake is the application of liquid (salt brine) and solid (dry salt) chemical materials. Guidance for Shake and Bake is based on field data and adjusted with experts' feedback. Applications with Shake and Bake only focused on deicing. Anti-icing events were not observed in the field. When increasing the amount of liquid, reducing the amount of solid salt should be considered to decrease the overall amount of salt used. At temperatures below 15°F, mechanical removal was observed in the field and recommended by practioners when snow is not sticking to save the application of material until the end of the storm or to target rush hour traffic. Also, at cold temperatures, blending or direct application of more effective chemical deicers may be implemented, while considering the higher costs associated with those materials. Guidance for Shake and Bake applications is provided in Table 9.

Table 5.4. Application Rates for Light Snow with Salt Brine (<1 in/hr., <4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Field Data Details		
			NaCl	Storms	Locations	Agencies
32°F	Steady or rising	Icy patches	30-50	8	4	Outagamie (WI), Shawano (WI), Price (WI), and Marathon (WI)
32°F	Below is imminent	Slush or light snow	30-60	6	4	Utah (UT), Brown (WI), Outagamie (WI), and Washington (WI)
25-32°F	Remaining in range	Light snow cover	40-65	37	10	Nebraska (NE), Farmington Hills (MI), Outagamie (WI), Washington (WI), Wood (WI), Brown (WI), Marquette (WI), Shawano (WI), Jefferson (WI), and Marathon (WI)
20-25°F	Remaining in range	Light snow cover	50-90	7	3	Nebraska (NE), Shawano (WI), Wood (WI)

Table 5.5. Application Rates for Light Snow with Magnesium Chloride (<1 in/hr., <4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Field Data Details		
			$MgCl_2$	Storms	Locations	Agencies
32°F	Below is imminent	Slush or light snow	30	2	1	Oregon (OR)
25-32°F	Remaining in range	Light snow cover	30	1	1	Oregon (OR)
20-25°F	Remaining in range	Light snow cover	30	1	1	Oregon (OR)

Table 5.6. Application Rates for Light Snow with Salt Brine and Calcium Chloride (< 1 in/hr., < 4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Field Data Details		
			NaCl and $CaCl_2$ 90/10 Blend	Storms	Locations	Agencies
20-25°F	Remaining in range	Light snow cover	20-45	4	3	Farmington Hills (MI), Minnesota (MN), and Shawano (WI)
15-20°F	Remaining in range	Light snow cover	40-60	4	3	Farmington Hills (MI), Outagamie (WI), and Shawano (WI)

Table 5.7. Application Rates for Light Snow with Salt Brine and Geomelt (< 1 in/hr., < 4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Field Data Details		
			NaCl and Geomelt 80/20 Blend	Storms	Locations	Agencies
32°F	Steady or rising	Icy patches	40	1	1	Farmington Hills (MI)
32°F	Below is imminent	Slush or light snow	40	1	1	Farmington Hills (MI)
15-32°F	Remaining in range	Light snow cover	40	3	1	Farmington Hills (MI)

Table 5.8. Application Rates for Light Snow with Salt Brine, Calcium Chloride, and Geomelt (< 1 in/hr., < 4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Field Data Details		
			NaCl, $CaCl_2$, and Geomelt 80/10/10 Blend	Storms	Locations	Agencies
15-20°F	Remaining in range	Light snow cover	40	1	1	Farmington Hills (MI)
0-15°F	Steady or falling	Light snow cover	45	1	1	Farmington Hills (MI)

Table 5.9. Application Rates for Light Snow with Shake and Bake (Salt Brine and Dry Salt) (< 1 in/hr., < 4" in 24 hrs.)

Pavement Temperature	Trend	Road Surface Condition	Liquid (gal/ln-mi)	Solid (lb/ln-mi)	Field Data Details		
			NaCl	Dry Salt	Storms	Locations	Agencies
32°F	Steady or rising	Dry	20-40	100-200	8	5	Minnesota (MN), Jefferson (WI), Marathon (WI), Brown (WI), and Washington (WI)
32°F	Below is imminent	Dry (snow forecast)	25-45	100-200	8	4	Utah (UT), Jefferson (WI), Brown (WI), and Washington (WI)
25-32°F	Remaining in range	Dry (snow forecast)	30-50	150-250	18	7	Utah (UT), Jefferson (WI), Outagamie (WI), Wood (WI), Brown (WI), Price (WI), and Washington (WI)
20-25°F	Remaining in range	Dry (snow forecast)	40-50	150-250	2	2	Jefferson (WI) and Outagamie (WI)
15-20°F	Remaining in range	Dry (snow forecast)	40-50	200-300	4	2	Jefferson (WI) and Outagamie (WI)
0-15°F	Steady or falling	Dry (snow forecast)	50-90	200-300	2	2	Brown (WI) and Outagamie (WI)

5.5. Practioner Feedback

5.5.1. Practices Below 20°F

Practitioner 1: Don't go above 55 gal/ln-mi and change the mixture. Add 10% Geomelt and still apply 50 gal/ln-mi. If pavement temperatures get to 0-5°F, $CaCl_2$ is added. In the 20-15°F, couple of hours in the middle of night, straight salt brine is used. If temperatures keep dropping, mixture is changed.

Practitioner 2: Really watch trending temperatures. If pavement temperatures are 15°F and up, stick with brine. If 15°F and going down, Beet Heat or AMP is added. May look to $CaCl_2$ once they get a tank.

Practitioner 3: Generally, put down around 40 gal/ln-mi between 25-32°F, and up it to around 50-60 gal/ln-mi from 15-25°F. $CaCl_2$ is added below 15°F.

Practitioner 4: Main source of deicers are $MgCl_2$ and solid salt. For pre-wet, usually use 10-20 gal/ton of $MgCl_2$, sometimes 25 gal/ton based on conditions. When doing liquid only, application rates of $MgCl_2$ are 25-35 gal/ln-mi since the spreader controllers have only two settings (two valves). Below 20°F, plow and apply pre-wetted abrasives as needed. Follow Oregon Deicer Application Guidelines (Table 5.10).

Table 5.10. Oregon Department of Transportation $MgCl_2$ Deicer Application Guidelines (ODOT 2017).

Deicing (During Storm)				
Pavement Temperature at the Time of Application	**Light Snow (≤ 1" per hour)**	**Moderate - Heavy Snow (≥ 1" per hour)**	**Freezing Fog/ Black Ice**	**Freezing Rain/ Sleet**
Over 30	15-30 (L) or 100-200 (S)	200-300 (S)	15-30 (L) or 100-200 (S)	200-300 (S)
26 to 30	20-40 (L) or 100-200 (S)	200-300 (S)	20-40 (L) or 100-200 (S)	200-300 (S)
21 to 25	20-40 (L) or 100-200 (S)	200-400 (S)	30-50 (L) or 100-200 (S)	200-300 (S)
15 to 20	40-60 (L) or 200-300 (S)	200-500 (S)	40-60 (L) or 200-300 (S)	200-300 (S)
Below 15	PA	PA	AA	AA

Notes: (L) = Liquid Mag ($MgCl_2$) gallons per lane mile, (S) = Solid Salt (NaCl) pounds per lane mile, PA = Plow and apply pre-wetted abrasives as needed, AA = Apply pre-wetted abrasives as needed.

Practitioner 5: Below 20°F start using $MgCl_2$ based products such as GHCO Torch and Envirotech Apex at a rate of 30-60 gal/ln-mi in combination with 150-300 lb/ln-mi of dry salt (Shake and Bake). Does not use $MgCl_2$ at 25-32°F since it becomes supper slippery and has had bad experiences with car pile ups. It may be more expensive to implement proprietary products, but results outperform other surrounding jurisdictions or treatments using just salt brine or solid salt.

Practitioner 6: Implements 50-60 gal/ln-mi in the 15-20°F range. May add another 20 gal/ln-mi if temperatures drop further. Salt brine much more resilient than was previously thought. Application rates of 100 gal/ln-mi of salt brine with 150 lb/ln-mi of solid salt when doing Shake and Bake. Has used straight salt brine in steady temperatures all the way down to 8°F. May use straight salt brine in the range of 10-20°F in steady conditions.

5.5.2. Blending Applications

Practitioner 1: Geomelt works great for bridge decks. To do anti-frost, 5% Geomelt in blend with brine and stays for a long time. It helps material stick and lasts for up to four days as long as there is no heavy precipitation. Usually implement it during Thanksgiving since people are not around.

Practitioner 5: Has experience using organic based products in the past. Although believes it does not have deicing properties and it is used to keep material on the road for a prolonged time.

Practitioner 6: Has been blending for a long time and has conducted several independent laboratory and field tests. Has not seen significant improvement with melting properties when blending alternative products with salt brine. For instance, a blend of salt brine, Geomelt, and $CaCl_2$ of 80/10/10 compared with 85/10/5 did not show much difference from the 5% increase in $CaCl_2$, a minimal 0.2-degree eutectic temperature difference.

Geomelt softens material for plowing. Does not see large benefit for lower temperatures with non-chloride-based additives such as sugar-based products. Cost is an important factor when blending. Produces salt brine at $0.10/gal and blending with more expensive additives will increase cost. Use non-chloride additives primarily to keep material on the road, not for melting. Dilution of solution occurs with blending. Blending is more for residual value than melting value. High focus should be on salt brine rather than additives. How to keep the active ingredient on the pavement? That is where the non-chloride additives come in.

Practitioner 7: 5% sugar additives gave the desired results from a sticking perspective. At lower than 5% may get into a functional issue of how to blend.

Practitioner 8: All liquid routes have a blend of salt brine, Calcium Chloride, and organics. Ratios are 80% brine, 10% Chloride and 10% organic. Ratios can be adjusted for colder road temperatures. Blend at temps from 32 degrees down to 5-10 degrees above zero. Granular application rates vary from 100 lbs to 250-300 lbs a lane mile.

5.5.3. Shake and Bake Applications

Practitioner 1: Liquid never goes over 35 gal/ln-mi when pre-wetting solid salt. Between 200-250 lb/ln-mi of solid salt. May apply 300 lb/ln-mi of solid salt when the temperatures go to 0°F. Start mixing Geomelt to work at lower temperatures. May implement Shake and Bake using $CaCl_2$ if it gets really cold. Practitioner never used straight $CaCl_2$, only when blending. It is lot more expensive. Learnt to lower expectations on non-busy roads. Go out late morning, put down salt and liquid. Let it sit, let the sun beat on it. At the end of the day clear it and put some material out.

Practitioner 5: Has been implementing Shake and Bake since the mid-80s. Uses a larger size of salt grains, does not use fine salt for Shake and Bake.

Practitioner 6: Believes that a heavier liquid application with less solid salt is more effective. A little concerned with the amount of solid salt observed in the field data with Shake and Bake which is up to 500 lb/ln-mi for cold temperatures. Believes that the spreader settings may be set on high speed which really covers multiple lanes, and the actual material per lane used is less than specified. Between 10-20°F uses 100 gal/ln-mi with 200-250 lb/ln-mi of solid salt at most. Interested to see more $MgCl_2$ and $CaCl_2$ used in Shake and Bake at lower temperatures.

APPENDIX A. APPLICATION RATE LITERATURE REVIEW

Blackburn and Associates (2014). *Establishing Effective Salt and Anti-Icing Application Rates Recommendations of Application Rates for Pre-Wetted Salt and Liquid Brine*. Report No. TPF – 5(218). Clear Roads, Minnesota Department of Transportation.

Table A1. Application Rates Several Brine Solutions (Blackburn and Associates 2014).

