DEPARTMENT OF TRANSPORTATION

Salt Brine Blending to Optimize Deicing and Anti-Icing Performance and Cost Effectiveness: Phase III

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An evaluation of deicers and anti-icers and plowing, in parallel conditions on actual pavements to assess intuitions based on observations and anecdotal evidence.

- Anti-icer persistence
- Deicer effectiveness
- Plow effectiveness
- Pavement study of anti-icer persistence

Factor interaction such as truck traffic plus snow moisture condition, deicer use or roadway crosswind and deicer distribution have significant impact on differences in winter maintenance performance and deicer efficiency.

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FINAL REPORT

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Canterbury Park and Valleyfair provided large pavement areas for plowing and deicing evaluations. Their flexibility, support and overall contribution to this effort is warmly appreciated.

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EXECUTIVE SUMMARY

This report presents the evaluation of winter maintenance efforts, including applications of deicers and anti-icers and plowing, in parallel conditions on actual pavements to assess intuitions based on observations and anecdotal evidence. Parallel conditions eliminate the issue of test sections being in slightly different geographies. Three different aspects were evaluated in this effort:

- Deicer effectiveness, techniques and materials evaluated at two proximal facilities across parallel treatment lanes of up to 1,000 feet in length;
- Plow effectiveness, techniques and equipment evaluated at the same locations as the deicer effectiveness evaluation; and,
- Anti-icer persistence, measured in response to both: actual traffic through drainage off defined roadway sections of an elevated highway; and precipitation through drainage off asphalt and Portland cement concrete pavements in a laboratory setting.

Results of this work indicate factor interaction such as truck traffic plus deicer use or roadway crosswind and deicer distribution may have significant impact on differences in winter maintenance performance and deicer efficiency.

CHAPTER 1: INTRODUCTION

Roadway deicing and snow removal has a rich tradition of observational science, both during operational aspects and in stand-alone research studies. The scientific method (formulate hypothesis, predict outcome, test outcome, and analyze results) is a vibrant presence in the cab of every plow truck, as operators study storm events, plan their deicing efforts, plow and spread deicer, then review the outcome perhaps 60 minutes later on a following pass of a plow truck route. Every driver who repeats a route is immediately confronted with comparisons, whether between the current pass and the previous one, the current storm and the last one, or the current winter and the coldest/stormiest/biggest winter in past memory.

While drivers are a treasure trove of results, the difficulty comes with comparison between locations or even geographies. If it "plays in Peoria," will the same technique play with a dry ground blizzard in Minnesota, wet Nor'easter snow in Maine, or deep mountain pass snow in Colorado? Sometimes, the question is simpler: Will a given technique work as well on the back side of a hill, where the sun may not shine at quite the same angle or the wind blows a bit colder?

Further complicating matters is the wide variety of chemical treatments now available for deicing. Work conducted by the principal investigator previously under MnDOT Agreement 96319 evaluated the ice melt capacity and field performance factors of deicers and deicer blends, and developed a temperature-based cost model for comparison of relative field performance through the evaluated deicers and deicer blends. Over 50 deicer and anti-icer compounds and compound blends were evaluated for ice melt capacity in over 1,400 determinations, at temperatures ranging from 30° F to -30° F. Values of ice melt capacity observed in this previous study ranged from zero (no melting caused) to 12.7 mL brine created/mL of deicer brine applied and were generally found to be strongly associated with temperature.

Factors other than ice melt capacity were also identified that influence deicer effectiveness. These factors were indicated to investigators during eleven meetings or presentations by MnDOT Maintenance and Operations staff plus municipal, county, and vendor personnel. Factors such as road surface characteristics, traffic characteristics, weather conditions, sun level and/or presence, wind and pavement type and age were considered important but not appropriate for the previous laboratory study, and were, therefore, recommended for subjective inclusion in the cost model.

The objective of this study is to evaluate winter maintenance efforts, including applications of deicers and anti-icers and plowing, in parallel conditions on actual pavements to assess intuitions based on observations and anecdotal evidence. Parallel conditions take away the issue of test sections being in slightly different geographies. Three different aspects were evaluated in this effort:

- Deicer effectiveness, techniques and materials evaluated at two proximal facilities across parallel treatment lanes of up to 1,000 feet in length;

- Plow effectiveness, techniques and equipment evaluated at the same locations as the deicer effectiveness evaluation; and,
- Anti-icer persistence, measured in response to both: actual traffic through drainage off defined roadway sections of an elevated highway; and precipitation through drainage off asphalt and Portland cement concrete pavements in a laboratory setting.

Each effort contributes to identification of best practices for winter maintenance. Whether MnDOT, city or county personnel, or private contractor, winter deicing is a high-intensity, high-cost effort that can surely use greater characterization of performance benefits of available deicer and anti-icer products for use in predicting efforts required for expected driver level of service.

This study continues the work begun under MnDOT Agreement 02829, in which work was conducted by the principal investigator during the winter of 2013-14 to characterize and test the factors influencing deicer and plow effectiveness using an outdoor pavement facility with nine 1000-ft-long lanes for treatment areas, separated to prevent incidental cross-treatment, located in Shakopee, Minnesota, at two proximal locations (Druschel, 2014). This study further refines the evaluations done in the previous work, focusing on interrelationships between factors and testing the effects in a wider range of conditions.

1.1 HISTORY OF ROADWAY DEICING

Clearing snow from roadways is an effort as old as roadways themselves, at least in cold climates. Truck mounted plows came into wide use by the 1920s. Abrasives such as sand, coal bottom ash or clinker were used to increase friction on icy roadways, once plowed. During the winter of 1941-42, New Hampshire became the first state to establish a systematic use of salt for deicing (TRB Special Report 235, 1991). About 1 million tons per year of salt were used for deicing in 1950; by 1970, 10 million tons per year were being used, an amount that has remained consistent though adjusted by winter-to-winter variation (USGS, 2014). The rapid increase of salt usage from 1950-1970 coincides with the rise of driver expectation for bare pavements during winter conditions, excepting storm events (TRB Special Report 235, 1991).

Distribution of deicer on roadways has progressed from basic to quite advanced techniques as noted below (TRB Special Report 235, 1991, and author observation):

- 1940s: stationing of a shoveler in the back of a dump truck;
- 1950s: installation of a spinner plate below gravity fed chute for full roadway broadcast;
- 1970s: distribution through a smaller spinner plate or line drop onto high side of travel lane, to encourage undercutting of ice through brine drainage;
- 1980s: incorporation of pre-wetting treatment on to granular deicer to improve roadway adherence and resistance to bounce or blow off;
- 1990s: introduction of pre-storm chemical treatment of pavements to anti-ice;

- 2000s: matching deicer spreading technologies with “smart vehicle” techniques such as maintenance decision support system (MDSS), automated vehicle location (AVL) and road weather information systems (RWIS); and,
- 2010s: introduction of brine blending systems and multi-component liquid chemical systems.

Deicing material selection has been a consideration constant since the introduction of deicing as a technique, as cost-benefit analyses have accompanied the use of rock salt (bulk mined sodium chloride), solar salt (evaporated remains of solution mined or sea water originated salt), magnesium chloride, calcium chloride, acetates, alcohols, carbohydrates and any other product available in bulk that can reduce the freeze point of water.

1.2 PREVIOUS STUDIES OF DEICING AND ANTI-ICING PERFORMANCE

Description of previous studies taken from the report of MnDOT Agreement 02829, (Druschel, 2014):

> Evaluations of deicing and anti-icing performance occur with every winter storm event, with every driver on a given roadway affected by snow or ice. Given the difficulty of driving in winter conditions, it is no wonder this anecdotal evaluation occurs. However, formal studies of performance in the technical literature are few, particularly studies with evaluations of factors rather than comparisons of procedures.
>
> Chollar (1988) summarizes field studies done during the winter of 1986 – 87 comparing the performance of calcium magnesium acetate (CMA) and rock salt at four locations: Wisconsin, Massachusetts, Ontario and California. CMA was found to deice slower than rock salt although eventually reached a similar performance level. CMA was also found to have roadway distribution and persistence issues caused by lower-density particles: (1) particles would spread farther than rock salt (ending off the vehicle lane); and (2) were more susceptible to wind erosion from the roadway. Operational issues were also identified with CMA, including distributor clogging due to material softening with moisture absorbance and increased adherence to vehicle windshields.
>
> Sypher:Mueller (1988) describe field trials of CMA and sodium formate (NaFo) against the performance of sodium chloride done during the winter of 1987 – 88 in Ottawa, Ontario. The purpose of this study was to assess deicer alternatives that were associated with lower environmental, vegetation and corrosion damage than with sodium chloride. Test sections were designated for the application treatments plus a no-application control using two parallel roadways: a two-lane, low-volume, low-speed city road; and a four-lane, high-volume, moderate-speed regional road (traffic amounts were not provided). This study was the first to use friction testing as a measure of deicer performance. Slower melt times for both alternative deicers and higher application rate needed for equivalent performance of CMA were noted. Cost increases of 33 and 13 times the cost of sodium chloride were noted for CMA and NaFo, respectively.

Raukola et al. (1993) described an anti-icing program evaluation in Finland that used a residual chloride measurement to assess anti-icing persistence on pavement in a medium-duty roadway with 6,100 average daily traffic. Anti-icing was applied in liquid form only for this study. Decreases in surface chloride concentration were found to be associated with roadway moisture most of all. Other factors positively correlated to a decline in surface chloride concentration included traffic, initial application amount, and applicator speed. No difference in the pattern of persistence was noted between sodium chloride and calcium chloride.

Manning and Perchanok (1993) evaluated the use of CMA at two locations in Ontario using a comparison with rock salt for performance measures. The two locations differed greatly in temperature, precipitation and traffic conditions. Four different winter periods were used from 1986 – 87 to 1990 – 91. With heavy traffic and light snow, CMA was generally equivalent to rock salt, although 20 – 70% more CMA was applied in an attempt to match the ionic characteristics of rock salt. Both light-traffic and heavy-snow conditions caused decreases in performance of CMA relative to rock salt.

Stotterud and Reitan (1993) discussed the findings of an anti-icing evaluation in Norway that considered weather factors on ice prevention. Performance was assessed by friction measurements. Anti-icing was negatively affected by snow intensity, lower temperatures and the occurrence of freezing rain. Duration (persistence) of anti-icing materials was found to be reduced by increases in traffic or surface moisture, either as frost or drizzle. Persistence could be as long as 2 or 3 days on the tested roadway if low temperatures and low humidity occurred prior to the storm event. Pavement type and age were discussed as factors in performance, but no clear trend was identified and only differences were discussed.

Woodham (1994) describes a testing program that used a single storm event in 1991 with twelve roadway sections of 0.1 mile each in a single community in Colorado. Four different material preparations were evaluated: (1) magnesium chloride and sand; (2) calcium chloride and sand; (3) sodium chloride (rock salt) and sand; and (4) magnesium chloride, sodium chloride and sand. Salt of any type was limited to 80 pounds per lane mile due to societal constraints. Sand component amount was varied in the blends, as an objective of the study was to find a lower amount of sand in a blend that would achieve expected performance or better. Prewetting was also evaluated and found to greatly improve deicing time. Magnesium chloride – sand and sodium chloride – sand mixtures were found to perform best.

Blackburn et al. (1994) presented a large and comprehensive study of anti-icing, consisting of liquid, solid and prewet solid anti-icing materials and techniques tested at fourteen locations in nine states (CA, CO, MD, MN, MO, NV, NY, OH and WA) during the winters of 1991 – 92 and 1992 – 93. Materials and techniques were tested against control sections where conventional snow and ice control practices of the particular state were used. Friction testing and chloride residual testing were used for performance measurement, and results were presented along with weather, pavement condition and air temperature records. State departments of transportation were the testing agencies, and training materials were developed within the study for anti-icing techniques, testing methods and quality control procedures. Difficulties encountered included the lack of equipment available for prewetting, equipment targeted for the low treatment levels associated with anti-icing, and a lack of vendor testing of operational characteristics of spreading equipment.

Findings of Blackburn et al. (1994) included a mixed outcome about the reduction of overall salt use, as some locations experienced increases in salt use and some locations first decreased then increased salt use. Salt use outcome variations were attributed to the contrasts of winter storm patterns between the two years. Overall, anti-icing at 100 pounds per lane mile with liquid or prewetted solid was found to greatly improve roadway operation during winter conditions when temperatures were above 20° F; dry solids were found to have persistence on the roadway inadequate for effective anti-icing due to blow off or traffic effects. Prewet rates of 5 – 6 gal/ton and 10 – 12 gal/ton were found minimal but effective for prewetting on the spinner and in the truck bed, respectively, although recommendation was given to increase the rate by 50% for greater effectiveness and reliability of method. Magnesium chloride was evaluated and found to be an effective anti-icing material as a liquid or prewet on sodium chloride. Anti-icing techniques were found to be ineffective or even detrimental if used during freezing rain or drizzle events, or on compacted snow.

Blackburn et al. (1993) presented preliminary observations of techniques and the overall program later presented Blackburn, et al. (1994).