Pavement Temperature °F	Solid NaCl, lb/LM	23% NaCl liquid, gal/LM	Solid 90-92% $CaCl_2$, lb/LM	32% $CaCl_2$ liquid, gal/LM	Solid 100% $MgCl_2$, lb/LM	27% $MgCl_2$ liquid, gal/LM	Solid 100% Kac, lb/LM	50% Kac liquid, gal/LM	Solid 96% CMA, lb/LM	25% CMA liquid, gal/LM
31-32	100	44	110	31	90	32	168	32	170	18
26-30	100	44	110	31	90	32	168	32	170	18
21-25	100	44	110	31	93	33	154	29	160	17
16-20	100	44	107	30	88	32	140	26	150	16
11-15	100	44	103	29	85	30	130	24	150	16
6-10	100	44	103	29	83	29	130	24	140	15
Below 5										

Table A2. Pretreatment for Snow and Frost/Black Ice Events (Blackburn and Associates 2014).

PRETREATMENT OF ROAD SURFACES FOR SNOW AND FROST/BLACK ICE EVENTS				
Pavement temperature, °F, at time of precipitation onset	**APPLICATION RATES FOR PREWETTED SOLID SALT AND LIQUID SALT (SODIUM CHLORIDE)**			
	Anticipated Event Type			
	Snow		Frost/Black ice	
	Solid, lb/lane-mi	Liquid, gal/lane-mi	Prewetted solid NaCl, lb/lane-mi	Liquid NaCl, gal/lane-mi
Over 30	110	48	100	44
26 to 30	160	70	130	57
21 to 25	210	92	160	70
16 to 20	250	109	190	83
Below 15	PA	NR	AA	NR

Notes: PA = Plow and Apply Abrasives as Needed, AA = Apply Abrasives as Needed,NR = Not Recommended.

MAINTENANCE ACTION NOTES:

1. Dry (non-prewet) salt should **only** be used as a pretreatment on low speed, low volumeroads.
2. Other Liquid chemicals – Application rates and advisability will vary with chemical type,concentration, road temperature and relative humidity at the time of application.
3. Dry and prewet solid salt should be distributed in 3 to 4 foot bands, near the high side ofeach travel lane.
4. Some highway agencies have found that by prewetting dry salt with a chloride-basedchemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above.

Table A3. Pretreatment for Freezing Rain and Sleet Events (Blackburn and Associates 2014).

PRETREATMENT OF ROAD SURFACES FOR FREEZING RAIN AND SLEET EVENTS				
Pavement temperature, °F, at time of precipitation onset	APPLICATION RATES FOR PREWETTED SOLID SALT AND LIQUID SALT (SODIUM CHLORIDE)			
	Anticipated Event Type			
	Freezing rain		Sleet	
	Solid, lb/lane-mi	Liquid NaCl, gal/lane-mi	Prewetted solid NaCl, lb/lane-mi	Liquid NaCl, gal/lane-mi
Over 30	125	55	120	NR
26 to 30	175	76	175	NR
21 to 25	225	NR	230	NR
16 to 20	275	NR	275	NR
Below 15	AA	NR	PA	NR

Notes: PA = Plow and Apply Abrasives as Needed, AA = Apply Abrasives as Needed,NR = Not Recommended.

MAINTENANCE ACTION NOTES:

1. Dry (non-prewet) salt should **only** be used as a pretreatment on low speed, low volume roads.
2. Other Liquid chemicals – Application rates and advisability will vary with chemical type, concentration, road temperature and relative humidity at the time of application.
3. Dry and prewet solid salt should be distributed in 3 to 4 foot bands, near the high side of each travel lane.
4. Some highway agencies have found that by prewetting dry salt with a chloride based chemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above.
5. Liquid chemicals should be used to pretreat for Light Freezing Rain events only.
6. Sleet usually does not bond to the road readily. Try plowing only as the initialtreatment and apply chemicals only if bonded.

Table A4. Treatment for Snow Events with Dry Salt, Pre-Wetted Salt, and Liquid Salt Brine (Blackburn and Associates 2014).

SNOW Within-Event Application Rates for Dry Salt, Prewetted Salt and Liquid Salt Brine (Sodium Chloride)						
Pavement temperature, °F, at time of application	APPLICATION RATE					
	Pounds per Lane-Mile (Gallons per Lane-Mile)					
	Snow Event Type					
	Light snow		Moderate snow		Heavy snow	
	Anti-icing	Deicing	Anti-icing	Deicing	Anti-icing	Deicing
Over 30	110 (48)	240 (NR)	130 (57)	265 (NR)	150 (66)	290 (NR)
26 to 30	160 (70)	350 (NR)	175 (76)	375 (NR)	190 (83)	400 (NR)
21 to 25	200 (87)	425 (NR)	210 (92)	450 (NR)	220 (96)	475 (NR)
16 to 20	230 (100)	500 (NR)	240 (105)	525 (NR)	250 (109)	PA (NR)
11 to 15	260 (NR)	PA (NR)	270 (NR)	PA (NR)	280 (NR)	PA (NR)
Below 10	PA (NR)	PA (NR)	PA (NR)	PA (NR)	PA (NR)	PA (NR)

Notes: NR = Not Recommended, PA = Plow and Apply Abrasives as Needed.

MAINTENANCE ACTION NOTES:

1. Application rates may be increased by 25% for cycle time greater than 3 hours.
2. For maximum effectiveness, salt should be placed in 3ft. to 4ft. bands on the high side of each travel lane. As pavement temperature becomes lower and /or the event intensity becomes very heavy, the spread pattern should be further narrowed.
3. For pavement temperatures over 32ºF and likely to remain at that level, try plowing without spreading salt, especially, if the snow is not bonded to the pavement.

4. It may be uneconomical and operationally impossible to use application rates in excess of 500 pounds per lane-mile. Many agencies choose to use sand/salt mixtures in lower pavement temperature situations until warmer pavement temperature conditions are present.
5. Some highway agencies have found that by prewetting dry salt with a chloride based chemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above.

Table A5. Treatment for Frost and Black Ice Events with Dry Salt, Pre-Wetted Salt, and Liquid Salt Brine (Blackburn and Associates 2014).

FROST AND BLACK ICE Within-Event Application Rates for Dry Salt, Prewetted Salt and Liquid Salt Brine (Sodium Chloride)				
Pavement temperature, °F, at time of application	**APPLICATION RATE**			
	Anti-icing		Deicing	
	Dry and pre-wet dry salt (lb/lane-mi)	Salt brine (gal/lane-mi)	Dry and pre-wet dry salt (lb/lane-mi)	Salt brine (gal/lane-mi)
Over 30	100	44	225	98
26 to 30	130	57	250	109
21 to 25	160	70	275	120
16 to 20	190	83	300	NR
Below 15	AB	NR	AB	NR

Notes: NR = Not Recommended, AB = Apply Abrasives as Needed

MAINTENANCE ACTION NOTES:

1. If possible, dry salt should not be used, due to the high potential for bounce and scatter and traffic displacement.
2. Material should be spread reasonably uniformly across the travel lanes.
3. Some highway agencies have found that by prewetting dry salt with a chloride based chemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above

Table A6. Treatment for Freezing Rain Events with Dry Salt, Pre-Wetted Salt, and Liquid Salt Brine (Blackburn and Associates 2014).

FREEZING RAIN Within-Event Application Rates for Dry Salt, Prewetted Salt and Liquid Salt Brine (Sodium Chloride)						
Pavement temperature, °F, at time of application	**APPLICATION RATE** Pounds per Lane-Mile (Gallons per Lane-Mile)					
	Freezing Rain Event Type					
	Light freezing rain		Moderate freezing rain		Heavy freezing rain	
	Anti-icing	Deicing	Anti-icing	Deicing	Anti-icing	Deicing
Over 30	110 (48)	240 (NR)	130 (NR)	265 (NR)	150 (NR)	290 (NR)
26 to 30	170 (74)	350 (NR)	180 (NR)	375 (NR)	190 (NR)	400 (NR)
21 to 25	200 (87)	425 (NR)	210 (NR)	450 (NR)	220 (NR)	475 (NR)
16 to 20	230 (NR)	500 (NR)	240 (NR)	525 (NR)	250 (NR)	AA (NR)
11 to 15	260 (NR)	AA (NR)	270 (NR)	AA (NR)	280 (NR)	AA (NR)
Below 10	AA (NR)	AA (NR)	AA (NR)	AA (NR)	AA (NR)	AA (NR)

Notes: NR = Not Recommended, AA = Apply Abrasives as Needed.

MAINTENANCE ACTION NOTES:

1. Application rates may be increased by 25% for treatment cycle time greater than 3 hours.

2. For maximum effectiveness, salt should be placed in 3ft. to 4ft. bands on the high side of each travel lane. In the case of heavy freezing rain or thick ice on the pavement, a very narrow band of salt should be placed on the high side wheel path of each travel lane.
3. For frost/black ice/light freezing rain, a more general distribution pattern across the travel lanes is recommended.
4. It may be uneconomical and operationally impossible to use application rates in excess of 500 pounds per lane-mile. Many agencies choose to use sand/salt mixtures in lower pavement temperature situations until warmer pavement temperature conditions are present.
5. Some highway agencies have found that by pre-wetting dry salt with a chloride based chemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above.

Table A7. Treatment for Sleet Events with Dry Salt, Pre-Wetted Salt, and Liquid Salt Brine (Blackburn and Associates 2014).

SLEET Within-Event Application Rates for Dry Salt, Prewetted Salt and Liquid Salt Brine (Sodium Chloride)						
Pavement temperature, °F, at time of application	**APPLICATION RATE** Pounds per Lane-Mile (Gallons per Lane-Mile)					
	Sleet Event Type					
	Light sleet		Moderate sleet		Heavy sleet	
	Anti-icing	Deicing	Anti-icing	Deicing	Anti-icing	Deicing
Over 30	120 (NR)	265 (NR)	145 (NR)	290 (NR)	165 (NR)	320 (NR)
26 to 30	175 (NR)	385 (NR)	195 (NR)	410 (NR)	210 (NR)	440 (NR)
21 to 25	220 (NR)	465 (NR)	230 (NR)	500 (NR)	240 (NR)	525 (NR)
16 to 20	250 (NR)	PA (NR)	260 (NR)	PA (NR)	280 (NR)	PA (NR)
11 to 15	285 (NR)	PA (NR)	300 (NR)	PA (NR)	310 (NR)	PA (NR)
Below 10	PA (NR)	PA (NR)	PA (NR)	PA (NR)	PA (NR)	PA (NR)

Notes: NR = Not Recommended, PA = Plow and Apply Abrasives as Needed.

MAINTENANCE ACTION NOTES:

1A. Sleet usually does not bond to the road readily. Try plowing only as the initial treatment and apply chemicals only if bonded.
1B. The ice component of sleet is very high and will quickly overwhelm the limited amount of chemical that liquids are capable of delivering to the road surface.
2. Application rates may be increased by 25% for cycle time greater than 3 hours.
3. For maximum effectiveness, salt should be placed in 3ft. to 4ft. bands on the high side of each travel lane. As pavement temperature becomes lower and/or the event intensity becomes very heavy, the spread pattern should be further narrowed.
4. It may be uneconomical and operationally impossible to use application rates in excess of 500 pounds per lane-mile. Many agencies choose to use sand/salt mixtures in lower pavement temperature situations until warmer pavement temperature conditions are present.
5. Some highway agencies have found that by prewetting dry salt with a chloride based chemical, or prewetting dry salt with a chloride based chemical mixed with an organic/carbohydrate additive, the application rate of the dry salt component can be reduced from that given in the table above.