Ketcham et al. (1998) produced a follow-on study to Blackburn, et al. (1994) using eight of the sites previously studied and adding eight new sites. Fifteen states were involved in the study (IA, KS, MA, NH, OR and WI were added), although results were only reported from twelve sites in eleven states addressing average daily traffic of 3000 – 40,000 vehicles. The goal of this study, similar to the previous study, was to evaluate new techniques of anti-icing in comparison with conventional practices of the particular state, with the objective to further encourage development and implementation of the new anti-icing practices. As before, performance was measured with friction tests and pavement observations, while perceptions of passenger vehicle handling after treatment was added. Results were graphed across the storm times then evaluated with statistical evaluations of friction values by pavement conditions and treatment approach (either conventional or anti-icing based). Two to fourteen storms per year were evaluated for each site. A wide range of treatment materials were evaluated including rock salt, fine salt, calcium chloride, magnesium chloride, potassium acetate, and abrasives.

In the study by Ketcham et al. (1998), friction was found to be reduced by lower air temperatures (greatest effect), higher precipitation rates and decreasing traffic volume (least effect). Snowfall intensity was also identified, as packed snow was observed to occur after an upturn in intensity, although the results were not quantified. Friction was consistently worse with “snow” conditions than with “light snow” conditions. Cost analyses of five highway sections were inconclusive, as anti-icing techniques resulted in both lower and higher costs. Reasons for the costs to increase included higher-priced chemicals being used, test operations not being completely typical, and anti-icing not being "tuned" to achieve the full potential of ice prevention and removal. Additionally, clean up of abrasives (when used) was identified as a significant cost.

Anti-icing performance factors identified by Ketcham et al. (1998) as needing further evaluation included:

- Lower levels of service being incorporated as a flexible storm response;
- Rural versus urban roadway treatments;
- Abrasives as a complementary strategy to anti-icing;
- The effective application of solids and prewet solids for anti-icing;
- Persistence of anti-icing treatments between storms;
- The optimum timing of anti-icing treatments ahead of storms;
- Interaction of anti-icing with open graded pavement courses; and,
- Effective anti-icing techniques for freezing rain conditions.

Highway Innovative Technology Evaluation Center (1999) presents an evaluation of applications and techniques using Ice Ban Magic liquid deicer product. Seven state highway agencies (AK, CO, IN, NE, NY, WA and WI) and one county were involved. Performance advantages were observed in comparison to magnesium chloride at low temperatures and with residual material lasting from one storm to the next. Advantages over sodium chloride brine were also observed when used as either a prewet or stockpile treatment. However, Ice Ban was found to be particularly susceptible to occurrences of refreeze and freezing rain, in that lower effectiveness than traditional materials was observed under these conditions.

Two laboratory studies have particular applicability to this project. Trost et al. (1987) described deicing as fundamentally controlled by undercutting, allowing traffic to break up delaminated ice. Undercutting was further described as a two-phased behavior, first being controlled by ice melt capacity in a thermodynamic process and second being controlled by diffusion and density gradients in a kinetic process. Shi et al. (2013) connected this two-phase behavior to observations of time being a highly significant factor in roadway ice melting: Melting occurred within 30 minutes of application for magnesium chloride and calcium chloride but within 60 minutes for sodium chloride.

Recent work by Blomqvist et al. (2011) showed that anti-icing and deicing operations could be negatively affected by the roadway wetness as traffic removes salt through splash and spray as well as run off:

> "Road surface wetness, as shown from the wheel tracks, related positively to the rate of residual salt loss. The wetter the surface, the faster the salt left the wheel tracks. On a

wet road surface, the salt in the wheel tracks was almost gone after only a couple of hundred vehicles had traveled across the surface, whereas on a moist road surface, it would take a couple of thousand vehicles to reach the same result."

Blomqvist et al. (2011) suggests that, while road wetness has a significant impact, it is first and foremost traffic that appears to reduce deicer persistence. This finding matches the conclusions of Raukola et al. (1993) and Stotterud and Reitan (1993), noted previously. However, this finding appears different than the finding noted by Ketcham et al. (1998) that decreasing traffic reduces friction; in essence, that traffic is helpful to anti-icing. It may be these two findings are describing two different behaviors within anti-icing:

- Vehicle as breaker of ice, perhaps by dislodging undercut ice; and,
- Vehicle as remover of salt chemical, perhaps by mobilizing salt water spray or splash.

Publications that apply specifically to the work in this project and the factors studied in this phase of research have also been identified.

Muthumani et al. (2014) explored the differences between lab and field tests for evaluation of deicing and anti-icing chemicals, and suggested approaches for reducing the discrepancies in test conditions to improve the applicability for actual traffic conditions.

Wahlin and Klein-Paste (2015) evaluated the effects of deicing chemicals on the hardness of compacted snow and whether deicers cause an increase in snow compaction bonded to the pavement. The experiments of that study showed that increasing deicer concentration caused softer snow, and that there were modest but statistically significant differences between different deicers. The softer snow was a result of bond weakening within the snow structure, similar to what happens during the physical change of snow structure with increasing temperature around the melt point. No connection was demonstrated, only theorized, about roadway pavement snow compaction, such as with a continued snowfall after deicer treatment.

Dur and Evrensel (2015) studied the wake flow around moving snow plow vehicles using computation modelling and found that deflectors and airfoils had a significant effect in the control of clouding and debris splash around the plow. Implementation of airfoils could help keep clean the warning lights on the back of a plow vehicle. No actual tests were done though, and only theoretical characteristics of snow were considered.

Several studies have been conducted with the goal of plow route optimization, some taking advantage of temperature modeling and real-time weather measurement, either fixed-location or vehicle mounted.

- Salazar-Aguilar et al. (2012) evaluated synchronized routing of plow vehicles, such that multiple lane highways would be efficiently incorporated into a winter maintenance model. Chien et al. (2014) also looked at this question.

- Arvidsson (2017) considered the costs related to road condition, accident risk, fuel consumption, environmental consequences and other socio-economic effects as a way to improve the quantification of costs and benefits for snow clearing efforts.
- Dussault et al. (2013) evaluated the optimum plow route organization, incorporating the benefit of previously cleared roads for plow vehicle transit to areas of operation.
- Perrier et al. in four separate publications constructed models of winter maintenance optimization involving plow routes (Perrier et al. 2006a), snow disposal locations (Perrier et al. 2006b), depot locations (Perrier et al. 2007a) and fleet sizing (Perrier et al. 2007b).
- Crow et al. (2016) developed a cost-benefit analysis for incremental equipment acquisition, specifically looking at specialty equipment with unique snow clearing or treatment capabilities.
- Nordin and Arvidsson (2014) evaluated the change to energy costs of traffic caused by varying levels of winter maintenance and weather conditions. This work pointed at the importance of the threshold weather level for initiation of snow clearing efforts for determination of the energy costs.
- Testeshev and Timohovetz (2017) provided an assessment of benefits effected by travel speed management for traffic in winter snow conditions.
- Optimization of deicer efforts by weather conditions is considered by Kramberger and Zerovnik (2008).

Trenouth et al. (2015) developed a road salt application planning tool for winter deicing operations using models for snow depletion, plowing, salt-induced melting, and salt wash off. The planning tool was assessed at three field sites using the concept of “bare pavement regain time” plus various chloride and flow measurement instruments placed in drainage structures.

Barros et al. (2013) considered the airborne transportation of contaminants and debris from roadways, attempting to define a safe distance for protection of human health. Roadway deicers were not specifically mentioned or addressed, but the geometry of the dispersion was defined for two other materials. Similarly, Zhu et al. (2012) considered dispersion away from roadways but specifically considered dust without definition of chemical constituency related to seasonality.

Pavements with additives or aggregates that can enhance or even cause deicing are evaluated in several publications, including: Gomis et al. (2015); Li et al. (2013); Luo et al. (2015); Wang et al. (2016); and Zhao (2011). Pavement degradation caused by deicers is evaluated in Goh et al. (2011) and Opara et al. (2016).

CHAPTER 2: DEICER EFFECTIVENESS STUDY

Work conducted by the Principal Investigator previously under MnDOT Agreement 96319 evaluated the ice melt capacity and field performance factors of deicers and deicer blends, and developed a temperature-based cost model for comparison of relative field performance through the evaluated deicers and deicer blends (Druschel, 2012). Over 50 deicer and anti-icer compounds/compound blends were evaluated for ice melt capacity in over 1400 determinations, at temperatures ranging from 30° F down to -30° F. Values of ice melt capacity observed in this study ranged from zero (no melting caused) to 12.7 mL brine created / mL of deicer brine applied, and were generally found to be strongly associated with temperature.

Of great importance were factors other than ice melt capacity that influence roadway clearing and deicer effectiveness. These factors were indicated to investigators during eleven meetings or presentations by MnDOT Maintenance and Operations staff plus municipal, county, and vendor personnel. Factors such as road surface characteristics, traffic characteristics, weather conditions, sun level/presence, wind and pavement type and age were considered important but not appropriate for the previous laboratory study, and were, therefore, recommended for subjective inclusion in the cost model.

Under MnDOT Agreement 02829, work was conducted by the Principal Investigator during the winter of 2013-14 to characterize and test the factors influencing deicer and plow effectiveness using an outdoor pavement facility with nine 1000-ft long lanes for treatment areas, separated to prevent incidental cross-treatment, located in Shakopee, Minnesota, at two proximal locations (Druschel, 2014). The treatment area length was set to provide sufficient room for normal highway operating speeds of plow trucks with deicer distribution. Time-lapse cameras were placed sufficiently close to treatment areas to observe and document post-plow pavement in high definition. Evaluations of deicing effectiveness were made considering the following factors:

- Time and temperature;
- Snow structure;
- Deicer application rate;
- Traffic, both car and truck;
- Prewetting deicer at point of distribution; and,
- Wind and sun or overcast.

In this current effort, the previous work was continued and expanded, particularly evaluating effects of traffic, prewet and weather conditions of sun or overcast. Two facilities were set up in Shakopee, Minnesota, at proximal locations. At the first facility, nine 900-ft long lanes were set up for treatment using plow truck distribution of deicers at highway speeds. The second facility was set up using four 500-ft long lanes, each lane segmented into five 100-ft long sections for hand distribution of deicers, allowing greater concurrent factor evaluation.

Because the winters of 2015-16 and 2016-17 were mild and with low amounts of snow, additional evaluations were made of hand-applied deicers on compacted snow, with observations made by photography and thermography (infrared photographs).

2.1 TEST METHOD

2.1.1 Method Design

For this evaluation of plow effectiveness and contributing factors, pavement lanes were set up and defined where plowing could be done without actual traffic such that experimental approaches could be tried out and compared without potential for compromising public safety. Two facilities were set up, one sufficiently long such that plow trucks could reach and maintain highway speeds of approximately 30 mph during deicer distribution, the second sufficiently subdivided to allow greater concurrent factor evaluation. Time-lapse and hand held camera photographs plus infrared thermography were used to augment observation notes and to document the effectiveness of deicing techniques for the different snow, sun and temperature conditions.

Deicing effectiveness was evaluated by factors including: temperature, time, truck traffic, car traffic, prewet, coloration, and chloride content. Evaluations were done on after snows but on non-storm days to closely model actual efforts without significantly diverting equipment necessary for actual road maintenance during storms.

2.1.2 Field Sites

Shakopee was targeted for project field sites to provide locations accessible both to researchers from Minnesota State, Mankato and maintenance personnel of MnDOT Metro District, with potential for additional access by maintenance personnel of other nearby MnDOT Districts or volunteer municipal or county departments of public works. Pavement lanes were set up in Shakopee at two locations with large parking lots not typically used during winter months:

- Canterbury Park, 1100 Canterbury Road; in the stable area parking lot on the south side of the facility, adjacent to 12th Avenue East and 0.3 mile west of Canterbury Road South.
- ValleyFair!, One Valley Fair Drive; in the back (north) parking lot on the north east corner of the facility, located north of TH 101 about 2.5 miles west of US 169.

Figure 1 Test areas: Canterbury Park (top) and ValleyFair! (bottom).

Access agreements were negotiated and agreed upon during early November, 2015. Prior to a lasting snowfall each year, researchers with support from MnDOT Metro District maintenance staff performed pavement surveys to locate and document surface discontinuities that could either interfere with or be damaged by plowing. Test lanes were configured to avoid such discontinuities. Lane marking was done with pin flags of various colors; colors were assigned to designate the sides of individual lanes. Pin flags were anchored through 6 in x 3 in x 2 in “sewer” (hollow core) bricks to 8 in x 8 in x ¾ in wooden plates and stabilized by 1 ft lengths of ¾ in diameter Schedule 40 PVC pipe. Anchoring was done to prevent penetration of the pavement by the flags yet maintain the flags in spite of winter winds.

2.1.3 Weather Measurement

A Kestrel 4000 handheld weather station (Nielsen-Kellerman, Boothwyn, PA), capable of determining temperature, relative humidity, dew point and wind speed, was used to determine conditions during field operations (Figure 2a). A dial thermometer (Figure 2b) was used for illustration and photographic documentation, but was not considered sufficiently accurate to represent field conditions. Weather measurements were primarily made using National Weather Service data obtained from Flying Cloud Airport, Eden Prairie, Minnesota, approximately 2 miles north of either field site (documentation during 2015-16 was from a paid subscription to WeatherSpark.com).

Figure 2 Weather monitoring tools: handheld weather station; dial thermometer.