Fay, L., Akin, M., and Muthumani, A. (2018). *Estimating the Application Rate of Liquid Chloride Products Based on Residual Salt Concentration on Pavement*. Report No. 1601. Center for Environmentally Sustainable Transportation in Cold Climates, University of Alaska Fairbanks.

Table A8. Application Rates and Remaining Material on Pavement (Fay et al. 2018)

Pavement Type (C=concrete or A=asphalt)	Salt Brine app rate (gal/LM)	Measured Chloride Concentration (mg/L)	Percent of chloride in the plowed off snow (%)	Percent of chloride remaining on the pavement (%)
A	36.1	406	54.4	45.6
A	59.5	1110	87.9	12.1
A	47.8	865	85.2	14.8
C	55.7	141	11.6	88.4
C	27.9	14.3	2.4	97.6
C	39.3	187	21.9	78.1

Porter, L. W. (2018). *Training Video for the Implementation of Liquid-Only Plow Routes*. Report No. CR 16-06). Minnesota Department of Transportation.

Table A9. Recommended Anti-Icing Parameters Prior to a Storm Event (Porter 2018).

Parameter	**Salt Brine**	**Magnesium Chloride**	**Calcium Chloride**
Pavement Temperature[1]	15°F or above	0°F or above[2]	0°F or above[2]
Time Remaining Until Storm	Within 24 hours[3]	Within 48 hours[3]	Within 48 hours[3]
Precipitation	None[4]	None[4]	None[4]

Notes:
1. Consider temperature trends (increasing/decreasing temperatures)
2. Additives are available can reduce the freezing point of magnesium chloride. Magnesium chloride and calcium chloride are not recommended at pavement temperatures above 40°. Work with vendors to verify temperatures.
3. Applying anti-icing closer to the storm reduces the chances of traffic pushing the treatment off the roadway.
4. Rainfall prior to a snow storm event dilutes liquid applications, which reduces their effectiveness

Table A10. Recommended Direct Liquid Application Parameters During a Storm Event (Porter 2018).

Parameter	**Most Favorable for Liquid Treatment**	**Consider Using Liquid Treatment**
Pavement Temperature[1]	15°F or above (salt brine) 0°F or above (magnesium chloride)[2] 0°F or above (calcium chloride)[2]	15°F or above (salt brine) 0°F or above (magnesium chloride)[2] 0°F or above (calcium chloride)[2]
Storm Intensity (inches/hour)	Light Snow (less than 0.5 inch/hour)	Medium Snow (0.5 to 1.0 inch/hour)
Moisture Content[3]	Ordinary (approx. 10:1 snow/liquid ratio)[3]	Dryer Snowfall

Notes:
1. Consider temperature trends (increasing/decreasing temperatures)
2. Additives are available can reduce the freezing point of magnesium chloride. Similar temperature ranges are recommended for calcium chloride. Work with vendors to verify temperatures.
3. Wet snow can dilute liquid applications, which reduces their effectiveness

Table A11. Suggested Liquid Roadway Treatments Application Rates (adjust based on local experience) (Porter 2018).

Event Type	**Pavement Temperature**			
For 2-Hour (or less) Cycle Times	**32-30°F**	**29-27°F**	**26-24°F**	**23-15°F**
Light Snow (less than 0.5 inch/hour)	20 gplm	35 gplm	40 gplm	55 gplm
Medium Snow (0.5 to 1.0 inch/hour)[1]	35 gplm	45 gplm	55 gplm	Not Recommended
For 3-Hour Cycle Times[3]	**32-30°F**	**29-27°F**	**26-24°F**	**23-15°F**
Light Snow (less than 0.5 inch/hour)	35 gplm	50 gplm	65 gplm	80 gplm
Medium Snow (0.5 to 1.0 inch/hour)[1]	50 gplm	65 gplm	80 gplm	Not Recommended

Notes:
1. For medium snow events, only consider using liquid treatments based on your experience, and when other factors are highly favorable, such as pavement temperature and moisture content.

2. It is suggested to generally supplement the liquid application with a light direct pre-wet granular application (70 pplm) when possible (especially as dilution-refreeze potential increases).
3. For cycle times greater than 2 hours, supplementing liquids with direct granular is strongly suggested.
4. For magnesium chloride, calcium chloride, additives, and blends, work with vendors to verify application rates.

Ohio Local Technical Assistance Program (2018). *Snow and Ice Control Treatments – Brine plus Salt*. Ohio Department of Transportation.

Table A12. Application Rates on Typical 24' Two-Lane Roads (Ohio LTAP 2018).

Dry Pavement, Light Snow Less Than 0.5"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 35 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 35 gallons/mile	30° F to 27° F Recommended Plow and treat @ 40 gallons/mile	27° F to 24° F Recommended Plow and treat @ 45 gallons/mile	24° F to 21° F Recommended Plow and monitor conditions	Below 21° F Plow and monitor conditions
Wet Pavement, Light Snow Less Than 0.5"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 35 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 35 gallons/mile	30° F to 27° F Recommended Plow and treat @ 40 gallons/mile	27° F to 24° F Recommended Plow and treat @ 45 gallons/mile	24° F to 21° F Recommended Plow and treat @ 50 gallons/mile	Below 21° F Plow and treat @ 60+ gallons/mile**
Dry Pavement, Medium Snow 0.5" to 1"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 40 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 40 gallons/mile	30° F to 27° F Recommended Plow and treat @ 50 gallons/mile	27° F to 24° F Recommended Plow and treat @ 60 gallons/mile	24° F to 21° F Recommended Plow and monitor conditions	Below 21° F Plow and monitor conditions
Wet Pavement, Medium Snow 0.5" to 1"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 40 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 40 gal./mile	30° F to 27° F Recommended Plow and treat @ 50 gallons/mile	27° F to 24° F Recommended Plow and treat @ 60 gallons/mile	24° F to 21° F Recommended Plow and treat @ 70 gallons/mile	Below 21° F Plow and treat @ 90+ gal./mile**
Dry Pavement, Heavy Snow More Than 1"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 50 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 50 gallons/mile	30° F to 27° F Recommended Plow and treat @ 70 gallons/mile	27° F to 24° F Recommended Plow and treat @ 90 gallons/mile	24° F to 21° F Recommended Plow and monitor conditions	Below 21° F Plow and monitor conditions
Wet Pavement, Heavy Snow More Than 1"/Hour					
Above 32° F Bridges and Icy Spots Plow and treat @ 50 gallons/mile	32° F to 30° F Acceptable Plow and treat @ 50 gallons/mile	30° F to 27° F Recommended Plow and treat @ 70 gallons/mile	27° F to 24° F Recommended Plow and treat @ 90 gallons/mile	24° F to 21° F Plow and treat @ 110 gal./mile**	Below 21° F Plow and monitor conditions
Freezing Rain					
Above 32° F Bridges and Icy Spots Plow and treat @ 40 gallons/mile	32° F to 30° F Recommended Plow if needed and treat @ 60 gallons/mile	30° F to 27° F Recommended Plow if needed and treat @ 70 gallons /mile	27° F to 24° F Recommended Plow if needed and treat @ 80 gallons max/mile	24° F to 21° F Recommended Plow if needed and treat @ 110 gallons/mile**	Below 21° F Recommended Plow if needed and treat @ 150+ gallons/mile**
Black Ice					
Above 32° F Bridges and Icy Spots Apply anti-icing material prior to the formation of black ice^	32° F to 30° F Recommended Apply anti-icing material prior to the formation of black ice^	30° F to 27° F Recommended Apply anti-icing material prior to the formation of black ice^	27° F to 24° F Recommended Apply anti-icing material prior to the formation of black ice^	24° F to 21° F Recommended Apply anti-icing material prior to the formation of black ice^	Below 21° F Recommended Apply anti-icing material prior to the formation of black ice++

Notes:
** these tables are based on pavement temperature. If the air temperature is below 21° F, increase by 10 gallons/lane mile for each 10° F. If the air temperature is below 10° F, reapply liquid or apply 50 to 100 pounds of salt per lane mile with the liquid to maintain surface from refreezing.
^ Apply anti-icing brine @ 20 to 40 gallons/lane mile.
++ Do not apply liquid brine when the pavement temperature is below 20° F.

Minnesota Department of Transportation (2012). *Minnesota Snow and Ice Control Handbook*. Second Revision. Minnesota Local Road Research Board, MnDOT.

Table A13. MnDOT Anti-Icing Application Rate Guidelines (MnDOT 2012).

Condition	Gallons/Lane Mile			Other Products
	$CaCl_2$	$MgCl_2$	Salt Brine	
1. Regularly scheduled applications	15 – 25	15 – 25	20 – 40	Follow manufacturers' recommendations.
2. Prior to frost or black ice event	15 – 25	15 – 25	20 – 40	
3. Prior to light or moderate snow	15 – 25	15 – 25	20 – 50	

Notes: At temps below 15 degrees, it may be more cost-effective to use a chemical other than NaCl.

Table A14. MnDOT Anti-Icing Application Rate Guidelines (MnDOT 2012).

Pavement Temp. (˚F) and Trend (↑↓)	Weather Condition	Maintenance Actions	Lbs/ two-lane mile			
			Salt Prewetted/ Pretreated with Salt Brine	Salt Prewetted/ Pretreated with Other Blends	Dry Salt*	Winter Sand (abrasives)
>30° ↑	Snow	Plow, treat intersections only	80 (40/lane mile)	70	100*	Not recommended
	Frz. rain	Apply chemical	80 – 160	70 – 140	100 – 200*	Not recommended
30° ↓	Snow	Plow & apply	80 – 160	70 – 140	100 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30˚ ↑	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	150 – 200	130 – 180	180 – 240*	Not recommended
25 - 30˚ ↓	Snow	Plow & apply chemical	120 – 160	100 – 140	150 – 200*	Not recommended
	Frz. rain	Apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25˚ ↓	Snow or frz. rain	Plow & apply chemical	160 – 240	140 – 210	200 – 300*	400
20 - 25˚ ↓	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↓	Snow	Plow & apply chemical	200 – 280	175 – 250	250 – 350*	Not recommended
	Frz. rain	Apply chemical	240 – 320	210 – 280	300 – 400*	400
15 - 20° ↓	Snow or Frz. rain	Plow & apply chemical	240 – 320	210 – 280	300 – 400*	500 for frz. rain
0 to 15˚ ↑↓	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	300 – 400	Not recommended	500 – 750 spot treat as needed
< 0˚	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	400 – 600**	Not recommended	500 – 750 spot treat as needed

Notes: * Dry salt is not recommended. It is likely to blow off the road before it melts ice, **A blend of 6 – 8 gal/ton $MgCl_2$ or $CaCl_2$ added to NaCl can melt ice as low as -10˚.

Missouri Department of Transportation (2019). *Operator's Guide for Anti-Icing*. Engineering Policy Guide. MoDOT.

Table A15. Application Rate Winter Event: Frost, Flurries, Freezing Fog, Blowing Snow and Refreeze (MoDOT 2019).