2.1.4 Cameras and Photography

Field conditions were documented through photography using two different camera systems. Handheld, high resolution photographs were taken using a Nikon D3000 camera with a 70-300 mm telephoto lens from an elevated platform (Nikon Corporation, Tokyo, Japan). Time-lapse photographs were taken using Bushnell 6MP Trophy Cam game cameras (Bushnell Outdoor Products, Overland Park, KS) operating in time-lapse mode. Time-lapse cameras were pole mounted at approximately a 6-ft height, with poles attached to concrete block bases.

At the ValleyFair! site, time-lapse cameras were installed at lane stations 1+00 (facing down lane) and 8+00 (facing oncoming trucks) for each lane, meaning 100 ft from the start of the lane. At the Canterbury Park site, time lapse cameras were installed at each of five, 100-foot increments, facing down lane. Time increments of 1 minute were typically used. Date and time stamps were made on time-lapse photographs, though battery jostles could cause time stamps to revert to a factory start date (circa 2014). All photographs had file origination information that could provide time of capture for verification, if needed.

2.1.5 Infrared Camera and Thermography

Infrared camera thermographs were used to analyze the rate and distribution of deicer activity. Pavement temperatures were also evaluated with thermographs, particularly assessing variations across recently plowed and treated lanes. The infrared camera was a hand held FLIR E6 with a 160 x 120 infrared resolution and a concurrent photographic (visual image) camera (FLIR Systems, Wilsonville, OR). The temperature imagery of the FLIR camera provides a colorized scale from the warmest (yellow or white) temperatures to the coldest (purple or black) temperatures, with a center point temperature determination shown (Figure 3).

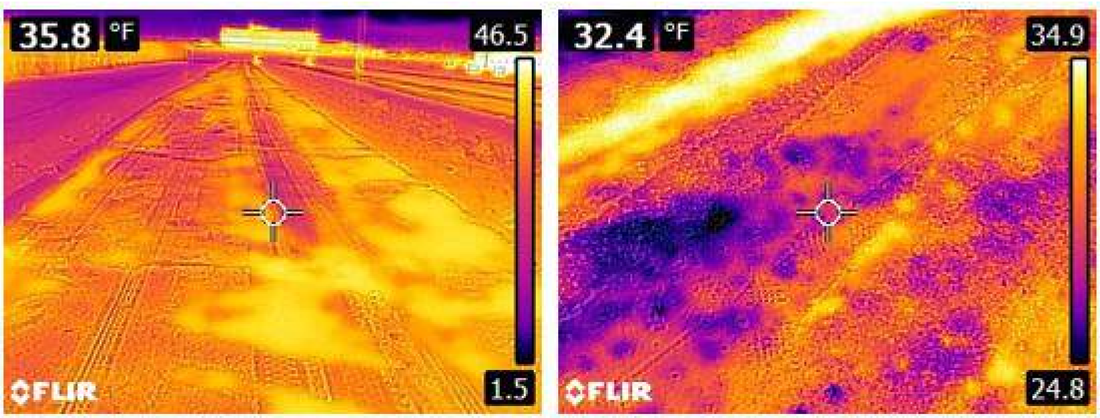


Figure 3 FLIR infrared thermographs: plowed lane (left); and deicer close up (right).

In thermographs, deicer action is typically seen initially as intense cold spots, as the deicer compound undergoes ionic separation (e.g., rock salt NaCl becomes dissolved Na^+ and Cl^- ions). It is the increase in ionic concentration of the water that causes freeze point lowering and subsequent snow and ice melting.

2.1.6 Plow and Deicer Spreading Operations

Highway speed deicer spreading (distribution) was done by maintenance personnel from MnDOT Metro District using equipment from the Chaska Truck Station. Snow plowing was done ahead of deicing, though whether plowing was done concurrent with the deicer distribution or as a separate truck operation was determined by the conditions of a particular experiment.

Typical highway speed distribution equipment was a 2006 Sterling tandem axle, automatic transmission dump truck with front, right wing and underbody plows (Figure 4a). Side mounted (saddle) tanks were used to carry brine materials used for prewetting granular deicer (Figure 4b). A transverse auger was mounted in the rear of the dump body to feed deicer either to the left or right chute. Granular deicer was maintained in contact with the auger by frequent plow body raising such that the granular deicer would shift to the back of the plow body where the auger was located. Deicer would fall through the chute to a distributor (spinner) plate (Figure 4c). Prewet was poured via gravity onto the granular deicer when on the distributor plate (Figure 4d). The distributor plate rotated when the truck was in forward motion, spreading deicer rather than having a straight drop (Figure 5). Note that Metro District deicer application equipment on board trucks was calibrated at the start of the 2015-16 season, according to the maintenance staff.

a) MnDOT tandem axle dump truck with front and right wing plows engaged.

b) MnDOT truck with saddle tanks for prewet fluid.

c) Salt distributor behind left rear wheel (not in motion/not being fed deicer at time of photo).

d) Prewet flow and deicer drop onto salt distributor (in motion at time of photo).

Figure 4 Plow and deicer equipment on a MnDOT truck used for this study.

Figure 5 MnDOT truck spreading deicer off left rear while moving forward on a lane where plowing was done previously by another truck.

Hand application of deicers was done by a researcher on foot shaking out deicer over a premeasured and marked area, either a 53 ft lane length (i.e., 1% of a lane mile) or a 5 ft long compacted wheel track (Figure 6). For the full lane width treatment, distribution was through a plastic shaker with a wide top that had holes in it. For the compacted wheel track, distribution was out of a small polyethylene bag. Premeasured amounts of deicer, massed in the laboratory and brought to the test facility in a polyethylene bag, were treated with a measured amount of a prewet (if needed) just prior to distribution (Figure 7).

Figure 6 Distribution of deicer on marked areas: full lane width treatment (top); and compacted wheel track treatment (bottom).

Figure 7 Application of prewet to premeasured amount of deicer: full lane width treatment using a 500 mL bottle as container of premeasured prewet (top); and compacted wheel track treatment using a 3 mL disposable syringe to field-measured the amount of prewet

2.2 RESULTS

Field activities related to deicing evaluation are listed in Tables 1 and 2, by date and weather conditions, for Winter 2015-16 and Winter 2016-17, respectively. Individual lane treatments for highway speed distribution analyses are described in the following tables:

- Table 3: 1/5/2016
- Table 4: 2/5/2016
- Table 5: Hand application (full lane width) of 2/11/2016
- Table 6: 1/19/2017
- Table 7: 1/26/2017

Note that additional field activities occurred on 12/12/2016, but no deicing was done, only plowing. Treatments for thermographic analysis by hand application of deicers and prewets are listed in Table 8 for all dates of testing and analysis.

Documentation of weather conditions was obtained from the National Weather Service station at the Flying Cloud Airport, Eden Prairie, Minnesota, approximately 2 miles north of either site. Data was interpreted using the WeatherSpark.com web service, in a paid subscription. Graphical representations of the weather at different time scales are provided in Appendix A for: the whole testing season from late December to mid March; for the months of December, January and February (when applicable); and for each day of field activities. Results are given for both the 2015-16 and 2016-17 test seasons.

Time-lapse photographs of each lane during plowing and deicing activities for highway speed distribution analyses plus hand application (full lane width) analyses are provided in summary form in Appendix B for activities of Winter 2015-16 and Appendix C for activities of Winter 2016-17. Time-lapse photographs are provided for times prior to plowing, immediately after plowing, then 10, 20, 30 and 60 minutes after plowing. Where noted, “camera malfunction” typically represents a camera that did not withstand the snow thrown by the passing plow; photographs of the lane were therefore not obtained until the camera was picked up and repositioned.

Thermographs and photographs of each deicer solid and prewet treatment combination, as analyzed during deicing by hand application, are provided in summary form by date of testing in Appendix D. Photographs and thermographs are provided for 20, 50 and 80 minutes after application for warmer testing days of 1/14/2016 and 1/31/2016, and 20 and 120 minutes after application for the colder testing day of 1/12/2016.

Table 1 Deicing activities by date and weather conditions for Winter 2015-16 activities.

Date	Weather	Deicing Activities
1/05/2016 ValleyFair! Highway speed application	28°F, clear and sunny dew point 18°F wind 15-20 mph	Initial cutting of lanes. 600#/LM rock salt; 15 gal/ton RG8 10% prewet; car traffic/truck traffic/no traffic
1/12/2016 Canterbury Park Hand application	5°F, clear and sunny dew point -10°F wind 8-12 mph	Thermographic evaluation of deicer activity on compacted snow as influenced by chloride content, coloration, and prewet
1/14/2016 Canterbury Park Hand application	30°F, overcast dew point 17°F wind 8-12 mph	Thermographic evaluation of deicer activity on compacted snow *Repeat of 1/12/2016 but warmer and without solar influence*
1/31/2016 Canterbury Park Hand application	39°F, overcast dew point 29°F wind 5-8 mph	Thermographic evaluation of deicer activity *Repeat of 1/12/2016 but even warmer*
2/5/2016 ValleyFair! Highway speed application	22°F, clear and sunny dew point 15°F wind 12-15 mph	600#/LM rock salt; 15 gal/ton RG8 10% prewet; car traffic/truck traffic/no traffic *Repeat of 1/5/2016 with colder temperatures*
2/11/2016 Canterbury Park Hand application	11°F, clear and sunny dew point -2°F wind 8-12 mph	600#/LM deicers; prewet/no prewet; car traffic/no traffic Five different solid deicers
Note: There was insufficient snow cover before 12/24/2015 by which to plow and deice; there was insufficient cold as of 2/11/2016 to maintain snow cover until MnDOT plow and deicing trucks were available. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 2 Deicing activities by date and weather conditions for Winter 2016-17 activities.

Date	Weather	Deicing Activities
12/12/2016 ValleyFair! Highway speed plowing	5°F, clear to light overcast dew point -3°F wind 3-5 mph	Initial cutting of lanes. Plowing only; no deicer application as temperatures too low.
1/19/2017 ValleyFair! Highway speed application	35°F, clear and sunny dew point 32°F wind 5-8 mph	400#/LM rock salt; no prewet; car traffic/truck traffic/no traffic; evaluation of traffic timing/delay effects.
1/19/2017 Canterbury Park Deicer application	35°F, clear and sunny dew point 32°F wind 5-8 mph	400#/LM rock salt; no prewet; truck traffic/no traffic; evaluation of traffic timing/delay effects.
1/26/2017 ValleyFair! Highway speed application	25°F, overcast dew point 19°F wind 8-12 mph	400#/LM rock salt; 15 gal/ton of 10% RG8 prewet; car traffic/truck traffic/no traffic; evaluation of traffic and prewet interaction effects.
1/26/2017 Canterbury Park Deicer application	25°F, overcast dew point 19°F wind 8-12 mph	400#/LM rock salt; 15 gal/ton of 10% RG8 prewet; truck traffic/no traffic; evaluation of traffic, timing, and prewet interaction effects.
Note: There was insufficient snow cover before 12/12/2016 by which to plow and deice; there was insufficient cold as of 2/16/2017 to maintain frost in the pavement subgrades and ensure support for plowing activities. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 3 Deicing activities by lane for 1/05/2016; 28°F, clear and sunny, dew point 18°F, wind 15-20 mph.

Lane	Deicer, Rate & Prewet Condition	Traffic Condition
VF1	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 3 passes beginning within 5 minutes after deicer application
VF2	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 3 passes beginning within 5 minutes after deicer application
VF3	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 10 passes beginning within 5 minutes after deicer application
VF4	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 10 passes beginning within 5 minutes after deicer application
VF5	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	No traffic
VF6	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 5 passes beginning within 5 minutes after deicer application
VF7	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 5 passes beginning within 5 minutes after deicer application
VF8	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 1 pass beginning within 5 minutes after deicer application
VF9	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 1 pass beginning within 5 minutes after deicer application
Notes: VF denotes a lane at Valleyfair!. Lanes are numbered from north to south. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 4 Deicing activities by lane for 2/05/2016; 22°F, clear and sunny, dew point 15°F, wind 12-15 mph.

Lane	Deicer, Rate & Prewet Condition	Traffic Condition
VF1	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 3 passes beginning within 5 minutes after deicer application
VF2	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 3 passes beginning within 5 minutes after deicer application
VF3	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 10 passes beginning within 5 minutes after deicer application
VF4	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 10 passes beginning within 5 minutes after deicer application
VF5	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	No traffic
VF6	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 5 passes beginning within 5 minutes after deicer application
VF7	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 5 passes beginning within 5 minutes after deicer application
VF8	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Truck, 1 pass beginning within 5 minutes after deicer application
VF9	Rock Salt, 600#/LM RG8 10% prewet, 15 gal/ton	Car, 1 pass beginning within 5 minutes after deicer application
Notes: VF denotes a lane at Valleyfair!. Lanes are numbered from north to south. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 5 Deicing activities by lane and subsection for 2/11/2016; 11°F, clear and sunny, dew point -2°F, wind 8-12 mph.