PAVEMENT TEMPERATURE RANGE AND TREND	**TRAFFIC CONDITION**	**INITIAL OPERATION**			**SUBSEQUENT OPERATIONS**			**COMMENTS**
		Maintenance action	**Spread rates**		**Maintenance action**	**Spread rates**		
			Pre-wetted solid salt (lb/ln-mi)	**Brine (gal/ln-mi)**		**Pre-wetted solid salt (lb/ln-mi)**	**Brine (gal/ln-mi)**	
Above 32ºF steady or rising	Any level	None, see comments			None, see comments			1) Monitor pavement temperature closely; begin treatment if starts to fall to 32ºF and below and is at or below dew point
28 to 32ºF, remaining in range or falling to 32ºF or below, *and* equal to or below dew point	Traffic rate less than 100 vehicles per hr	Apply brine or pre-wetted solid salt	25-65	11-28	Reapply pre-wetted solid salt as needed	25-65		1) Monitor pavement closely; if pavement becomes wet or if thin ice forms, reapply salt at higher indicated rate. 2) Do not apply brine on ice so thick that the pavement cannot be seen
	Traffic rate greater than 100 vehicles per hr	Apply brine or pre-wetted solid salt	25-65	11-28	Reapply brine pre-wetted solid salt as needed	25-65	11-28	
20 to 28ºF, remaining in range *and* equal to or below dew point	Any level	Apply brine or pre-wetted solid salt	65-130	28-57	Reapply brine pre-wetted solid salt as needed	65-130	28-57	1) Monitor pavement closely; if thin ice forms, reapply salt at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency 3) It is not advisable to apply a brine at the indicated spread rate when the pavement temperature drops below 20ºF
10 to 20ºF, remaining in range *and* equal to or below dew point	Any level	Apply pre-wetted solid salt	130-200		Reapply pre-wetted solid salt as needed	130-200		1) Monitor pavement closely; if thin ice forms, reapply salt at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency
Below 10ºF, steady or falling	Any level	Apply abrasives			Apply abrasives as needed			1) Monitor pavement closely, salt will have limited melting power in this temperature range. 2) Liquid calcium chloride may be used for pre-wetting salt/abrasive mix at colder temperatures.

Notes: **TIMING.** (1) Conduct initial operation in advance of freezing. Apply brine up to 3 hr in advance. Use longer advance times in this range to effect drying when traffic volume is low. Apply pre-wetted solid salt 1 to 2 hr in advance. (2) In the absence of precipitation, brine at 33 gal/lane-mi has been successful in preventing bridge deck icing when placed up to 4 days before freezing on higher volume roads and 7 days before on lower volume roads.

Table A16. Application Rate Winter Event: Dusting to 1 in. of Snow, Sleet or other Frozen Precipitation (MoDOT 2019).

PAVEMENT TEMPERATURE RANGE AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	Pavement surface at time of initial operation	Maintenance action	Salt Spread Rates		Maintenance action	Salt Spread Rates		
			Pre-wetted solid salt (lb/ln-mi)	Brine (gal/ln-mi)		Pre-wetted solid salt (lb/ln-mi)	Brine (gal/ln-mi)	
Above 32ºF, steady or rising	Dry, wet, slush or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 32ºF and below 2) Treat icy patches if needed with pre-wetted solid salt at 100 lb/lane-mi; plow if needed
Above 32ºF, 32ºF or below is imminent; *ALSO* **15 to 32ºF**, remaining in range	Dry	Apply brine or pre-wetted solid salt	100	44	Plow as needed; reapply liquid or solid chemical when needed	100	44	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) It is not advisable to apply a straight brine at the indicated spread rate when the pavement temperature drops below 20ºF 3) Do not apply brine onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply liquid or solid salt	100	44				
0 to 15ºF, remaining in range	Dry, wet, slush, or light snow cover	Apply pre-wetted solid chemical	200		Plow as needed; reapply pre-wetted solid chemical when needed	200		1) Abrasives may be added to the salt to enhance traction at colder temperatures 2) Liquid calcium chloride may be used for pre-wetting solid salt at colder temperatures
Below 0ºF, steady or falling	Dry or light snow cover	Plow as needed			Plow and apply salt/abr. mix as needed			1 If pavement becomes slick apply salt/abrasive mix to enhance traction. Salt will have limited melting power in this temperature range. 2) Pre-wet salt/abrasive mix with liquid calcium chloride.

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

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

Table A17. Application Rate Winter Event: 1 – 6 in. of Snow/Frozen Precipitation in 24 hours or a Trace to 1/2 in. of Ice (MoDOT 2019).

PAVEMENT TEMPERATURE RANGE AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS					COMMENTS
	Pavement surface at time of initial operation	Maintenance action	Salt spread rates		Maintenance action	Salt spread rates				
			Pre-wetted solid salt (lb/ln-mi)	Brine (gal/ln-mi)		Pre-wetted solid salt (lb/ln-mi)		Brine (gal/ln-mi)		
						Light snow	Heavier snow	Light snow	Heavier snow	
Above 32ºF, steady or rising	Dry, wet, slush or light snow cover	None, see comments			None, see comments					1) Monitor pavement temperature closely for drops toward 32ºF and below 2) Treat slick patches if needed with pre-wetted salt at 100 lb/lane-mi or brine 44 gal/ln-mi; plow if needed
Above 32ºF, 32ºF or below is imminent; *ALSO* **20 to 32ºF**, remaining in range	Dry	Apply brine or pre-wetted salt	100	44	Plow as needed; reapply brine or pre-wetted solid salt when needed	100	200	44	88	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) Do not apply brine onto heavy snow accumulation or packed snow 3) After heavier snow periods and during light snow fall, reduce salt rate to 100 lb/lane-mi or 44 gal/ln-mi brine; continue to plow and apply salt as needed
	Wet, slush, or light snow cover	Apply brine or pre-wetted salt	100	44						
10 to 20ºF, remaining in range	Dry, wet, slush, or light snow cover	Apply pre-wetted salt	200		Plow as needed; reapply pre-wetted solid salt when needed	200	250			1) Reduce salt rate to 200 lb/lane-mi after heavier snow periods and during light snow fall; continue to plow and apply salt as needed 2) Liquid calcium chloride may be used for pre-wetting salt at colder temperatures.
Below 10ºF, steady or falling	Dry or light snow cover	Plow as needed			Plow and apply salt/abrasive mix as needed					1) As pavement becomes slick apply salt/abrasive mix to enhance traction. Salt will have limited melting power at this temperatures

Notes: **SALT APPLICATIONS.** (1) Time initial and subsequent salt applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2***) Anticipate increases in snowfall intensity. Apply higher rate treatments prior to or at the beginning of heavier snowfall periods to prevent development of packed and bonded snow.*** (3) Apply salt ahead of traffic rush periods occurring during storm. **PLOWING.** If needed, *plow before salt applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table A18. Application Rate Winter Event: 6 – 12 in. of Snow in 24 Hours or ½ to ¾ in. of Ice (MoDOT 2019).

PAVEMENT TEMPERATURE RANGE AND TREND	**INITIAL OPERATION**				**SUBSEQUENT OPERATIONS**			**COMMENTS**
	Pavement surface at time of initial operation	**Maintenance action**	**Salt spread rates**		**Maintenance action**	**Salt spread rates**		
			Pre-wetted solid salt (lb/ln-mi)	**Brine (gal/ln-mi)**		**Pre-wetted solid salt (lb/ln-mi)**	**Brine (gal/ln-mi)**	
Above 32ºF steady or rising	Dry, wet, slush or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 32ºF and below 2) Treat slick patches if needed with pre-wetted salt at 100 lb/lane-mi or with brine at 44 gal/ln-mi; plow if needed
Above 32ºF, 32ºF or below is imminent; *ALSO* **30 to 32ºF**, remaining in range	Dry	Apply brine or pre-wetted solid salt	100	44	Plow accumulation and reapply brine or solid salt as needed	100	44	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 200 lb/lane-mi to accommodate longer operational cycles 2) Do not apply brine onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply brine or pre-wetted solid salt	100	44				
20 to 30ºF remaining in range	Dry	Apply brine or pre-wetted solid salt	150-200	65-87	Plow accumulation and reapply brine or solid salt as needed	200	87	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 400 lb/lane-mi to accommodate longer operational cycles 2) Do not apply brine onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply brine or pre-wetted solid salt	150-200	65-87				
10 to 20ºF, remaining in range	Dry, wet, slush, or light snow cover	Apply pre-wetted solid salt	200		Plow accumulation and reapply brine or solid salt as needed	250		1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 500 lb/lane-mi to accommodate longer operational cycles 2) Liquid calcium chloride may be used for pre-wetting salt at colder temperatures
Below 10ºF, steady or falling	Dry or light snow cover	Plow as needed			Plow accumulation as needed	250		1) As pavement becomes slick apply salt/abrasive mix to enhance traction. Salt will have limited melting power in this temperature range.

Notes: **SALT APPLICATIONS.** (1) Time initial and subsequent salt applications to *prevent* deteriorating conditions or development of packed and bonded snow--***timing and frequency of subsequent applications will be determined primarily by plowing requirements***. (2) Apply salt ahead of traffic rush periods occurring during storm. **PLOWING.**

Table A19. Application Rate Winter Event: More than 12 in. of Snow in 24 Hours or more than ¾ in. of Ice (MoDOT 2019).

PAVEMENT TEMPERATURE RANGE AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	Pavement surface at time of initial operation	Maintenance action	Salt spread rates		Maintenance action	Salt spread rates		
			Pre-wetted solid salt (lb/ln-mi)	Brine (gal/ln-mi)		Pre-wetted solid salt (lb/ln-mi)	Brine (gal/ln-mi)	
Above 32ºF steady or rising	Dry, wet, slush or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 32ºF and below 2) Treat slick patches if needed with pre-wetted salt at 100 lb/lane-mi or with brine at 44 gal/ln-mi; plow if needed
Above 32ºF, 32ºF or below is imminent; *ALSO* **30 to 32ºF**, remaining in range	Dry	Apply brine or pre-wetted solid salt	100	44	Plow accumulation and reapply brine or solid salt as needed	100	44	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 200 lb/lane-mi to accommodate longer operational cycles 2) Do not apply brine onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply brine or pre-wetted solid salt	100	44				
20 to 30ºF remaining in range	Dry	Apply brine or pre-wetted solid salt	150-200	65-87	Plow accumulation and reapply brine or solid salt as needed	200	87	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 400 lb/lane-mi to accommodate longer operational cycles 2) Do not apply brine onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply brine or pre-wetted solid salt	150-200	65-87				
10 to 20ºF, remaining in range	Dry, wet, slush, or light snow cover	Apply pre-wetted solid salt	200		Plow accumulation and reapply brine or solid salt as needed	250		1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 500 lb/lane-mi to accommodate longer operational cycles 2) Liquid calcium chloride may be used for pre-wetting salt at colder temperatures
Below 10ºF, steady or falling	Dry or light snow cover	Plow as needed			Plow accumulation as needed	250		1) As pavement becomes slick apply salt/abrasive mix to enhance traction. Salt will have limited melting power in this temperature range.

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

Shi, X., Xu, G., Du, S., Akin, M., Bergner, D., and Brown, P. (2019). *Material Application Methodologies Guidebook*. Report No.15-01. Clear Roads, Minnesota Department of Transportation.

Table A20. Application Rate Guidelines for Light Snow (< 1 in/hr., < 4” in 24 hrs.) (Shi et al. 2019).