Lane	Section (100 ft length)	Deicer	Prewet	Traffic Condition
CP1 (Inside line, SE to NW direction)	A	Rock Salt	RG8 10% prewet, 15 gal/ton	No traffic
	B	Magnesium Chloride		
	C	Calcium Chloride		
	D	Ice Slicer		
	E	Ice Melter		
CP2 (Inside line, NW to SE direction)	A	Ice Melter	No prewet	No traffic
	B	Ice Slicer		
	C	Calcium Chloride		
	D	Magnesium Chloride		
	E	Rock Salt		
CP3 (Outside line, SE to NW direction)	A	Rock Salt	RG8 10% prewet, 15 gal/ton	Car, 5 passes beginning within 30 minutes after deicer application
	B	Magnesium Chloride		
	C	Calcium Chloride		
	D	Ice Slicer		

	E	Ice Melter		
CP4 (Outside line, NW to SE direction)	A	Ice Melter	No prewet	Car, 5 passes beginning within 30 minutes after deicer application
	B	Ice Slicer		
	C	Calcium Chloride		
	D	Magnesium Chloride		
	E	Rock Salt		
Notes: CP denotes a lane at Canterbury Park. Prewet listed as RG8 10% is also salt brine 90%, and was applied and mixed just prior to application by hand shaker.				

Table 6 Deicing activities by lane for 1/19/2017; 35°F, clear and sunny, dew point 32°F, wind 5-8 mph.

Lane	Deicer, Rate & Prewet Condition	Traffic Condition
VF1	Rock Salt, 400#/LM No prewet	No traffic
VF2	Rock Salt, 400#/LM No prewet	Car, 5 passes with no delay after deicer application
VF3	Rock Salt, 400#/LM No prewet	Car, 5 passes delayed 20 minutes after deicer application
VF4	Rock Salt, 400#/LM No prewet	Car, 5 passes delayed 40 minutes after deicer application
VF5	Rock Salt, 400#/LM No prewet	No traffic
VF6	Rock Salt, 400#/LM No prewet	Truck, 5 passes with no delay after deicer application
VF7	Rock Salt, 400#/LM No prewet	Truck, 5 passes delayed 20 minutes after deicer application
VF8	Rock Salt, 400#/LM No prewet	Truck, 5 passes delayed 40 minutes after deicer application
VF9	Rock Salt, 400#/LM No prewet	No traffic
CP1	Rock Salt, 400#/LM No prewet	Truck, 5 passes delayed 20 minutes after deicer application
CP2	Rock Salt, 400#/LM No prewet	No traffic

CP3	Rock Salt, 400#/LM No prewet	Truck, 5 passes delayed 40 minutes after deicer application
CP4	Rock Salt, 400#/LM No prewet	Truck, 5 passes with no delay after deicer application
Notes: VF denotes a lane at Valleyfair!. CP denotes a lane at Canterbury Park. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 7 Deicing activities by lane for 1/26/2017; 25°F, overcast, dew point 19°F, wind 8-12 mph.

Lane	Deicer, Rate & Prewet Condition	Traffic Condition
VF1	Rock Salt, 400#/LM 10% RG8 prewet	Car, 5 passes with no delay after deicer application
VF2	Rock Salt, 400#/LM 10% RG8 prewet	No traffic
VF3	Rock Salt, 400#/LM 10% RG8 prewet	Car, 5 passes delayed 20 minutes after deicer application
VF4	No deicer No prewet	Car, 5 passes with no delay after plowing (no deicer application)
VF5	Rock Salt, 400#/LM 10% RG8 prewet	No traffic
VF6	Rock Salt, 400#/LM 10% RG8 prewet	Truck, 5 passes with no delay after deicer application
VF7	Rock Salt, 400#/LM 10% RG8 prewet	No traffic
VF8	Rock Salt, 400#/LM 10% RG8 prewet	Truck, 5 passes delayed 20 minutes after deicer application
VF9	Rock Salt, 400#/LM No prewet	No traffic
CP1	Rock Salt, 400#/LM 10% RG8 prewet	No traffic
CP2	Rock Salt, 400#/LM No prewet	No traffic

CP3	Rock Salt, 400#/LM 10% RG8 prewet	Truck, 5 passes with no delay after deicer application
CP4	Rock Salt, 400#/LM No prewet	Truck, 5 passes with no delay after deicer application
Notes: VF denotes a lane at Valleyfair!. CP denotes a lane at Canterbury Park. Prewet listed as RG8 10% is also salt brine 90%, and is applied at point of distribution off the plow truck.		

Table 8 Solids and prewet conditions included during thermographic and photographic analyses of deicing on compacted snow wheel tracks.

Solid	Prewet[1, 2]	Date		
		1/12/2016[3]	1/14/2016[4]	1/31/2016[5]
Rock Salt	Salt Brine	X	X	X
	Apex	X	X	X
	Freezegard	X	X	X
	RG8 10% Salt Brine 90%	X	X	X
	Molasses 1% DI Water 99%	X	X	X
	Molasses 3% DI Water 97%	X	X	X
	Molasses 5% DI Water 95%	X	X	X
	Molasses 10% DI Water 90%	X	X	X
	Orange Dye in DI Water	X	X	X
	Red Dye in DI Water	X	X	X
	Blue Dye in DI Water	X	X	X
	Yellow Dye in DI Water	X	X	X
	None	X	X	X
Sand	Salt Brine	X	X	X
	Apex	X	X	X
	Freezegard	X	X	X
	RG8 10% Salt Brine 90%	X	X	X
	Molasses 1% DI Water 99%	X	X	X

	Molasses 3% DI Water 97%	X	X	X
	Molasses 5% DI Water 95%	X	X	X
	Molasses 10% DI Water 90%	X	X	X
	Orange Dye in DI Water	X	X	X
	Red Dye in DI Water	X	X	X
	Blue Dye in DI Water	X	X	X
	Yellow Dye in DI Water	X	X	X
	None	X	X	X
Walnut Particles	None	X	X	X
Garnet Sand	None	X	X	X
Black Sand	None	X	X	X
Silt	None	X	X	X
Ice Melter	None	X	X	X
Ice Slicer	None	X	X	X
Magnesium Chloride	None	No	X	X
Calcium Chloride	None	No	X	X

Notes:

[1] All prewets applied at 15 gal/ton and mixed just prior to application by hand shaker.

[2] DI water: deionized water, a product of reverse osmosis treatment.

[3] Weather of 1/12/2016: 5°F, clear and sunny, dew point -10°F, wind 8-12 mph

[4] Weather of 1/14/2016: 30°F, overcast, dew point 17°F, wind 8-12 mph

[5] Weather of 1/31/2016: 39°F, overcast, dew point 29°F, wind 5-8 mph

2.3 EVALUATIONS

The objective of deicing for this project was improvement in open, un-iced pavement, primarily observed as creation then enlargement of the un-iced patches, interpreted to represent improved driving conditions. Evaluation of deicing results was made for selected factors using time-lapse photography of treated lanes, primarily represented by the photographs presented in Appendices B and C, augmented by the thermography and photography presented in Appendix D.

2.3.1 Effect of Temperature

Temperature is a critical factor for deicing, as it controls both the amount of frozen precipitation that can be melted by an ionic freeze point depressant (e.g., rock salt) as well as the melt time. Deicer performance is generally a function of ice melt capacity (Table 9), defined as the amount of ice melted (brine created) per the amount of deicer applied, with units of mL brine created / g of deicer applied for solid form deicers. Ice melt capacity determinations do not consider when melting occurs, only if it occurs by 120 minutes after deicer application; hence it is considered an ultimate melting value. Melt time is also an important factor for deicing, in that a quicker melt will improve roadways sooner. Quicker melt action also results in lesser performance degradation from deicer removal by tire spray, wind blow or surface drainage.

Table 9 Ice melt capacity for rock salt (from Druschel, 2012).

Temperature	Ice Melt Capacity (mL brine created/g deicer applied)
28°F	8
20°F	6
12°F	2
0°F	0

2.3.2 Evaluations of 2015-16 Winter

2.3.2.1 Evaluation 2016-1

Deicing behavior at the test facility was evaluated for temperature and melt time effects by comparing photographs from CD5 of January 5th and February 5th, 28° F and 22° F air temperatures respectively, when 600 pounds per lane mile of rock salt was applied with a prewet of RG8 10% with no traffic

(Appendix B and Table 10). Slight openings of pavement can be seen at 10 minutes after application at both temperatures. Enlargement of the open pavement can be observed occurring at 20 minutes after application in both temperatures, and the wheel lanes under the rock salt distribution point is mostly ice free. By 60 minutes after application, a broad area of the lane is open and exposed, with the warmer (28° F) temperature having a moderately larger open area than the colder (22° F) temperature day, matching the behavior expected with a higher ice melt capacity at the warmer temperature.

Table 10 Comparison of deicing over two times and two temperatures.

Time after deicer application	28°F (1/05/2016)	22°F (2/05/2016)
20 minutes		
60 minutes		
Notes: Deicer application of 600 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution. No traffic application on test lanes shown.		

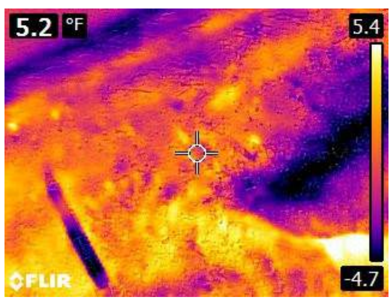
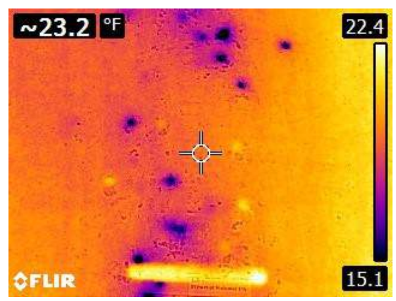
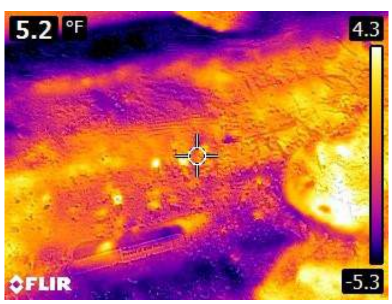
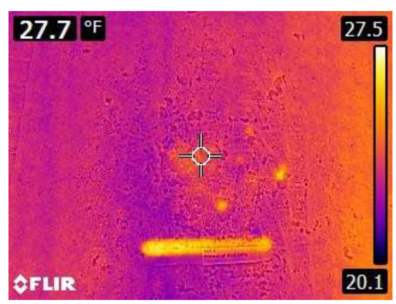
The temperature and melt time behavior of these two applications suggests that the test conditions of the field evaluation are coherent with and sufficiently model laboratory conditions, validating the experimental approach of this work.

2.3.2.2 Evaluation 2016-2

A review of the thermography for rock salt treatment of compacted snow in wheel tracks with no prewet or traffic application supports the conclusion about the validity of the experimental approach

(Table 11). Cold spots show where salt grains are in contact with the compacted snow, as thermal content of the snow pack is taken up for energy to drive the ionic separation as the rock salt dissolves into the water matrix. These cold spots can be seen in the 20-minute thermograph for the 30° F application but not in the 20-minute thermograph for the 5° F application, as the colder temperature is at a point of near zero activity and ice melt capacity for rock salt. Note that the cold spots are dissipated and gone from the 50-minute thermograph of the 30° F application, as the rock salt has been ionically separated either fully (supply of rock salt exhausted) or to the limit of the ice melt capacity (supply of water matrix exhausted; solubility limit achieved) by that time. Also note that the 120-minute thermograph for the 5° F application shows no cold spots, indicating that the temperature is simply below the limit of ionic separation and the associated ice melt, and not just slow to react.

Table 11 Comparison of deicing over two times and two temperatures using thermography.

<table>
<tr><th>Time after deicer application</th><th>5°F in bright sun
(1/12/2016)</th><th>30°F and overcast
(1/14/2016)</th></tr>
<tr><td>20 minutes</td><td>
</td><td>
</td></tr>
<tr><td>120 minutes (left) and 50 minutes (right)</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">Notes: Deicer application of to compacted snow of wheel tire tracks with no prewet or traffic application on test sections shown.</td></tr>
</table>

2.3.2.3 Evaluation 2016-3

Traffic effects were evaluated and quantified in this study after the results of Druschel (2014) indicated that traffic helped quicken and expand the amount of compacted snow melted for a given deicer treatment; the goal herein being to quantify the amount of traffic required to achieve a given level of melt improvement. MnDOT maintenance personnel have reported their anecdotal observations that traffic, particularly truck traffic, could make a substantial improvement in roadway deicing. The hypothesis is that the vehicle pressure creates a closer physical contact between the deicer grain and the ice, particularly if the ice is not fully consolidated, i.e., lightly packed snow. Also, truck traffic might create better deicing because truck tires are often inflated to 90 psi, rather than the 35 psi typical of passenger vehicles, resulting in greater vehicle pressure.

After plowing and deicer application (rock salt at 600 lbs/LM with 15 gal/ton of RG8 10% prewet), car and truck traffic was applied to the treated surface at one, three, five and ten passes. One lane received no traffic after plowing and deicer application. This experimental approach was repeated on two separate field days, January 5th at 28° F air temperature and February 5th at 22° F air temperature (with no precedent traffic, the pavement temperature was considered to be in general equilibrium with the air temperature as there were no rapid changes occurring at the time of the tests). Photographs of treated lanes are provided in Appendix B, at times representing just after plowing and deicing treatment, just after traffic completion, and 10, 20, 30, and 60 minutes after traffic completion (note that, in Appendix B, some time lapse photographs for February 5th at 22° F are missing due to equipment malfunction).