Pavement Temp. Range, Trend	Road Surface Condition	Material Application					
		Liquid (G/LM)			Solid (lb/LM)		
		NaCl	$MgCl_2$	$CaCl_2$	Dry NaCl	Pre-Wet NaCl	Abrasives (less than 20% salt added)
32°F steady or rising	Dry	NR			NR		
	Icy patches	20-40	15-35	15-35	120-160	110-150	NR
32°F or below is imminent	Dry (snow forecast)	20-40	15-35	15-35	NR	75-125	NR
	Slush or light snow	30-40	15-30	15-30	140-180	100-150	NR
25°-32°F, remaining in range	Dry (snow forecast)	30-50	20-40	20-40	NR	100-125	NR
	Light snow cover	40-60	20-40	20-40	160-200	125-175	NR
20°-25°F, remaining in range	Dry (snow forecast)	40-60	30-50	30-50	NR	125-175	NR
	Light snow cover	50-80	20-40	20-40	200-250	175-225	NR
15°-20°F, remaining in range	Dry (snow forecast)	NR	40-60	45-65	NR	175-225	NR
	Light snow cover	NR	45-65	45-65	250-300	200-250	500-750
0°-15°F, steady or falling	Dry (snow forecast)	NR			NR	200-250	NR
	Light snow cover	NR			NR	200-250	600-750
Below 0°F, steady or falling	Light snow cover	NR			NR	NR	600-750

Notes:
1. Use lower end of range for lower LOS or shorter cycle times
2. Use higher end of range for higher LOS, longer cycle times, or greater dilution potential
3. Plow to remove as much snow or ice as possible before material application
4. Abbreviations: lb/LM = pounds per lane mile, G/LM = gallons per lane mile, NR = Not Recommended

Table A21. Application Rate Guidelines for Moderate Snow (1–2 in/hr., about 4–8” in 24 hrs.) (Shi et al. 2019).

Pavement Temp. Range, Trend	Road Surface Condition	Material Application					
		Liquid (G/LM)			Solid (lb/LM)		
		NaCl	$MgCl_2$	$CaCl_2$	Dry NaCl	Pre-Wet NaCl	Abrasives (less than 20% salt added)
32°F steady or rising	Dry	NR			NR		
	Icy patches	30-50	15-35	15-35	140-160	120-160	NR
32°F or below is imminent	Dry (snow forecast)	20-40	15-35	15-35	NR	75-125	NR
	Slush or light snow	NR	NR	NR	140-180	100-150	NR
25°-32°F, remaining in range	Dry (snow forecast)	30-50	20-40	20-40	NR	100-150	NR
	Light snow cover	50-80	20-40	20-40	180-220	160-190	NR
20°-25°F, remaining in range	Dry (snow forecast)	40-60	30-50	30-50	NR	150-200	NR
	Light snow cover	NR	NR	NR	250-300	220-260	NR
15°-20°F, remaining in range	Dry (snow forecast)	NR	40-70	30-70	NR	200-250	NR
	Light snow cover	NR	40-75	30-70	325-375	275-325	500-750
0°-15°F, steady or falling	Dry (snow forecast)	NR			NR	300-350	NR
	Light snow cover	NR			NR	300-350	600-900
Below 0°F, steady or falling	Light snow cover	NR			NR	NR	600-900

Notes:

1. Use lower end of range for lower LOS or shorter cycle times
2. Use higher end of range for higher LOS, longer cycle times, or greater dilution potential
3. Plow to remove as much snow or ice as possible before material application
4. Abbreviations: lb/LM = pounds per lane mile, G/LM = gallons per lane mile, NR = Not Recommended

Table A22. Application Rate Guidelines for Heavy Snow (>2 in/hr. >8” in 24 hrs.) (Shi et al. 2019).

Pavement Temp. Range, Trend	Road Surface Condition	Material Application					
		Liquid (G/LM)			Solid (lb/LM)		
		NaCl	$MgCl_2$	$CaCl_2$	Dry NaCl	Pre-Wet NaCl	Abrasives (less than 20% salt added)
32°F steady or rising	Dry	NR			NR		
	Icy patches	30-60	15-35	15-35	150-180	130-170	NR
32°F or below is imminent	Dry (snow forecast)	20-40	15-35	15-35	NR	100-150	NR
	Slush or light snow	NR	NR	NR	150-200	125-175	NR
25°-32°F, remaining in range	Dry (snow forecast)	40-60	20-40	20-40	NR	125-175	NR
	Light snow cover	60-90	NR	NR	225-275	175-250	NR
20°-25°F, remaining in range	Dry (snow forecast)	NR	30-50	NR	NR	200-250	NR
	Light snow cover	NR	NR	NR	275-325	225-300	NR
15°-20°F, remaining in range	Dry (snow forecast)	NR	40-70	NR	NR	200-250	NR
	Light snow cover	NR	NR	NR	300-350	275-325	500-750
0°-15°F, steady or falling	Dry (snow forecast)	NR			NR	300-350	NR
	Light snow cover	NR			NR	400-500	600-900
Below 0°F, steady or falling	Light snow cover	NR			NR	NR	600-900

Notes:
1. Use lower end of range for lower LOS or shorter cycle times
2. Use higher end of range for higher LOS, longer cycle times, or greater dilution potential
3. Plow to remove as much snow or ice as possible before material application
4. Abbreviations: lb/LM = pounds per lane mile, G/LM = gallons per lane mile, NR = Not Recommended

Table A23. Application Rate Guidelines for Freezing Rain (Shi et al. 2019).

Pavement Temp. Range, Trend	Road Surface Condition	Material Application					
		Liquid (G/LM)			Solid (lb/LM)		
		NaCl	$MgCl_2$	$CaCl_2$	Dry NaCl	Pre-Wet NaCl	Abrasives (less than 20% salt added)
32°F steady or rising	Icy patches	NR			NR	125-175	NR
32°F or below is imminent	Slush or ice	NR			180-240	140-180	NR
25-32F, remaining in range	Slush or ice	NR			200-275	180-225	NR
20°-25°F, remaining in range	Slush or ice	NR			250-350	225-300	500
15°-20°F, remaining in range	Slush or ice	NR			350-450	300-400	500-750
0°-15°F, steady or falling	Slush or ice	NR			NR	NR	600-750
Below 0°F, steady or falling	Slush or ice	NR			NR	NR	750-900

Notes:

1. Use lower end of range for lower LOS or shorter cycle times
2. Use higher end of range for higher LOS, longer cycle times, or greater dilution potential
3. Plow to remove as much snow or ice as possible before material application
4. Abbreviations: lb/LM = pounds per lane mile, G/LM = gallons per lane mile, NR = Not Recommended

Nixon, W. (2011). The Science of Snow and Ice Control. Michigan Winter Operations Conference, November 2011. University of Iowa, Asset Insight Technologies.

Table A24. Pre-wetted Salt Application Rates (Nixon 2011).

Salt Application Rate Guidelines							
Prewetted salt @ 12' wide lane (assume 2-hr route)							
Surface Temperature (°Fahrenheit)		**32-30**	**29-27**	**26-24**	**23-21**	**20-18**	**17-15**
lbs of salt to be applied per lane mile	Heavy Frost, Mist, Light Snow	50	75	95	120	140	170
	Drizzle, Medium Snow 1/2" per hour	75	100	120	145	165	200
	Light Rain, Heavy Snow 1" per hour	100	140	182	250	300	350
Prewetted salt @ 12' wide lane (assume 3-hr route)							
Surface Temperature (Fahrenheit)		**32-30**	**29-27**	**26-24**	**23-21**	**20-18**	**17-15**
lbs of salt to be applied per lane mile	Heavy Frost, Mist, Light Snow	75	115	145	180	210	255
	Drizzle, Medium Snow 1/2" per hour	115	150	180	220	250	300
	Light Rain, Heavy Snow 1" per hour	150	210	275	375	450	525

Illinois Department of Transportation (2002). *Bureau of Operations Maintenance Policy Manual*. IDOT.

Table A25. Frost Control (IDOT 2002).

	INITIAL OPERATIONS				ONGOING OPERATIONS			
			Spread Rate Range (Per Lane Mile)			Spread Rate Range (Per Lane Mile)		
PAVEMENT TEMPERATURE FORECAST and RELATION TO DEW POINT TEMPERATURE RANGE AND TREND	Traffic Conditions	Suggested Actions	* Liquid Salt Solution	Pre-wet Solid Salt	Suggested Actions	Pre-wet Solid Salt**	Dry Salt	COMMENTS
Above 32°F --- Steady or Rising	All	See comments		N/A	See comments			Monitor pavement temperature and weather forecasts closely for drops to and below 32°F and frost potential
28° to 32°F --- temperatures staying in range and equal to or below dew point		Apply salt brine to bridge decks and frost prone locations 2 to 3 times weekly	20 to 50 gal. per mile		Apply chemicals as needed.	75 to 150 lbs.	100 to 200 lbs.	
20° to 28°F --- temperatures staying in this range and equal to or below dew point		Apply salt brine to bridge decks and frost prone locations 2 to 3 times weekly	30 to 60 gal. per mile		Apply chemicals as needed.	150 to 350 lbs.	150 to 400 lbs.	It is not advisable to apply Liquid Salt Solution when pavement temperatures drop below 20°F
10° to 20°F --- temperatures staying in this range and equal to or below dew point		N/A			Apply chemicals as needed.	250 to 500 lbs.	500 lbs.	

Notes: *Application rate for 28% solution, **Pre-wet with 23% salt solution at 7 to 8 gallon per ton of dry salt.

Ohio Department of Transportation (2008). *Material Application Guidelines*. ODOT.

Table A26. Material Application Guidelines (ODOT 2002).

Ohio Department of Transportation													
Materials Application Guidelines													
Conditions			**Equipment**	**Pre-Treat**	**Light Snowfall***			**Heavy Snowfall** w/Plowing**			**Freezing Rain**		
Pavement Temperature, Range, and Trend	Pavement surface at time of operation	Recommended Maintenance Action	Recommended Snow Removal Equipment	*** 23 % of Solution of Salt Brine 23% (gal/mile)	Solid (#/mile)	*** ## Prewet solid (#/mile)	Comment #	Solid (#/mile)	*** ## Prewet solid (#/mile)	Comment #	Solid (#/mile)	*** ## Prewet solid (#/mile)	Comment #
Above 32°F Steady or Rising	Dry, wet, slush, or light snow cover	Monitor Road and Weather Conditions	Front Plow Wing Plow Underbody Plow	20 - 40			1, 2			1, 2			
Above 32°F Below is imminent	Dry	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader and Pre-wetting Tanks	20 - 40		50 to 100			50 to 100	3			
	Wet, slush, or light snow cover	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader		50 to 100	50 to 100		200 to 300	100 to 200	3	300 to 400	200 to 300	
25°F to 32°F Remaining in range	Dry	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader and Pre-wetting Tanks	20 - 40		50 to 100			100 to 200	3			
	Wet, slush, or light snow cover	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader		100 to 200	50 to 100	5	300 to 400	300 to 400	3, 5	300 to 400	300 to 400	5
20°F to 25°F Remaining in range	Dry	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader and Pre-wetting Tanks	20 - 40		100 to 200							
	Wet, slush, or light snow cover	Apply liquid or prewetted solid	Anti-Icing System or Salt Spreader		200 to 300	100 to 200	5, 6	Max 400	Max 400	5, 6	Max 400	Max 400	5, 6
15°F to 20°F Remaining in range	Dry	Monitor Conditions					4			4			4
	Wet, slush, or light snow cover	Apply solid materials	Salt Spreader		300 to 400	300 to 400	5, 6	Max 400	Max 400	5, 6	Max 400	Max 400	5, 6
Below 15°F Steady or falling	Dty	Monitor Conditions					4			4			4
	Wet, slush, or light snow cover	Plow as needed Apply salt with calcium chloride	Front Plow Wing Plow Underbody Plow			200 to 300	5		Max 400	5	Max 400	Max 400	5

Notes: * less than 2 inch per hour, ** 2 inch or more per hour, *** SEE ATTACHED FOR OTHER LIQUID ANTI/DE-ICER APPLICATION RATES, ## 8 to 10 GALLONS of salt brine per TON is recommended for pre-wet solid
1) Monitor temperatures and road pavement conditions for cold or icy spots. Treat problem areas as needed.
2) Treat icy spots at 100#/mile or 20 gal/mile, plow as needed.
3) Do not apply liquid to heavy snow accumulation or packed snow.
4) Do not apply chemicals and maintain dry pavement during windy conditions
5) A mixture of salt and abrasives is recommended or acceptable at these temperatures
6) Calcium Chloride may be used in temperatures less than 25 degrees F

Oregon Department of Transportation (2017). *Oregon Department of Transportation Deicer Application Guidelines*. ODOT.