Results for no traffic, car traffic, and truck traffic are summarized in Table 12 for January 5th at 28° F and Table 13 for February 5th at 22° F, at 20 minutes and 60 minutes after traffic completion as these times appear best representative of the melting process for the test temperatures. At 28° F, both truck traffic at three passes and car traffic at five passes substantially increase the melting compared to the no traffic condition. At 22° F, the improvement is less dramatic but can still be seen. Twenty-minute results show larger initial openings and more open area connectivity, while sixty-minute results show broad areas of melting relating to the tire track areas and subsequent down-gradient drainage.

Table 12 Comparison of deicing over two times by traffic application; January 5, 2016 at 28°F

Lane and traffic condition	20 minutes after traffic application	60 minutes after traffic application
VF5: No traffic		
VF1: Truck traffic three passes		
VF6: Car traffic five passes		
Notes: Deicer application of 600 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution.		

Table 13 Comparison of deicing over two times by traffic application; February 5, 2016 at 22°F

Lane and traffic condition	20 minutes after traffic application	60 minutes after traffic application
VF5: No traffic		
VF1: Truck traffic three passes		
VF7: Car traffic five passes		
Notes: Deicer application of 600 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution.		

Ice melting results can be evaluated by the amount of applied traffic as shown in Table 14, where 20-minute photographs are provided for none, one, three, five and ten passes of both car and truck vehicles for the January 5th day of 28° F temperature. It appears that traffic of three passes or more is required for the improvement of ice melting, as one pass does not provide apparent improvement. Conversely, it appears that five or ten passes do not provide substantially greater melt than achieved with three passes, although some difference in melt pattern can be observed.

Table 14 Comparison of deicing across a range of car and truck traffic applications; January 5, 2016 at 28°F, 20 minutes after traffic application.

Traffic condition	Car traffic	Truck traffic
No traffic		
One pass		
Three passes		
Five passes		
Ten passes		
Notes: Deicer application of 600 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution.		

Three or more passes of truck traffic does seem to provide wider melt areas than with similar amount of car traffic, perhaps due to wider tracks from dual wheels on each side of the truck rear axel. The tire pressure may also be an important factor, but discernment of wheel number, width or tire pressure was not possible within the conditions of this experimental round.

2.3.2.4 Evaluation 2016-4

Prewet is reportedly applied to solid deicer to bring about a quicker initiation of melting and to hold the deicer onto the roadway surface during windy conditions. Prewet effects were evaluated by comparing sections of pavement treated with prewetted (RG8 10% at 15 gal/ton) solid deicer to sections of pavement treated with plain solid deicer with both no traffic and traffic (five passes of a car). Deicer was hand-applied by distribution from a shaker across a full lane-width and along a defined lane distance to approximate a 600 lb/LM treatment rate. The tests were performed February 11th at 11° F temperature under an overcast sky.

Table 15 compares rock salt performance across the four test conditions. Deicer treatment with prewet appears to substantially increase the amount of undercutting, as shown by the areas darker than the white snow of the plow residual. Traffic appears to not substantially increase the amount of undercutting whether the deicer was prewet or not, perhaps reflecting the low level of ice melt capacity for rock salt at 11° F.

Table 15 Comparison of deicing by rock salt over conditions of prewetting and traffic; February 11, 2016 at 11°F

Traffic Condition	No Prewet Applied	Prewet Applied
No traffic		
Car traffic five passes		
Notes: Deicer application of 600 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of hand distribution. Photographs taken approximately 60 minutes after deicer and traffic application.		

Figures 8, 9, and 10 show contrasts of applications made on February 11th at 11° F temperature for across a range of solid deicers including: rock salt, magnesium chloride, calcium chloride and Ice Slicer. Magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) both have twice as many chloride ions per molecule than rock salt (sodium chloride, NaCl), and are therefore expected to have much more ice melt capacity and function at colder temperatures than rock salt. Ice Slicer is reported to be a blend of compounds, and was found to have ice melt capacity much higher than rock salt in Druschel (2012). Figure 8 contrasts the four materials after having been prewet (RG8 10% at 15 gal/ton). Figure 9 contrasts the four materials in application without prewet. Figure 10 contrasts the four materials in application with prewet and followed by traffic (5 passes by a car).

No matter the material and the associated activity, prewet appears to improve the melt activity shown by the amount of area with undercutting on the test section (comparing Figures 11 and 12). Contrasts of the materials demonstrate much less difference, in spite of the range of ice melt capacities from rock salt to the other materials.

Figure 8 Pavements treated at 600 lbs/LM of different deicer solids with 15 gal/ton prewet of RG8 10% (90% salt brine) applied at the point of hand distribution: rock salt (top left), magnesium chloride (top right), calcium chloride (bottom left), and Ice Slice

Figure 9 Pavements treated at 600 lbs/LM of different deicer solids with no prewet: rock salt (top left), magnesium chloride (top right), calcium chloride (bottom left), and Ice Slicer (bottom right). No traffic application. Photographs taken approximately 60

The added factor of traffic on the deicer with prewet again appears to make no substantial difference when compared to the non-traffic condition, for all four solid deicers in spite of the range of ice melt capacities. Perhaps the ice melt capacities are sufficiently low at 11° F, even though variable across the materials, that differences are not perceived.

2.3.2.5 Evaluation 2016-5

Because ice melt capacity degrades with lower temperature, solar effects causing warming of deicer materials could have a substantial benefit to deicing operations. Open pavements are typically observed to be about 10° F warmer than the surrounding compacted snow, when exposed to midday sun on a clear day. If the sun could similarly warm the individual deicer grains, if dark in color, either naturally or because of an applied prewet, deicing could perhaps occur at the ice melt capacity of the temperature of the warmed grain rather than the temperature of the snowpack.

Figure 10 Pavements treated at 600 lbs/LM of different deicer solids with 15 gal/ton prewet of RG8 10% (90% salt brine) applied at the point of hand distribution: rock salt (top left), magnesium chloride (top right), calcium chloride (bottom left), and Ice Slice

Solar warming of deicer products was evaluated by thermographic evaluation of chloride and non-chloride solids with a range of prewet materials placed on snow in a compacted wheel track (Table 8 and Figure 6). Non-chloride solids allowed the evaluation of prewet materials alone. Materials were evaluated from three days with different sun and temperature conditions:

- January 12th, 5° F, clear and sunny, with a very low dew point of -10° F and a wind of 8-12 mph;
- January 14th, 30° F, overcast, with a low dew point of 17° F and a wind of 8-12 mph; and,
- January 31st, 39° F, overcast, with a moderate dew point of 29° F and a wind of 5-8 mph.

The following observations were made by comparing the results from the three days:

1. Sand with or without chloride-based prewet material has less than a 4° F effect on compacted snow temperatures.
2. Calcium chloride or magnesium chloride prewet materials of RG8, Freezeguard or Apex cause particles to be 2 to 4° F colder than particles with different prewet materials, suggesting

thermodynamics of ionic separation are occurring, whether the solid particle has chloride or not.

3. Dyes can cause a particle warming in bright sun of 2 to 4° F, but the effect appears insignificant to influence deicing at the ambient temperature of 5° F associated with the bright sun.
4. The angle of sun becoming closer to perpendicular to the compacted snow surface can provide a 4 to 6° F warming effect.
5. Molasses solutions function like a weak dye, in that they absorbs the warmth from the sun, but that increasing proportion of molasses does not appear to significantly increase the warming effect, at least up to the 10% concentration tested.
6. Sodium chloride-based salt products exhibit no significant thermodynamic reaction at the ambient temperature of 5° F, further confirming the ice melt capacity of zero at this temperature.
7. Dyes and molasses solutions on sodium chloride-based salt products add 3 to 4° F of warmth to a grain, particularly the red-orange color, but it is an insufficient amount to trigger melting at the ambient temperature of 5° F.
8. Granular materials of non-chloride base do not exhibit significant temperature increases in the sun, in spite of some materials appearing to be very dark in nature such as “Black Beauty” (pumice) sand blasting sand or garnet sand.
9. Overcast days provide no thermodynamic boost by either solid or prewet material, except for the cooling of 2 to 4° F exhibited by the ionic separation.

2.3.3 Conclusions of 2015-16 Winter Evaluations

A deicing test facility was set up and procedures established. Nine 900-foot long lanes were set up in parallel at one location, and four 500-foot long lanes in parallel were created at a second location. Time-lapse photography worked well to document melting conditions, at least during daylight hours. Deicing results followed the expectations developed in laboratory studies for temperature, with warmer temperatures providing more melt from the deicer. Little melt was observed below about 10° F unless sunlight provided warming.

By these experiments, it appears that prewetting and traffic work similar to enhance the application of the solid deicer. Both factors appear to improve the contact area and allow the solid to reach more of the water matrix for the ionic separation of the solid material. Both factors are helpful to deicing operations. Both are also subject to the limitations of the relationship between temperature and ice melt capacity.

Prewet may function to provide a liquid water matrix that brings about a quicker initiation of melting, such that the solid deicer can ionically separate and dissolve into the prewet liquid that then adds more water by continuing the melting process in a progressive action limited only by the chemical solubility of the deicer in water. Traffic may improve deicing by creating a pressure zone in the residual snow such that air is pressed out and semi-solid ice grains are converted to water, both of which would allow more solid deicer to reach and enter the water matrix. In addition, both prewetting and traffic will assist grains of solid deicers to adhere onto the roadway surface during windy conditions. Traffic may further serve to spread the deicer around the pavement track and across the travel lane.

Because of the limited number of snow events during the winter of 2015-16, traffic and prewet factors could not be evaluated across a greater range of snow moisture, structure and temperature conditions. In particular, traffic effects should be quantified for temperatures associated with lower ice melt capacities, for snows of greater moisture, and for snows of greater compaction. These experiments are currently planned and funded for study during the winter of 2016-17.

These results may have significant importance to winter maintenance efforts. For example, if a road route is typically treated at 400 lbs/LM with rock salt supplied at $80/ton, the treatment cost would be $16/LM. Assuming the traffic effect applies at a given temperature and snow condition, perhaps three non-deicing trucks could help a lower level of treatment – say 200 lbs/LM – achieve the same performance as the 400 lbs/LM rate without traffic, meaning the deicing cost would be cut to $8/LM. If the non-deicing trucks cost $1/LM to operate (labor for driving and maintenance) and $0.50/LM for fuel, then three trucks would cost $4.50/LM. Treating at 200 lb/LM and having three trucks follow the treatment would therefore cost $13/LM. The benefits are substantial:

- Operational costs are cut by 22%;
- Chloride use in the environment is cut by 50%;
- Roadway deicing performance is held constant or improved; and,
- No increase in purchasing or material handling efforts required.

Of course, this simplified scenario does not take into account the purchase costs of the trucks, and assumes that the roadway being treated does not have reliable traffic patterns operating during the deicing time (e.g., early morning rural road, overnight urban road).

2.3.4 Evaluations of 2016-17 Winter

2.3.4.1 Evaluation 2017-1

Deicing behavior at the test facility was evaluated for temperature and melt time effects by comparing photographs from CP2 of January 19th (35° F air temperature with very dry snow) and CP2 of January 26th (25° F air temperature with moist snow), when 400 pounds per lane mile of rock salt was applied with no prewet and no applied traffic (Appendix C and Table 16). Both sets of conditions exhibit increased pavement opening with time, however there are significant differences likely related to the snow moisture conditions. For the very dry snow day, slight openings of pavement can be seen at 10 minutes after application, then enlargement of the open pavement can be observed occurring at 20 minutes after application with the wheel lanes under the rock salt distribution point mostly ice free by 60 minutes.

Table 16 Comparison of deicing progression over time at two different temperatures.

	35°F (1/19/2017) CP2	25°F (1/26/2017) CP2
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet used either day. No traffic application.		

In contrast, the moist snow opens broadly within 10 minutes after application, and by 20 minutes a broad area of the lane is open and exposed. These behaviors are opposite the behavior expected with only temperature as a factor, as there is a higher ice melt capacity at the warmer temperature, although the ice melt capacity difference is not very great between 25 and 35˚F. However, the activation and migration through the snow structure of the chloride appears to be much greater when the snow has moisture than when it is very dry.

2.3.4.2 Evaluation 2017-2

The increased activation and migration of the chloride was explored further by comparison of deicing effects on the very dry snow conditions of January 19th (35˚F; 400 pounds per lane mile of rock salt) with the moist snow conditions of January 26th (25˚F) when a prewet (10% RG8/90% salt brine) was added at the point of distribution to 400 pounds per lane mile of rock salt (Table 17). The prewet increases the speed of chloride activation and resulting pavement deicing, though the effect is not significantly increased from what was observed in Table 5.

2.3.4.3 Evaluation 2017-3

The effects of prewetting the rock salt deicer was evaluated on a single day (January 26th, 25˚F, moist snow) in side-by-side application as shown in Table 18, in which 400 pounds per lane mile of rock salt was applied to both CP1 and CP2, but CP1 had a prewet (10% RG8/90% salt brine) added at the point of distribution. No significant difference can be seen relating to the use of prewet, even as early as 10 minutes after deicer application.

Therefore, it appears that prewetting has the most impact when the snow is very dry, and perhaps little to no impact when the snow is moist.

Table 17 Comparison of deicing progression over time at two different temperatures and prewet conditions.

	35°F (1/19/2017) **No Prewet Applied (VF9)**	**25°F (1/26/2017)** **Prewet Applied At Point of Deicer Distribution (VF5)**
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017 and 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017. No traffic application.		

Table 18 Comparison of deicing progression over time at 25°F at two prewet conditions.

	Prewet Applied At Point of Deicer Distribution (CP1)	No Prewet Applied (CP2)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application on 1/26/2017 of 400 lbs/LM rock salt; where indicated, 15 gal/ton prewet of RG8 10% (salt brine 90%) was applied at the point of distribution. No traffic application.		

2.3.4.4 Evaluation 2017-4

Tables 19, 20 and 21 illustrate the effects of truck traffic; Table 19 with 35˚F very dry snow and no application of prewet to the 400 pounds per lane mile salt deicer; and Tables 20 and 21 with 25˚F moist snow with salt deicer (same rate of application) that had been prewetted at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Where applied, truck traffic was 5 passes beginning immediately after deicer application, with an attempt to keep the wheel lines of each pass aligned.

With the very dry snow condition and no prewet at 35˚F (Table 19), truck traffic provided a modest improvement in deicing effectiveness. A bigger initial opening was observed at 10 to 20 minutes after deicer application, but the increase was modest and not dramatically larger. More open area was observed at 30 to 60 minutes after application for the lane with truck traffic than the lane with no traffic, continuing the improvement with time.

With the moist snow condition and prewetted deicer at 25˚F (Table 20), truck traffic provided a substantial improvement in deicing effectiveness, with about double the area open than for the lane without traffic. The improvement also occurred quickly, with deicing well established by 10 minutes in that the wheel lines were open, followed by the area between the wheel lines being open by 20 minutes and continuing to enlarge at subsequent times.

Shorter times post-application were evaluated in Table 21, to further characterize the rapid deicing occurring with the moist snow condition and prewetted deicer at 25˚F. The wheel lines can be seen to be open as of 3 minutes after deicer application, probably occurring with the application of the truck traffic and corresponding to perhaps the third pass of the truck. By 7 minutes, the open areas are observed to be expanding beyond just the wheel lines.

These results are interpreted as the truck traffic appearing to improve the timing of the salt-snow contact, the ionic disassociation, and the melt point depression effects of the deicing. Specifically, it seems as though the truck tire pressure speeds along the melt process. Additionally, the deicer appears to be spread further from the point of distribution by tread churn and tire spray, perhaps also by further distribution of undercut fluids. These are all beneficial results, leading to quicker deicing and pavement opening of a treated area, meaning a quicker achievement of a safer road than without truck traffic.

Table 19 Comparison of deicing progression over time at 35°F with truck traffic and no prewet.

	No Truck Traffic (VF9)	Truck Traffic of 5 Passes (VF6)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017.		

Table 20 Comparison of deicing progression over time at 25°F with truck traffic and prewet.

	No Truck Traffic (VF5)	Truck Traffic of 5 Passes (VF6)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017.		

Table 21 Comparison of deicing progression over time at 25°F with prewet and truck traffic.

	No Truck Traffic (VF5)	Truck Traffic of 5 Passes (VF6)
0 minutes after deicer application		
3 minutes after deicer application		
5 minutes after deicer application		
7 minutes after deicer application		
10 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017.		

2.3.4.5 Evaluation 2017-5

Tables 22, 23 and 24 illustrate the effects of car traffic; Table 22 with 35˚F very dry snow and no application of prewet to the 400 pounds per lane mile salt deicer; and Tables 23 and 24 with 25˚F moist snow with salt deicer (same rate of application) that had been prewetted at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Where applied, car traffic was 5 passes beginning immediately after deicer application, with an attempt to keep the wheel lines of each pass aligned.

With the very dry snow condition and no prewet at 35˚F (Table 22), car traffic did not appear to improve the deicing over the lanes with no traffic. No significant change or difference was noted.

With the moist snow condition and prewetted deicer at 25˚F (Tables 23 and 24), car traffic provided a modest improvement in deicing effectiveness, with slight increase in the area open than for the lane without traffic. As with truck traffic, the improvement occurred quickly, with deicing well established by 10 minutes in that the wheel lines were open plus about one third of the area between the wheel lines. At 10 minutes without traffic, wheel lines where only partially open. Traffic improved the extent of the open pavement area, though not as broadly as with truck traffic.

Table 22 Comparison of deicing progression over time at 35°F with car traffic and no prewet.

	No Car Traffic (VF9)	Car Traffic of 5 Passes (VF2)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017.		

Table 23 Comparison of deicing progression over time at 25°F with car traffic and prewet.

	No Car Traffic (VF5)	Car Traffic of 5 Passes (VF1)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017.		

Table 24 Comparison of deicing progression over time at 25°F with prewet and car traffic.

	No Car Traffic (VF5)	Car Traffic of 5 Passes (VF1)
0 minutes after deicer application		
3 minutes after deicer application		
5 minutes after deicer application		
7 minutes after deicer application		
10 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017.		

2.3.4.6 Evaluation 2017-6

Tables 25 and 26 further develop the comparison truck traffic to car traffic; Table 25 with 35˚F very dry snow and no application of prewet to the 400 pounds per lane mile salt deicer; and Table 26 with 25˚F moist snow with salt deicer (same rate of application) that had been prewetted at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Both traffic applications were 5 passes beginning immediately after deicer application, with an attempt to keep the wheel lines of each pass aligned.

With the very dry snow condition and no prewet at 35˚F (Table 125), neither traffic condition created substantial openings, but truck traffic did provide significantly better results. Truck traffic opened spots on the pavement quicker, and saturated ice/snow areas appear about two or three times bigger than with car traffic, when observed at 10 to 20 minutes. At 30 to 60 minutes, the lane with truck traffic has wide open pavement areas, while the lane with car traffic does not yet.

With the moist snow condition and prewetted deicer at 25˚F (Table 26), truck traffic provided a bigger open area than with car traffic, starting even with just a single pass. With five passes in the first three minutes after deicer application, the lane with truck traffic has a continuous zone open between the wheel tracks, whereas the lane with car traffic has only the wheel tracks open.

These results are interpreted as the higher (90 psi) pressures of truck tires provide substantially greater contact of the deicer with the snow or ice than with the lower (35 psi) pressures of car tires. The additional wheels of truck are also likely to contribute, although the truck used in these experiments was a “6-wheeler” having only an extra wheel on each side of the rear axel compared to the car’s “4-wheeler” configuration.

The greater diameter and deeper tread of a truck tire are also likely to contribute, particularly concerning the effects of tread churn and tire spray to the distribution of the deicer.

Undoubtedly, the higher pressures of the truck tires also contribute to the destruction of the ice crystal structure within the snow, opening migration pathways for the deicer to move and spread.

Table 25 Comparison of deicing progression over time at 35°F with truck or car traffic and no prewet.

	Truck Traffic of 5 Passes (VF6)	Car Traffic of 5 Passes (VF2)
0 minutes after deicer application		
10 minutes after deicer application		
20 minutes after deicer application		
30 minutes after deicer application		
60 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017.		

Table 26 Comparison of deicing progression over time at 25°F with prewet and both truck and car traffic.

	Truck Traffic of 5 Passes (VF6)	Car Traffic of 5 Passes (VF1)
0 minutes after deicer application		
3 minutes after deicer application		
5 minutes after deicer application		
7 minutes after deicer application		
10 minutes after deicer application		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017.		

2.3.4.7 Evaluation 2017-7

Tables 27, 28 and 29 illustrate the effects of timing for truck traffic; tables are oriented differently than the previous tables, comparing four different traffic application timings at 20 minutes and 60 minutes after deicer application. Traffic application timings were done at a given (delay) time after deicer application. Note that when traffic was delayed 40 minutes after deicer application, the 20-minute photograph shows conditions prior to any traffic yet applied, effectively the same as the no-traffic condition.

Table 27 presents deicing results at the Canterbury Park test facility with 35˚F very dry snow and no application of prewet to the 400 pounds per lane mile salt deicer; Table 17 presents deicing results of the same conditions but at the ValleyFair! test facility; and Table 18 presents deicing results at ValleyFair! test facility with 25˚F moist snow with salt deicer (same rate of application as before) that had been prewetted at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Where applied, truck traffic was 5 passes at the times elapsed after deicer application, with an attempt to keep the wheel lines of each pass aligned.

With the very dry snow condition and no prewet at 35˚F at Canterbury Park (Table 27), all traffic applications appear to improve deicing over the no-traffic condition. Delayed truck traffic appears to enlarge strips of continuously saturated or "rotted" ice, particularly when observed in the 60-minute photos.

With the same snow and temperature conditions at ValleyFair! (Table 28), the effect of delayed traffic enlarging strips of continuously saturated ice is also seen. However, more pavement openings occur in deiced areas with traffic not delayed than with delayed traffic, both in the 20- and 60-minute photos.

With the moist snow condition and prewetted deicer at 25˚F at ValleyFair! (Table 29), all conditions of truck traffic provided substantial improvements in deicing effectiveness, with no significant difference regarding the delay of the traffic.

These results are interpreted as

- With moist snow, delay of traffic application may slightly reduce the improvement to deicing of the traffic, as tread churn and tire spray applied earlier promotes the distribution of the deicer while the deicer is fully effective, prior to the deicer being solubilized into the snow or ice structure and used up.
- With dry snow, delay of traffic application may slightly increase the improvement to deicing of the traffic, as tread churn and tire spray occurs when the deicer has become activated in moisture created by melted snow and ice. It appears that the dry snow needs some time to develop moisture for the deicer to work, and the delayed tread churn and tire spray promotes distribution of activated (moistened) deicer.

Table 27 Effect of truck traffic timing effects at 35°F and no prewet; pavements of Canterbury Park test facility.

	20 Minutes After Deicer Application	**60 Minutes After Deicer Application**
Traffic not delayed (CP4)		
Traffic delayed 20 minutes after deicer application (CP1)		
Traffic delayed 40 minutes after deicer application (CP3)		
No traffic (CP2)		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017.		

Table 28 Effect of truck traffic timing effects at 35°F and no prewet; pavements of ValleyFair! test facility

	20 Minutes After Deicer Application	60 Minutes After Deicer Application
Traffic not delayed (VF6)		
Traffic delayed 20 minutes after deicer application (VF7)		
Traffic delayed 40 minutes after deicer application (VF8)		
No traffic (VF9)		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017.		

Table 29 Effect of truck traffic timing effects at 25°F with prewet; pavements of ValleyFair! test facility.

	20 Minutes After Deicer Application	**60 Minutes After Deicer Application**
Traffic not delayed (VF6)		
Traffic delayed 20 minutes after deicer application (VF8)		
Traffic delayed 40 minutes after deicer application	Test not performed.	Test not performed.
No traffic (VF5)		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017. Five passes of truck traffic applied unless noted otherwise.		

Tables 30 and 31 illustrate the effects of timing for car traffic; with Table 30 presenting deicing results at the ValleyFair! test facility with 35˚F very dry snow and no application of prewet to the 400 pounds per lane mile salt deicer; and Table 31 presenting deicing results at ValleyFair! test facility with 25˚F moist snow with salt deicer (same rate of application as before) that had been prewetted at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Where applied, car traffic was 5 passes at the times elapsed after deicer application, with an attempt to keep the wheel lines of each pass aligned.

With the very dry snow condition and no prewet at 35˚F at ValleyFair! (Table 30), all car traffic applications appear to improve deicing over the no-traffic condition. As with the delayed truck traffic, delayed car traffic appears to enlarge strips of continuously saturated or "rotted" ice, particularly when observed in the 60-minute photos. However, the effect is not as substantial as with truck traffic (Table 30).

With the moist snow condition and prewetted deicer at 25˚F at ValleyFair! (Table 31), all conditions of car traffic provided modest improvements in deicing effectiveness, though delayed traffic appears to slow opening of the pavement.

These results are interpreted as similar to the results of truck traffic.

Table 30 Effect of car traffic timing effects at 35°F and no prewet.

	20 Minutes After Deicer Application	60 Minutes After Deicer Application
Traffic not delayed (VF2)		
Traffic delayed 20 minutes after deicer application (VF3)		
Traffic delayed 40 minutes after deicer application (VF4)		
No traffic (VF9)		
Notes: Deicer application of 400 lbs/LM rock salt with no prewet on 1/19/2017. Five passes of car traffic applied unless noted otherwise.		

Table 31 Effect of car traffic timing effects at 25°F with prewet.

	20 Minutes After Deicer Application	**60 Minutes After Deicer Application**
Traffic not delayed (VF1)		
Traffic delayed 20 minutes after deicer application (VF3)		
Traffic delayed 40 minutes after deicer application	Test not performed.	Test not performed.
No traffic (VF5)		
Notes: Deicer application of 400 lbs/LM rock salt with 15 gal/ton prewet of RG8 10% (salt brine 90%) applied at the point of distribution on 1/26/2017. Five passes of car traffic applied unless noted otherwise.		