Table A27. Oregon Department of Transportation Deicer Application Guidelines, Anti-Icing (Before Storm) (ODOT 2017).

Anti-Icing (Before the Storm)			
Pavement Temperature at the time of application	Snow	Freezing Fog/Black Ice	Freezing Rain/Sleet
Over 30	15-30 (L)	15-30 (L) or 100-200 (S)	100-200 (S)
26 to 30	20-40 (L)	20-30 (L) or 100-200 (S)	100-200 (S)
21 to 25	30-50 (L)	20-40 (L) or 100-200 (S)	200-300 (S)
15 to 20	40-60 (L)	30-40 (L) or 200-300 (S)	200-400 (S)
Below 15	Not Recommended	Not Recommended	Not Recommended

Table A28. Oregon Department of Transportation Deicer Application Guidelines, Deicing (During the Strom) (ODOT 2017).

Deicing (During the Storm)			
Pavement Temperature at the time of application	Snow	Freezing Fog/Black Ice	Freezing Rain/Sleet
Over 30	15-30 (L)	15-30 (L) or 100-200 (S)	100-200 (S)
26 to 30	20-40 (L)	20-30 (L) or 100-200 (S)	100-200 (S)
21 to 25	30-50 (L)	20-40 (L) or 100-200 (S)	200-300 (S)
15 to 20	40-60 (L)	30-40 (L) or 200-300 (S)	200-400 (S)
Below 15	Not Recommended	Not Recommended	Not Recommended

Table A29. Oregon Department of Transportation Deicer Application Guidelines, After Storm (Precipitation has Stopped) (ODOT 2017).

After Storm (Precipitation has Stopped)				
Pavement Temperature at the time of application	Light Snow (1" per hour or less)	Moderate-Heavy Snow (More than 1" per hour)	Freezing Fog/Black Ice	Freezing Rain/Sleet
Over 30	15-30 (L) or 100-200 (S)	200-300 (S)	15-30 (L) or 100-200 (S)	200-300 (S)
26 to 30	20-40 (L) or 100-200 (S)	200-300 (S)	20-40 (L) or 100-200 (S)	200-300 (S)
21 to 25	20-40 (L) or 100-200 (S)	200-400 (S)	30-50 (L) or 100-200 (S)	200-400 (S)
15 to 20	40-60 (L) or 200-300 (S)	200-500 (S)	40-60 (L) or 200-300 (S)	200-500 (S)
Below 15	PA	PA	AA	AA

Notes: (L) = Liquid Mag ($MgCl_2$) gallons per lane mile, (S) = Solid Salt (NaCl) pounds per lane mile, PA = Plow and apply pre-wetted abrasives as needed, AA = Apply pre-wetted abrasives as needed.

Practical Tips/Best Management Practices

1. These are typical application rate ranges, and can be adjusted based on pavement/weather variables and to meet operational objectives.
2. Generally, choose a lower application rate when the pavement temperature trend is rising or steady, and a higher application rate when the temperature trend is falling.
3. Melting or "burning" all snow or ice from the pavement is not recommended- apply just enough to loosen the bond between the ice/compacted snow so that it can be effectively plowed off.
4. Time applications to prevent conditions from deteriorating and avoid the development of packed and bonded snow.
5. Plow as much snow and ice as possible (initial or re-application) before applying any deicing chemical. Target depth should be 2 inches or less.
6. Cycle times should allow time for product to work prior to plowing and re-application. Higher application rates can be used to accommodate longer cycle times by countering dilution of deicer caused by melting and/or precipitation.
7. All solids must be pre-wetted with liquid mag ($MgCl^2$) at a rate of 10-20 gallons/ton in order to maximize effectiveness.
8. The application of liquid deicer is not recommended when snow/ice is too thick to see pavement or if the pavement is wet.

ODOT Maintenance & Operations Branch - 2017

The following references were used to establish the deicer application rates:

1. Establishing Effective Salt and Anti-Icing Application Rates, Clear Roads Research Program, 2014.
2. Snow and Ice Control: Guidelines for Materials and Methods (Report 526), National Cooperative Highway Research Program, 2004.
3. Manual of Practice for an Effective Anti-Icing Program, Federal Highway Administration, 1996.

Washington Department of Transportation (n.d.). Chapter 6: Material Application Guidelines (Based on the FHWA Manual of Practice for an Effective Anti-icing Program). WSDOT.

Table A30. Light Snow, Using 32% Concentration of Calcium Chloride (WSDOT n.d.).

<table>
<tr><th rowspan="3">PAVEMENT TEMPERATURE RANGE, AND TREND</th><th colspan="3">INITIAL OPERATION</th><th colspan="2">SUBSEQUENT OPERATIONS</th><th>COMMENTS</th></tr>
<tr><th rowspan="2">Pavement surface at time of Initial operation</th><th rowspan="2">Maintenance Action</th><th>Chemical spread rate (gal/ln-mi)</th><th rowspan="2">Maintenance Action</th><th>Chemical spread rate (gal/ln-mi)</th><th rowspan="2">N/R = Not Recommended</th></tr>
<tr><th>Liquid $CaCl_2$</th><th>Liquid $CaCl_2$</th></tr>
<tr><td>Above 32°F, Steady or rising</td><td>Dry, wet, slush, or light snow cover</td><td>None, see comments</td><td>N/R</td><td>None, see comments</td><td>N/R</td><td>*Monitor pavement temperature closely
*Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed</td></tr>
<tr><td>32°F, or below is imminent</td><td>Dry</td><td rowspan="3">Apply liquid</td><td>15-35</td><td rowspan="3">Plow as needed; reapply liquid Chemical when needed</td><td>15-35</td><td>*Application rates will depend on dilution potential</td></tr>
<tr><td>ALSO 20° to 32°F, Remaining in range</td><td>Wet, slush, or light snow cover</td><td>20-40</td><td>20-40</td><td></td></tr>
<tr><td>15° to 20°F, Remaining in range</td><td>Dry, wet, slush, or light snow cover</td><td>30-65</td><td>30-65</td><td>*Application rates will depend on dilution potential</td></tr>
<tr><td>Below 15°F, Steady or falling</td><td>Dry or light snow cover</td><td>Plow as needed</td><td>N/R</td><td>Plow as needed</td><td>N/R</td><td>* It is not recommended that chemicals be applied in this temperature range
*Abrasives can be applied to enhance traction</td></tr>
</table>

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A31. Light Snow Storm with Period(s) of Moderate or Heavy Snow, Using 32% Concentration of Calcium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION			SUBSEQUENT OPERATIONS		COMMENTS
	Pavement surface at time of Initial operation	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $CaCl_2$	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $CaCl_2$	N/R = Not Recommended
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed
32°F, or below is imminent	Dry	Apply liquid	15-35	Plow as needed; reapply liquid Chemical when needed	15-35	*Do not apply liquid chemical onto heavy snow accumulation or packed snow *Application rates will depend on dilution potential
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover		20-40		20-40	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover		30-70		30-70	*Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R	Plow as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A32. Moderate or Heavy Snow Storm, Using 32% Concentration of Calcium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**			**SUBSEQUENT OPERATIONS**		**COMMENTS**
	Pavement surface at time of Initial operation	**Maintenance Action**	**Chemical spread rate (gal/ln-mi) Liquid $CaCl_2$**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi) Liquid $CaCl_2$**	**N/R = Not Recommended**
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed
32°F, or below is imminent	Dry	Apply pre-wet solid NaCl	N/R	Plow as needed; reapply pre-wet solid chemical as needed	N/R	*If sufficient moisture is present, solid chemical without pre-wetting can be applied *Do not apply liquid chemical onto heavy snow accumulation or packed snow
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover		N/R		N/R	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover		N/R		N/R	
Below 15°F, Steady or falling	Dry or light snow cover	Plow accumulation as needed	N/R	Plow accumulation as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A33. Frost or Black Ice, Using 32% Concentration of Calcium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**TRAFFIC CONDITION**	**INITIAL OPERATION**		**SUBSEQUENT OPERATIONS**		**COMMENTS**
		Maintenance Action	**Chemical spread rate (gal/ln-mi)**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi)**	**N/R = Not Recommended**
			Liquid $CaCl_2$		**Liquid $CaCl_2$**	
32°F, Steady or rising	Any level	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely; begin treatment if temperature starts to fall to 32°F or below and is at or below dew point
28°-32°F, remaining in range or falling 32°F or below, and equal to or below dew point	Traffic rate less than 100 vehicles per hour	Apply liquid chemical	10-25	Reapply liquid chemical as needed	10-25	*Application rates will depend on dilution potential
	Traffic rate greater than 100 vehicles per hour		20-35		20-35	
15° to 28°F, Remaining in range and equal to or below dew point	Any level		20-40		25-40	*Application rates will depend on dilution potential
Below 15°F, Steady or falling	Any level	Apply abrasives	N/R	Plow accumulation as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A34. Freezing Rainstorm, Using 30% Concentration of Magnesium Chloride, Using 32% Concentration Calcium Chloride, Using 25% Concentration of CMA, Using Solid Sodium Chloride (WSDOT n.d.).

<table>
<tr><th rowspan="3">PAVEMENT TEMPERATURE RANGE, AND TREND</th><th colspan="2">INITIAL OPERATION</th><th colspan="2">SUBSEQUENT OPERATIONS</th><th>COMMENTS</th></tr>
<tr><th rowspan="2">Maintenance Action</th><th>Chemical spread rate (gal/ln-mi)</th><th rowspan="2">Maintenance Action</th><th>Chemical spread rate (gal/ln-mi)</th><th rowspan="2">N/R = Not Recommended</th></tr>
<tr><th>Liquid NaCl</th><th>Liquid NaCl</th></tr>
<tr><td>Above 32°F, Steady or rising</td><td>None, see comments</td><td>N/R</td><td>None, see comments</td><td>N/R</td><td>*Monitor pavement temperature closely
*Treat icy patches if needed with pre-wetted solid chemicals at 100-150 lb/lane-mi</td></tr>
<tr><td>32°F, or below is imminent</td><td rowspan="3">Apply solid chemical</td><td>100-200</td><td rowspan="3">Reapply solid chemical as needed</td><td>100-200</td><td rowspan="3">*Monitor pavement temperature and precipitation closely
*Applications rates will depend on dilution potential</td></tr>
<tr><td>20° to 32°F, Remaining in range</td><td>200-300</td><td>200-300</td></tr>
<tr><td>15° to 20°F, Remaining in range</td><td>250-400</td><td>250-400</td></tr>
<tr><td>Below 15°F, Steady or falling</td><td>Apply abrasives</td><td>N/R</td><td>Apply abrasives as needed</td><td>N/R</td><td>* It is not recommended that chemicals be applied in this temperature range
*Abrasives can be applied to enhance traction</td></tr>
</table>

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A35. Sleet Storm, Using 32% Concentration Calcium Chloride (WSDOT n.d.).