2.3.4.8 Evaluation 2017-8

Table 32 illustrates the interaction effects of truck traffic and prewet; results are of the Canterbury Park test facility with 25˚F moist snow with salt deicer (same rate of application as before). Where used, prewet of the deicer was done at the point of distribution using 15 gal/ton of RG8 10% (salt brine 90%). Where applied, truck traffic was 5 passes done immediately after deicer application, with an attempt to keep the wheel lines of each pass aligned.

As shown in Table 32, the interaction of truck traffic with prewet can be evaluated by comparing the truck traffic on a prewetted deicer application to: (a) the traffic but no prewet condition; (b) the no traffic on a prewetted deicer application; and, (c) the no traffic, no prewet conditions. Results are presented in 5- and 10-minute (times after deicer application) photographs.

As seen previously, under these temperature and snow moisture conditions truck traffic after deicer application improves deicing in both prewet and no-prewet conditions, particularly illustrated in the 5-minute photographs. Note that by the 60-minute mark, in photographs not tabulated here but presented in Appendix C, deicing appears widespread for all conditions. Comparing prewet to no-prewet conditions with no traffic, there appears to be no significant difference with the use of the prewet under these temperature and snow moisture conditions, whether at the 5- or 10-minute mark. The interaction of truck traffic and prewet application appears to be dominated by the improvement due to truck traffic; no specific interaction benefit is identified.

However, as discussed earlier, the use of a prewet for very dry snow conditions would likely show improvement in deicing; therefore the interaction of truck traffic with the use of a prewet for very dry snow would likely demonstrate substantial benefit.

Table 32 Interaction of prewet and traffic effects at one temperature (25°F on 1/26/2017).

Part A: With prewet.		
	5 Minutes After Deicer Application	**10 Minutes After Deicer Application**
Truck traffic, five passes, no delay		
No traffic		
Part B: No prewet.		
	5 Minutes After Deicer Application	**10 Minutes After Deicer Application**
Truck traffic, five passes, no delay		
No traffic		
Notes: Deicer application of 400 lbs/LM rock salt; prewet used, where noted, was 15 gal/ton of RG8 10% (salt brine 90%) applied at the point of distribution. Five passes of truck traffic, applied with no delay, where noted.		

2.3.5 Conclusions of 2016-17 Winter Evaluations

A deicing test facility was set up and procedures established. Nine 900-foot long lanes were set up in parallel at one location, and four 500-foot long lanes in parallel were created at a second location. Time-lapse photography worked well to document melting conditions, at least during daylight hours. Deicing results followed the expectations developed in laboratory studies for temperature, with warmer temperatures providing more melt from the deicer.

Not using a prewet on deicer materials made a substantial and significant difference when attempting to deice in very dry snow conditions, even though the temperatures were considered warm (35˚F). On a colder day (25˚F) but with moist snow conditions, prewetting deicer seemed to make little difference. Deicing efficiency and effectiveness were observed to be greater with moister conditions (either natural moisture or prewet moisture when the snow is very dry), which is interpreted as moisture improving the activation and migration of the chloride through the snow structure for broader distribution of the deicing effects.

Truck traffic applied to a snow/ice surface after a deicer application was found to provide a modest improvement when the snow condition was very dry, and a substantial improvement when the snow condition was moist. The improvement generally took the form of open pavement areas forming sooner and becoming wider than without the traffic condition. As noted during a previous study from Winter 2015-16, truck traffic appears to improve the contact area of the solid deicer and allow the solid to reach more of the water matrix for the ionic separation of the solid material, with the concurrent lowering of the melt point.

Car traffic was found to provide similar benefits as with truck traffic, but to a lesser extent.

Delay in traffic application after deicer distribution showed conflicting results, most likely dependent upon the snow moisture condition.

- With dry snow, delay of traffic application may slightly increase the improvement to deicing of the traffic, as tread churn and tire spray occurs when the deicer has become activated in moisture created by melted snow and ice. It appears that the dry snow needs some time to develop moisture for the deicer to work, and the delayed tread churn and tire spray promotes distribution of activated (moistened) deicer.
- With moist snow, a delay of traffic application may slightly reduce the traffic improvement to deicing of the traffic, interpreted as tread churn and tire spray applied earlier promotes the distribution of the deicer while the deicer is fully effective, prior to the deicer being solubilized into the snow or ice structure and used up.

Any potential interaction between the use of prewetting and the application of truck traffic for moist snow conditions appeared to be dominated by the improvement due to truck traffic; no specific interaction benefit is identified.

However, it was hypothesized that the interaction of truck traffic with the use of a prewet for very dry snow conditions would likely demonstrate substantial benefit.

CHAPTER 3: PLOW EFFECTIVENESS STUDY

Work conducted by the Principal Investigator previously under MnDOT Agreement 96319 evaluated the ice melt capacity and field performance factors of deicers and deicer blends, and developed a temperature-based cost model for comparison of relative field performance through the evaluated deicers and deicer blends. Over 50 deicer and anti-icer compounds/compound blends were evaluated for ice melt capacity in over 1400 determinations, at temperatures ranging from 30° F down to -30° F. Values of ice melt capacity observed in this study ranged from zero (no melting caused) to 12.7 mL brine created / mL of deicer brine applied, and were generally found to be strongly associated with temperature.

Of great importance were factors other than ice melt capacity that influence roadway clearing and deicer effectiveness. These factors were indicated to investigators during eleven meetings or presentations by MnDOT Maintenance and Operations staff plus municipal, county, and vendor personnel. Factors such as road surface characteristics, traffic characteristics, weather conditions, sun level/presence, wind and pavement type and age were considered important but not appropriate for the previous laboratory study, and were, therefore, recommended for subjective inclusion in the cost model.

Under MnDOT Agreement 02829, work was conducted by the Principal Investigator during Winter 2013-14 to characterize and test the factors influencing deicer and plow effectiveness using an outdoor pavement facility with nine 1000-ft long lanes for treatment areas, separated to prevent incidental cross-treatment, located in Shakopee, Minnesota, at two proximal locations. The length of plowed areas was set to provide sufficient room for normal highway operating speeds of plow trucks. Time-lapse cameras were placed sufficiently close to treatment areas to observe and document post-plow pavement in high definition. Plow trucks were supplied by MnDOT Metro District and Carver County on non-storm days. Evaluations were made of:

- Scrape (cut) quality and cast at different speeds
- Scrape quality and cast at differing locations with different snow structure
- Scrape quality and cast at different snow moisture and temperature conditions

The previous work was continued and expanded under this current agreement. In particular, MnDOT requested that comparisons be made across the different cutting edges available and across different types and sizes of plows. Performance factors evaluated included: cut, cast, clouding, and compaction of residual snow. The method was refined for these factor evaluations and two rounds of plowing evaluations made: first, using nine plow trucks of different cutting edges and configurations, supplied by Carver County Departments of Public Works; and, second, using one plow in a test for variability across three different replicate runs at three different operational speeds.

3.1 TEST METHOD

3.1.1 Method design

For this evaluation of plow effectiveness and contributing factors, pavement lanes were set up and defined where plowing could be done without actual traffic such that experimental approaches could be tried out and compared without potential for compromising public safety. Lane lengths of 900 to 1000 ft long were defined, plus additional space for turning, so that plow trucks could reach and maintain highway speeds of approximately 30 mph. Time-lapse and hand held camera photographs were used to augment observation notes and to document the effectiveness of plowing techniques for the different snow conditions.

Different plow, cutting edge and truck configurations were tested, under actual snow conditions. Plow trucks were used on non-storm days to closely model actual efforts without significantly diverting equipment necessary for actual road maintenance during storms.

3.1.2 Field Sites

As with the deicing study, Shakopee was targeted for project field sites to provide locations accessible both to researchers from Minnesota State, Mankato and maintenance personnel of MnDOT Metro District, with potential for additional access by maintenance personnel of other nearby MnDOT Districts or volunteer municipal or county departments of public works. Pavement lanes were set up in Shakopee at two locations with large parking lots not typically used during winter months:

- Canterbury Park, 1100 Canterbury Road; in the stable area parking lot on the south side of the facility, adjacent to 12th Avenue East and 0.3 mile west of Canterbury Road South.
- ValleyFair!, One Valley Fair Drive; in the back (north) parking lot on the north east corner of the facility, located north of TH 101 about 2.5 miles west of US 169.

Access agreements were negotiated and agreed upon during early November, 2016. Prior to a lasting snowfall, researchers with support from MnDOT Metro District maintenance staff performed pavement surveys to locate and document surface discontinuities that could either interfere with or be damaged by plowing. Test lanes were configured to avoid such discontinuities. Lane marking was done with pin flags of various colors; colors were assigned to designate the sides of individual lanes. Pin flags were anchored through 6 in x 3 in x 2 in “sewer” (hollow core) bricks to 8 in x 8 in x ¾ in wooden plates and stabilized by 1 ft lengths of ¾ in diameter Schedule 40 PVC pipe. Anchoring was done to prevent penetration of the pavement by the flags yet maintain the flags in spite of winter winds. Initial lane cuts were made December 12th; afterwards flags were reset on measured locations to represent 100-ft stationing along both sides of each lane.

Figure 11 Test areas: Canterbury Park (top) and ValleyFair! (bottom).

3.1.3 Weather Measurement

A Kestrel 4000 handheld weather station (Nielsen-Kellerman, Boothwyn, PA), capable of determining temperature, relative humidity, dew point and wind speed, was used to determine conditions during field operations (Figure 12a). A dial thermometer (Figure 12b) was used for illustration and photographic documentation, but was not considered sufficiently accurate to represent field conditions. Weather measurements were augmented with documentation from a paid subscription to WeatherSpark.com, used for interpreting National Weather Service data obtained from Flying Cloud Airport, Eden Prairie, Minnesota, approximately 2 miles north of either field site.

Figure 12 Weather monitoring tools: handheld weather station; dial thermometer.

3.1.4 Cameras and Photography

Field conditions were documented through photography using two different camera systems. Handheld, high resolution photographs were taken using a Nikon D3000 camera with a 70-300 mm telephoto lens from a elevated platform. Time-lapse photographs were taken using Bushnell 6MP Trophy Cam game cameras (Bushnell Outdoor Products, Overland Park, KS) operating in time-lapse mode. Time-lapse cameras were pole mounted at approximately a 6-ft height, with poles attached to concrete block bases.

At the ValleyFair! site, time-lapse cameras were installed at lane stations 1+00 (facing down lane) and 8+00 (facing oncoming trucks) for each lane, meaning 100 ft from the start of the lane,. At the Canterbury Park site, time lapse cameras were installed at each of five, 100-foot increments, facing down lane. Time increments of 1 minute were typically used. Date and time stamps were made on time-lapse photographs, though battery jostles could cause time stamps to revert to a factory start date (circa 2014). All photographs had file origination information that could provide time of capture for verification, if needed.

3.1.5 Plow Operations

Plowing was done by winter maintenance personnel from MnDOT Metro District or Carver County. A student research assistant interviewed each plow operator for details of the truck, plows and cutting edges, and recorded answers on a checklist. The student researcher then rode with the operator during the test plow, monitoring the speed and operations of the truck. When called, trucks were asked to pull up to the designated lane, accelerate, then maintain speed within one to two miles per hour of the target speed, holding the speed steady until the last 100 feet of the lane. Front and wing plows were to be both fully deployed. Note that plowed lanes were generally used for subsequent deicing study, but no deicing or other chemical distribution was done until after the plowing was documented.

3.2 RESULTS

Plow evaluations are included in Appendix E; weather of plow evaluation days is included in Appendix A. Two events were studied in detail. First, nine plow trucks of different cutting edges and configurations were supplied by Carver County Department of Public Works for testing at ValleyFair! on February 5, 2016 (Table 33). Second, a single plow truck was used for testing at ValleyFair! on December 12, 2016, configured as a single tandem axel dump truck with a one way Falls plow that had a Joma cutting edge installed (Figure 13). Three different operation speeds were used on each of three lanes, with the goal of evaluating the influence of speed and the variability across similar plow runs.

Performance factors evaluated during both study events included: cut, cast, clouding, and compaction of residual snow, as: for the first event, a function of the combined plow, cutting edge and truck configuration (Table 34); and for the second event, as a function of plow speed (Table 35). The description of these performance factors is provided for each individual plow on the evaluations provided in Appendix E.

Table 33 Plow trucks tested (all from Carver County) on February 5, 2016.

Figure 13 Plow and truck used for testing on December 12, 2016 (from MnDOT Chaska Truck Station).

Table 34 Plow truck configurations tested (all from Carver County) on February 5, 2016.

Test Lane	Truck Number	Front Plow	Cutting Edge
VF1	401	Not given	Winter Polarflex
VF2	1313	Henderson Two Way	Polarflex
VF3	0702	Falls Model 312	Kennametal
VF4	1311	Henderson	Joma
VF5	1501	Falls Dozer	Kennametal
VF6	1408	DOK	Kennametal
VF7	0502	Falls Stationary	Joma
VF8	702	Towmaster Reversible	Joma
VF9	0901	Falls Articulating	Joma
Weather during plow tests: overcast, 28°F, wind 6 mph from south, dew point 21°F. Front plow and cutting edge information as provided by plow truck operators.			

Table 35 Plow configurations tested (truck from MnDOT Chaska Truck Station) on December 12, 2016.