<table>
<tr><th rowspan="2">PAVEMENT TEMPERATURE RANGE, AND TREND</th><th colspan="2">INITIAL OPERATION</th><th colspan="2">SUBSEQUENT OPERATIONS</th><th>COMMENTS</th></tr>
<tr><th>Maintenance Action</th><th>Liquid $CaCl_2$</th><th>Maintenance Action</th><th>Liquid $CaCl_2$</th><th>N/R = Not Recommended</th></tr>
<tr><td>Above 32°F, Steady or rising</td><td>None, see comments</td><td>N/R</td><td>None, see comments</td><td>N/R</td><td rowspan="5">Go to Sodium Chloride Chart</td></tr>
<tr><td>32°F, or below is imminent</td><td rowspan="3">Apply solid NaCl</td><td rowspan="3">N7R</td><td rowspan="3">Plow accumulation and reapply pre-wet solid chemical as needed</td><td rowspan="3">N/R</td></tr>
<tr><td>20° to 32°F, Remaining in range</td></tr>
<tr><td>15° to 20°F, Remaining in range</td></tr>
<tr><td>Below 15°F, Steady or falling</td><td>Plow as needed</td><td>N/R</td><td>Plow as needed</td><td>N/R</td></tr>
</table>

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A36. Light Snow, Using 30% Concentration Magnesium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION			SUBSEQUENT OPERATIONS		COMMENTS
	Pavement surface at time of Initial operation	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$	N/R = Not Recommended
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed
32°F, or below is imminent	Dry	Apply liquid	15-35	Plow as needed; reapply liquid chemical when needed	15-35	*Application rates will depend on dilution potential
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover		20-40		20-40	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover		45-65		45-65	*Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R	Plow as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A37. Light Snow with Period(s) of Moderate or Heavy Snow, Using 30% Concentration Magnesium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**			**SUBSEQUENT OPERATIONS**		**COMMENTS**
	Pavement surface at time of Initial operation	**Maintenance Action**	**Chemical spread rate (gal/ln-mi)** **Liquid $MgCl_2$**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi)** **Liquid $MgCl_2$**	**N/R = Not Recommended**
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed
32°F, or below is imminent	Dry	Apply liquid	15-35	Plow as needed; reapply liquid chemical when needed	15-35	
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover		20-40		20-40	*Application rates will depend on dilution potential
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover		45-70		45-70	*Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R	Plow as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A38. Moderate or Heavy Snow Storm, Using 30% Concentration Magnesium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION			SUBSEQUENT OPERATIONS		COMMENTS
	Pavement surface at time of Initial operation	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$	Maintenance Action	Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$	N/R = Not Recommended
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 15-35 GPLM… plow if needed
32°F, or below is imminent	Dry	Apply pre-wet solid NaCl	N/R	Plow as needed; reapply pre-wet solid chemical as needed	N/R	*If sufficient moisture is present, solid chemical without pre-wetting can be applied *Do not apply liquid chemical onto heavy snow accumulation or packed snow
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover		N/R		N/R	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover		N/R		N/R	
Below 15°F, Steady or falling	Dry or light snow cover	Plow accumulation as needed	N/R	Plow accumulation as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.
SOLID DEICER See Sodium Chloride for application recommendations.

Table A39. Frost or Black Ice, Using 30% Concentration Magnesium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**TRAFFIC CONDITION**	**INITIAL OPERATION**		**SUBSEQUENT OPERATIONS**		**COMMENTS**
		Maintenance Action	**Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi) Liquid $MgCl_2$**	**N/R = Not Recommended**
32°F, Steady or rising	Any level	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely; begin treatment if temperature starts to fall to 32°F or below and is at or below dew point
28°-32°F, Remaining in range or falling 32°F or below, and equal to or below dew point	Traffic rate less than 100 vehicles per hour	Apply liquid chemical	15-35	Reapply liquid chemical as needed	15-30	*Application rates will depend on dilution potential
	Traffic rate greater than 100 vehicles per hour		20-35		20-35	
15° to 28°F, Remaining in range and equal to or below dew point	Any level		25-40		25-40	*Application rates will depend on dilution potential
Below 15°F, Steady or falling		Apply abrasives as needed	N/R	Plow accumulation as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:

CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.

PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible

CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A40. Freezing Rainstorm, Using 30% Concentration Magnesium Chloride, Using 32% Concentration of Calcium Chloride, Using 25% Concentration of CMA, Using Solid Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**		**SUBSEQUENT OPERATIONS**		**COMMENTS**
	Maintenance Action	**Chemical spread rate (gal/ln-mi)** **Liquid NaCl**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi)** **Liquid NaCl**	**N/R = Not Recommended**
Above 32°F, Steady or rising	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with pre-wetted solid chemicals at 100-150 lb/lane-mi
32°F, or below is imminent	Apply solid chemical	100-200	Reapply solid chemical as needed	100-200	*Monitor pavement temperature and precipitation closely *Applications rates will depend on dilution potential
20° to 32°F, Remaining in range		200-300		200-300	
15° to 20°F, Remaining in range		250-400		250-400	
Below 15°F, Steady or falling	Apply abrasives	N/R	Apply abrasives as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A41. Sleet Storm, Using 30% Concentration Magnesium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**		**SUBSEQUENT OPERATIONS**		**COMMENTS**
	Maintenance Action	**Liquid $MgCl_2$**	**Maintenance Action**	**Liquid $MgCl_2$**	**N/R = Not Recommended**
Above 32°F, Steady or rising	None, see comments	N/R	None, see comments	N/R	Go to Sodium Chloride Chart
32°F, or below is imminent	Apply solid NaCl	N7R	Plow accumulation and reapply pre-wet solid chemical as needed	N/R	
20° to 32°F, Remaining in range					
15° to 20°F, Remaining in range					
Below 15°F, Steady or falling	Plow as needed	N/R	Plow as needed	N/R	

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A42. Light Snow, Using 23% Concentration Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	Pavement surface at time of Initial operation	Maintenance Action	Chemical spread rate (gal/ln-mi or lb/ln-mi)		Maintenance Action	Chemical spread rate (gal/ln-mi or lb/ln-mi)		N/R = Not Recommended
			Liquid NaCl	Solid or pre-wet solid (lb)		Liquid NaCl	Solid or pre-wet solid (lb)	
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R		None, see comments	N/R		*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 100 lb/ln-mi; plow if needed
32°F, or below is imminent	Dry	Apply liquid or pre-wet solid chemical	40-50	75-125	Plow as needed; reapply liquid or solid chemical when needed	40-50	75-125	*Application rates will depend on dilution potential
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	20-40	100-210		40-90	100-210	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover	Apply liquid or pre-wet solid chemical	45-70	200-240	Plow as needed; reapply pre-wet solid chemical when needed	N/R	200-240	*If sufficient moisture is present, solid chemical without pre-wetting can be applied *Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R		Plow as needed	N/R		* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A43. Light Snow Storm with Period(s) of Moderate or Heavy Snow, Using 23% Concentration Sodium Chloride (WSDOT n.d.).

	INITIAL OPERATION				SUBSEQUENT OPERATIONS					COMMENTS
PAVEMENT TEMPERATURE RANGE, AND TREND	**Pavement surface at time of Initial operation**	**Maintenance Action**	**Chemical spread rate (gal/ln-mi or lb/ln-mi)**		**Maintenance Action**	**Chemical spread rate (gal/ln-mi or ln/ln-mi)**				**N/R = Not Recommended**
			Liquid NaCl	**Solid or pre-wet solid**		**Liquid NaCl**		**Solid or pre-wet solid**		
						Light snow	**Heavier snow**	**Light snow**	**Heavier snow**	
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R		None, see comments	N/R				*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 40-65 GPLM; plow if needed
32°F, or below is imminent	Dry	Apply liquid or pre-wet solid chemical	40-65	75-150	Plow as needed; reapply liquid or solid chemical when needed	40-50	50-65	75-125	150-200	*Do not apply liquid chemical onto heavy snow accumulation or packed snow *Application rates will depend on dilution potential
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	65-90	175-200		40-90	80-90	100-210	190-200	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover	Apply liquid or pre-wet solid chemical	N/R	200-230	Plow as needed; reapply pre-wet solid chemical when needed	N/R		200-230	200-250	*If sufficient moisture is present, solid chemical without pre-wetting can be applied *Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R		Plow as needed	N/R				* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A44. Moderate or Heavy Snow Storm, Using 23% Concentration Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**							**COMMENTS**
	Pavement surface at time of Initial operation	**Maintenance Action**	**Chemical spread rate (gal/ln-mi or lb/ln-mi)**		**Maintenance Action**	**Chemical spread rate (gal/ln-mi or lb/ln-mi)**		**N/R = Not Recommended**
			Liquid NaCl	**Solid or pre-wet solid**		**Liquid NaCl**	**Solid or pre-wet solid**	
Above 32°F, Steady or rising	Dry, wet, slush, or light snow cover	None, see comments	N/R		None, see comments	N/R		*Monitor pavement temperature closely *Treat icy patches if needed with chemical at 40-65 GPLM; plow if needed
32°F, or below is imminent	Dry	Apply liquid or pre-wet solid chemical	40-65	75-150	Plow accumulation and reapply liquid or solid chemical as needed	50-65	150-200	*Do not apply liquid chemical onto heavy snow accumulation or packed snow *Application rates will depend on dilution potential
ALSO 20° to 32°F, Remaining in range	Wet, slush, or light snow cover	Apply solid chemical	N/R	175-200	Plow accumulation and reapply pre-wet solid chemical as needed	80-90	190-200	
15° to 20°F, Remaining in range	Dry, wet, slush, or light snow cover	Apply pre-wet solid chemical	N/R	200-230	Plow as needed; reapply pre-wet solid chemical when needed	N/R	200-250	*If sufficient moisture is present, solid chemical without pre-wetting can be applied *Application rates will depend on dilution potential
Below 15°F, Steady or falling	Dry or light snow cover	Plow as needed	N/R		Plow as needed	N/R		* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A45. Frost or Black Ice, Using 23% Concentration Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	TRAFFIC CONDITION	INITIAL OPERATION			SUBSEQUENT OPERATIONS			COMMENTS
		Maintenance Action	Chemical spread rate (gal/ln-mi or lb/ln-mi)		Maintenance Action	Chemical spread rate (gal/ln-mi or lb/ln-mi)		N/R = Not Recommended
			Liquid NaCl	Solid or pre-wet solid		Liquid NaCl	Solid or pre-wet solid	
32°F, Steady or rising	Any level	None, see comments	N/R		None, see comments	N/R		*Monitor pavement temperature closely; begin treatment if temperature starts to fall to 32°F or below and is at or below dew point
28° to 32°F, Remaining in range or falling 32°F or below, and equal to or below dew point	Traffic rate less than 100 vehicles per hour	Apply liquid or pre-wet solid chemical	45-60	100-130	Reapply liquid or pre-wet solid chemical when needed	45-60	100-130	*Application rates will depend on dilution potential
	Traffic rate greater than 100 vehicles per hour		45-75	100-130		45-75	100-130	
20° to 28°F, Remaining in range and equal to or below dew point	Any level		65-80	165-200		65-80	165-200	*Application rates will depend on dilution potential
15° to 28°F, Remaining in range and equal to or below dew point		Apply pre-wet solid chemical	N/R	175-225	Reapply pre-wet solid chemical when needed	N/R	175-225	
Below 15°F, Steady or falling		Apply abrasives as needed	N/R		Apply abrasives as needed	N/R		* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A46. Freezing Rainstorm, Using 30% Concentration Magnesium Chloride, Using 32% concentration Calcium Chloride, Using 25% concentration of CMA, Using solid Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	**INITIAL OPERATION**		**SUBSEQUENT OPERATIONS**		**COMMENTS**
	Maintenance Action	**Chemical spread rate (lb/ln-mi)**	**Maintenance Action**	**Chemical spread rate (lb/ln-mi)**	**N/R = Not Recommended**
Above 32°F, Steady or rising	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with pre-wetted solid chemicals at 100-150 lb/lane-mi
32°F, or below is imminent	Apply solid chemical	100-200	Reapply solid chemical as needed	100-200	*Monitor pavement temperature and precipitation closely *Applications rates will depend on dilution potential
20° to 32°F, Remaining in range		200-300		200-300	
15° to 20°F, Remaining in range		250-400		250-400	
Below 15°F, Steady or falling	Apply abrasives	N/R	Apply abrasives as needed	N/R	* It is not recommended that chemicals be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Table A47. Sleet Storm, Using 23% Concentration Sodium Chloride (WSDOT n.d.).

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION		SUBSEQUENT OPERATIONS		COMMENTS
	Maintenance Action	**Chemical spread rate lb/lane-mi NaCl**	**Maintenance Action**	**Chemical spread rate lb/lane-mi NaCl**	**N/R = Not Recommended**
Above 32°F, Steady or rising	None, see comments	N/R	None, see comments	N/R	*Monitor pavement temperature closely *Treat icy patches if needed with pre-wetted solid chemical at 100-150 lb/ln-mi
32°F, or below is imminent	Apply solid NaCl	125	Plow accumulation and reapply pre-wet solid chemical as needed	125	*Monitor pavement temperature and precipitation closely *Application rates will depend on dilution potential
20° to 32°F, Remaining in range		125-325		125-325	
15° to 20°F, Remaining in range		250-400		250-400	
Below 15°F, Steady or falling	Plow as needed	N/R	Plow as needed	N/R	*It is not recommended that chemical be applied in this temperature range *Abrasives can be applied to enhance traction

Notes:
CHEMICAL APPLICATIONS These application rates are starting points. Local experience should refine these recommendations. Time chemical applications to prevent deteriorating conditions or development of packed and bonded snow. Monitor temperature and humidity to determine application timing.
PLOWING Before applying any ice control chemical, the surface should be cleared of as much snow and ice as possible
CHEMICAL RATES The recommended snow and ice control material application rates depend on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period (window) between the current treatment and the next anticipated treatment.

Ketcham, S., Minsk, L. D., Blackburn, R. R., and Fleege, E. J. (1996). *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel*. No. FHWA-RD-95-202. United States. FHWA.

Table A48. Weather Event: Light Snow Storm (Ketcham et al. 1996).

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

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) Apply chemical ahead of traffic rush periods occurring during storm.
PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table A49. Weather Event: Light Snow Storm with Period(s) of Moderate or Heavy Snow (Ketcham et al. 1996).

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

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) *Anticipate increases in snowfall intensity. Apply higher rate treatments prior to or at the beginning of heavier snowfall periods to prevent development of packed and bonded snow*. (3) Apply chemical ahead of traffic rush periods occurring during storm. **PLOWING**. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table A50. Weather Event: Moderate or Heavy Snow Storm (Ketcham et al. 1996).

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

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

Table A51. Weather Event: Frost or Black Ice (Ketcham et al. 1996).

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

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

Table A52. Weather Event: Freezing Rain Storm (Ketcham et al. 1996).

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

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

Table A53. Weather Event: Sleet Storm (Ketcham et al. 1996).

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

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

APPENDIX B. SURVEY OF PRACTICE

B1. Survey Introduction

CLEAR ROADS

Project Number: TPF-5(353)

EXPANDING APPLICATION RATE GUIDANCE FOR SALT BRINE BLENDS FOR DIRECT LIQUID APPLICATION AND ANTI-ICING

Survey of Practice

Guidance on application rates for liquid deicers at low to moderate pavement temperatures and diverse roadway surface conditions are currently unavailable. The objective of this project is to expand liquid application rates guidance for anti-icing and deicing. Outcome based performance measures from field observations are limited. This project aims at identifying commonly used liquid blends and applications rates to test them at five to seven states. This survey of practice will serve to gather agencies' liquid application guidance, practices, and identify potential sites for the study.

B2. Survey Questions

A. Liquid Application Guidance and Practices

Q1. Does your agency use liquid applications for winter maintenance?

Q2. Do you have a guidance document for when to use liquids, at what application rates, and what frequency? Please upload guidance document or provide URL

Q3. Is your agency willing to share internal or commonly used application rates in a follow-up call?

Q4. Does your agency use liquid applications at pavement temperatures below 20°F?

Q5. What chemical materials does your agency use at pavement temperatures below 20°F?

Liquid

Q5.1. Salt Brine (23% NaCl)
Q5.2. Calcium Chloride (32% $CaCl_2$)
Q5.3. Magnesium Chloride (27% $MgCl_2$)
Q5.4. Potassium Acetate (50% KAc)
Q5.5. Calcium Magnesium Acetate (25% CMA)
Q5.6. Other liquid chemical materials

Solid

Q5.7. Solid Salt
Q5.8. Pre-wet salt
Q5.9. Calcium Chloride (90-92% $CaCl_2$)
Q5.10. Magnesium Chloride (100% $MgCl_2$)
Q5.11. Potassium Acetate (100% KAc)
Q5.12. Calcium Magnesium Acetate (96% CMA)
Q5.13. Other solid chemical materials

Q6. If Q5.6. or Q5.12 are selected. Please, describe OTHER liquid/solid chemical materials used

Q7. What blends are commonly used at your agency? For example: 90% Salt Brine and 10% Calcium Chloride

Q8. In which weather conditions does your agency COMMONLY USE liquid applications?

Pavement Temperature SURFACE CONDITION	Precipitation: Snow	Frost/Black Ice	Freezing Rain	Sleet
20-32°F **DRY**	☐	☐	☐	☐
20-32°F **WET**	☐	☐	☐	☐
15-20°F **DRY**	☐	☐	☐	☐
15-20°F **WET**	☐	☐	☐	☐
Below 15°F **DRY**	☐	☐	☐	☐
Below 15°F **WET**	☐	☐	☐	☐

Q9. What conditions would your agency AVOID using liquid applications?

Pavement Temperature SURFACE CONDITION	Precipitation: Snow	Frost/Black Ice	Freezing Rain	Sleet
20-32°F **DRY**	☐	☐	☐	☐
20-32°F **WET**	☐	☐	☐	☐
15-20°F **DRY**	☐	☐	☐	☐
15-20°F **WET**	☐	☐	☐	☐
Below 15°F **DRY**	☐	☐	☐	☐
Below 15°F **WET**	☐	☐	☐	☐

Q10. If Q1. response is No. In which conditions would your agency consider using liquid applications?

Pavement Temperature SURFACE CONDITION	Precipitation: Snow	Frost/Black Ice	Freezing Rain	Sleet
20-32°F **DRY**	☐	☐	☐	☐
20-32°F **WET**	☐	☐	☐	☐
15-20°F **DRY**	☐	☐	☐	☐
15-20°F **WET**	☐	☐	☐	☐
Below 15°F **DRY**	☐	☐	☐	☐
Below 15°F **WET**	☐	☐	☐	☐

Q11. Are liquid applications used in combination with solids at pavement temperatures below 20°F?

- Q11.1. Yes: Shake and bake (when liquid applications is immediately followed by solid application
- Q11.2. Yes: Slurries (extremely heavy pre-wetting at up to 70 gallons a ton)
- Q11.3. No

B. Performance Measures

Q12. What performance measures are used in your jurisdiction?

- Q12.1. Amount of material used
- Q12.2. Cost of material used
- Q12.3. Time to bare/wet
- Q12.4. Speed measurements
- Q12.5. Pavement friction
- Q12.6. Other

Q13. If Q12.6. Other is selected. Please, describe OTHER performance measures

Q14. What tools does your agency use for winter maintenance?

- Q14.1. MDSS
- Q14.2. AVL
- Q14.3. CLARIS
- Q14.4. Video feed
- Q14.5. Friction testing
- Q14.6. Other

Q15. If Q14.6. Other is selected. Please, describe OTHER tools for winter maintenance

Q16. Does your agency utilize performance-based testing in procuring deicers?

Q17. If Q16. Yes. Please, explain the performance-based testing procedure to procure deicers

C. Project Data Collection

Q18. Is your agency willing to provide data for the development of application rate guidelines with liquid applications?

Q19. If Q18. Yes is selected. Please, provide potential routes for data collection in your jurisdiction

	Route		miles	Data Collection Stations Available				
	Start	End	Miles	Traffic Count	Speed Measurements	Weather	Video	Other
Route 1 Name/Description				☐	☐	☐	☐	☐
Route 2 Name/Description				☐	☐	☐	☐	☐
Route 3 Name/Description				☐	☐	☐	☐	☐
Route 4 Name/Description				☐	☐	☐	☐	☐
Route 5 Name/Description				☐	☐	☐	☐	☐

Q20. If Q18. No is selected. Is your agency planning to implement liquid applications in the upcoming 2020-2021 winter season and would your agency be willing to provide data for the development of application rate guidelines with liquid applications?

	Route		miles	Data Collection Stations Available				
	Start	End	Miles	Traffic Count	Speed Measurements	Weather	Video	Other
Route 1 Name/Description				☐	☐	☐	☐	☐
Route 2 Name/Description				☐	☐	☐	☐	☐
Route 3 Name/Description				☐	☐	☐	☐	☐
Route 4 Name/Description				☐	☐	☐	☐	☐
Route 5 Name/Description				☐	☐	☐	☐	☐

D. Contact Information

Q21. Contact name
Q22. Position
Q23. Agency
Q24. Email
Q25. Phone number

B3. List of Contacts

Name	Organization	Email	Telephone
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John Angel	Nevada DOT	jangel@dot.nv.gov	(775) 834-8303
Rhett Arnell	Utah DOT	rarnell@utah.gov	(435) 979-7083
John Oliva	Caltrans	john.oliva@dot.ca.gov	(916) 654-2490
Ty Barger	Nebraska DOT	ty.barger@nebraska.gov	(402) 479-4787
Craig Bargfrede	Iowa DOT	craig.bargfrede@dot.iowa.gov	(515) 239-1355
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Joseph Bucci	Rhode Island DOT	joseph.Bucci@dot.ri.gov	(401) 734-4800
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Melissa Longworth	Michigan DOT	longworthM@michigan.gov	(517) 636-4386
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Shane Mark	Town of Newton, MA	smark@newtonma.gov	(617) 796-1494
Bryan Pickworth	Farmington Hills, MI	BPickworth@fhgov.com	(248) 871-2865

B4. Route Information Form

AGENCY NAME:

1. ROUTES			
State:		Route Study Design:	
Study Route (single route where liquid applications will be evaluated) **Study in Parallel** (liquid application in one direction and control application in the other direction) **Split Study** (route divided in two segments, one segment with liquid applications and other segment control) **Independent Study** (routes not connected, study and control routes with similar conditions within an area)			
Study Route		**Control Route**	
Location:		Location:	
Name:		Name:	
Direction:		Direction:	
Beginning:		Beginning:	
End:		End:	
Length (miles):		Length (miles):	
Number of lanes (by direction):		Number of lanes (by direction):	
Lane-mile (ln-mi):		Lane mile (ln-mi):	
Route Maintenance (24 hr, 18 hr, other)		Route maintenance (24 hr, 18 hr, other)	

2. MAP OF ROUTES
Study Route
Description
Control Route
Description

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