Test Lane	Truck Number	Front Plow	Cutting Edge	Operation Speed
VF1	214516	Falls One Way	Joma	30 mph
VF2	214516	Falls One Way	Joma	30 mph
VF3	214516	Falls One Way	Joma	30 mph
VF4	214516	Falls One Way	Joma	35 mph
VF5	214516	Falls One Way	Joma	35 mph
VF6	214516	Falls One Way	Joma	35 mph
VF7	214516	Falls One Way	Joma	25 mph
VF8	214516	Falls One Way	Joma	25 mph
VF9	214516	Falls One Way	Joma	25 mph
Weather during plow tests: overcast, 10°F, wind 5 mph from southwest, dew point -4°F. Front plow and cutting edge information as provided by plow truck operator and observation.				

3.3 EVALUATION

The objectives of plowing are to:

- Dislodge the snowpack;
- Control the flow of dislodged snow for predictable off-lane placement;
- Protect driver visibility, of both plow truck operator and any nearby vehicle traffic; and,
- Leave a roadway surface scraped bare or with a low amount of residual snow (likely to be removed using deicing techniques).

These objectives are best met with low equipment and labor cost, meaning effective snow removal in a single pass, preferably at speeds of around 25 to 30 mph typically recommended for highway plowing and deicing operations (speed selected to optimize safety and deicer application).

This study evaluates factors that can improve plowing performance in meeting these objectives. The energy required to move a given amount of snow (fuel efficiency) was not evaluated in this study, but would also relate to efficiency of operation.

3.3.1 Multiple Plow Evaluation

Plow cast appears similar across all nine plows tested, with some variation likely due to plow shape and curvature. Figure 14 displays front views of three types of plows evaluated: a one-way plow, a poly or flex plow, and a dozer plow. All three plows are operating at highway speed. The cast of the one-way plow is upward and carrying farther than the cast of the dozer plow that is more straight out and low, with the poly plow cast having a form in between the other two.

Figures 15 and 16 compare plows of similar types, one-way plows and dozer plows, respectively. Cast is different between the two plows of each pair, suggesting that the plow shape may not be the only controlling factor. Attack angle and plow angle may be significant too; note that these factors were not obtained during the evaluation of plows presented in Appendix E.

Clouding around the plows appears to be an individual plow characteristic, as seen in Figures 15 and 16 especially. Clouding may be high and far carrying, suggesting substantial entrainment of air in the dislodged snowpack, or may be low and close, suggesting low level of air entrainment. No particular pattern of clouding was identified by plow type. Attack angle and plow angle may be significant factors to clouding, as well as location and condition of the rubber flap or shroud and any added plates or other controlling geometric features.

Cut differences between plows were minor, and may be more reflective of the underlying pavement surface rather than the plow cutting edge. However, snow with higher level of moisture than plowed on the day of evaluation could have greater “stickiness” or cohesion, resulting in a presentation of greater differences in the cut. Even less differences were observed with the compaction left after the plow traveled over the residual amount, as the low moisture content of the snow exhibited very little tendency to compact.

Figure 14 Comparison of one-way (top; VF3), poly (flex, center; VF4), and dozer (bottom; VF5) plows.

Figure 15 Comparison of one-way plows with differing cast and cloud characteristics: low, tight cast with moderate clouding (left; VF7); and broad, moderately high cast with thick, opaque clouding (right; VF6).

Figure 16 Comparison of dozer plows with differing cast and cloud characteristics: low, tight cast with little clouding (left; VF8); and broad, turbulent cast with widespread, thick clouding (right; VF5).

3.3.2 Single Plow Speed and Variability Evaluation

Evaluating the effect of plow speed on the performance in meeting these objectives was done and may be seen in Tables 36, 37 and 38 that each show selected photographs of three similar plowing runs, all performed at the same speed and shown with two photos of each run. Each run is shown in two photographs, representing two different points of the plowing run; both the first and the second photograph of each plowing run was taken at approximately the same distance from the plowing run start as the first and second photographs of each other plowing run. Table 39 presents comparisons between the plow speeds.

For the tested plow, cast appears similar across all plow runs at a similar speed, with remarkably little variation. Snow cast from the plow barrel is tight and dense in formation, focused as it travels out away from the plow. The cast of the one-way plow has a slight upward direction when leaving the plow barrel at all speeds tested, with a higher ultimate height (the apogee of the cast) occurring at higher speeds as expected. Similarly, the cast distance increases with speed, reaching approximately 30 feet away from the travel lane at 35 mph but being as little as 15 feet away from the travel lane at 25 mph.

Clouding around the plow increases moderately with speed. Clouding at higher speeds is high and moderately far carrying, suggesting entrainment of air in the dislodged snowpack. Clouding at the lower speeds is low and close, suggesting low level of air entrainment. Clouding on the driver's side (left side of truck) changed proportionally more with increased speed than the clouding on the passenger's side (right side of truck), a concerning development as the height and density of the driver's side clouding could be enough to cause visibility issues with a passing car. Note that the increase in driver's side clouding that comes with speed occurs even though the plow has an installed end plate.

Cut differences were evaluated, and found to be highly similar between plow runs, no matter the speed. A uniform residual snow of thin (less than 1 inch) snow was left behind on all plow runs (Appendix E); speed did not seem to influence the amount of snow left behind.

Similarly, compaction differences were minor, particularly reflecting the light, dry nature of the snow during the day of plowing (Appendix E). Snow with a higher level of moisture than the snow plowed on the day of evaluation could have greater "stickiness" or cohesion, resulting in a presentation of greater differences in the compaction. The low moisture content of the snow at the time of the plow evaluation exhibited very little tendency to compact.

Table 36 Evaluation of replication: two photos each of three lanes plowed at the same speed. Lanes shown are Valley Fair 7 (top), 8 (middle) and 9 (bottom), all plowed at 25 mph.

Table 37 Evaluation of replication: two photos each of three lanes plowed at the same speed. Lanes shown are Valley Fair 1 (top), 2 (middle) and 3 (bottom), all plowed at 30 mph.

Table 38 Evaluation of replication: two photos each of three lanes plowed at the same speed. Lanes shown are Valley Fair 4 (top), 5 (middle) and 6 (bottom), all plowed at 35 mph.

Table 39 Comparison of plowing at different speeds of the same truck and plow.

VF Lane 8, 25 mph speed		
VF Lane 3, 30 mph speed		
VF Lane 5, 35 mph speed		

3.4 CONCLUSIONS

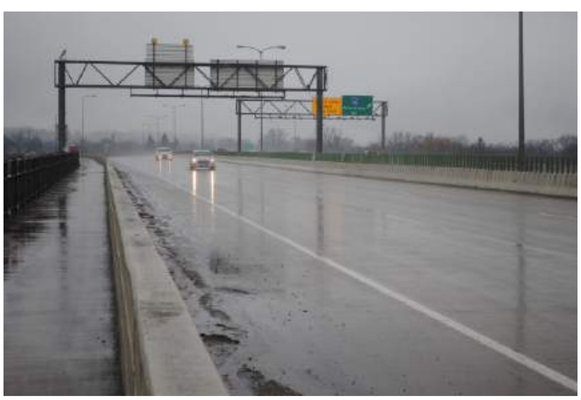
A plowing test facility was set up and procedures established. Nine parallel 900-foot long lanes were set up and used by nine plows operating at highway speeds. Time-lapse and hand held photography worked well to document snow clearing conditions, at least during daylight hours. Cast, clouding, cut, and compaction were evaluated and documented for each individual plow. Similarities and differences were considered for the range of plow types, but limited patterns were identified suggesting factors not yet isolated may be playing significant roles.

CHAPTER 4: ANTI-ICING PERSISTENCE STUDY

One technique of winter maintenance operations that has shown great promise is anti-icing, the pre-storm placement of deicer brine to clear pavement done to limit or prevent formation of icing on a roadway. Whether due to wind blown snow, ice fog, freezing rain, or simply wet snow becoming packed (Figure 17), anti-icing has been found to reduce formation and build up. However, winter maintenance operations have often found it difficult to mobilize the anti-icing application trucks, either because of labor shortages prior to a storm (resting crews before potential long shifts) or limited procurement of the anti-icing brine application equipment (Figure 18). Application of sodium chloride (rock salt) brine at typical rates between 10 and 30 gallons per lane mile (gal/LM) also provides a significant deicer material savings, as with a brine saturation of 23% concentration this rate calculates to 20 to 60 lb/LM, about 1/20th of the typical deicer application rate during a snow event.

a) Wind blown snow

b) Ice fog



c) Freezing rain

d) Wet snow becoming packed

Figure 17 Winter conditions conducive to ice buildup on roadways.

a) MnDOT truck spreading solid deicer with prewet off left rear.

b) Brine application truck during demonstration (non-winter day).

Figure 18 Deicer and anti-icer application equipment.

Work conducted by the Principal Investigator previously under MnDOT Agreement 96319 evaluated the ice melt capacity and field performance factors of over 50 deicer and anti-icer compounds/compound blends, and developed a temperature-based cost model for comparison of relative field performance through the evaluated deicer and anti-icer compounds or blends (Druschel, 2012). In a series of meetings and presentations, MnDOT Maintenance and Operations staff plus municipal, county, and vendor personnel indicated to investigators that additional factors other than ice melt capacity influence deicer effectiveness, including: road surface characteristics, traffic characteristics, weather conditions, sun level/presence, wind and pavement type and age.

Under MnDOT Agreement 02829, work was conducted by the Principal Investigator that studied the chloride response in drainage from pavements treated with anti-icer and deicer (Druschel, 2014). Chloride in pavement drainage typically started high then declined with flow, reaching a consistent residual value. Most of the change in chloride values would occur within 0.30 inches of precipitation or less. Slight differences were noted in chloride response in selected lanes due to wind effects. Persistence of chloride deicers was poor, as moisture of a storm event would quickly reduce chloride level and minimize leftover amounts to act as an anti-icer to follow on events. Chloride levels observed in the drainage represented only a fraction of the total amount reported as placed on the roadway, interpreted as indicating that deicer was removed primarily by plow cast.

This study aims to further characterize and define the factors related to anti-icer and deicer persistence during traffic and precipitation events, to minimize loss of anti-icer and deicer material and maximize deicing performance. The study was done on an elevated section of an active highway as an outdoor test facility, employing actual anti-icing on actual traffic with operational winter maintenance efforts unadjusted for research. Factors evaluated included: deicer application rate, time, temperature, precipitation, and traffic situation.

4.1 BACKGROUND

Trost et al. (1987) describes deicing as fundamentally controlled by undercutting, allowing traffic to break up delaminated ice. Undercutting is further described as a two-phased behavior, first being controlled by ice melt capacity in a thermodynamic process, and second being controlled by diffusion and density gradients in a kinetic process. The concept of undercutting appears to have led to the practice of anti-icing, in which a melt point depressant material is placed on pavement ahead of winter precipitation, such that the initial storm precipitation in the form of snow or ice are undercut or never achieve a bond to the pavement.

Raukola et al. (1993) describes an anti-icing program evaluation in Finland that used a residual chloride measurement to assess anti-icing persistence on pavement in a medium duty roadway with 6100 average daily traffic. Anti-icing was applied in liquid form, and decreases in surface chloride concentration were found to be associated with roadway moisture most of all. Other factors positively correlated to a decline in surface chloride concentration included traffic, initial application amount, and applicator speed. No difference in the pattern of persistence was noted between sodium chloride and calcium chloride.

Stotterud and Reitan (1993) discusses the findings of an anti-icing evaluation in Norway that considered weather factors on ice prevention. Performance was assessed by friction measurements. Anti-icing was negatively affected by snow intensity, lower temperatures and the occurrence of freezing rain. Duration (persistence) of anti-icing materials was found to be reduced by increases in traffic or surface moisture, either as frost or drizzle. Persistence could be as long as 2 – 3 days on the tested roadway, if low temperatures and low humidity occurred prior to the storm event. Pavement type and age were discussed as factors in performance, but no clear trend was identified only differences discussed.

Blackburn et al. (1994) presents a large and comprehensive study of anti-icing, consisting of liquid, solid and prewet solid anti-icing materials and techniques tested at fourteen locations in nine states (CA, CO, MD, MN, MO, NV, NY, OH and WA) during the winters of 1991 – 92 and 1992 – 93. Materials and techniques were tested against control sections where conventional snow and ice control practices of the particular state were used. Friction testing and chloride residual testing were used for performance measurement, and results were presented along with weather, pavement condition and air temperature records. State departments of transportation were the testing agencies, and training materials were developed within the study for anti-icing techniques, testing methods and quality control procedures. Difficulties encountered included the lack of equipment available for prewetting, equipment targeted for the low treatment levels associated with anti-icing, and a lack of vendor testing of operational characteristics of spreading equipment.

Findings of Blackburn et al. (1994) include a mixed outcome about the reduction of overall salt use, as some locations experienced increases in salt use and some locations first decreased then increased salt use. Salt use outcome variations were attributed to the contrasts of winter storm patterns between the two years. Overall, anti-icing at 100 pounds per lane mile with liquid or prewetted solid was found to greatly improve roadway operation during winter conditions when temperatures were above 20° F; dry solids were found to have persistence on the roadway inadequate for effective anti-icing due to blow off or traffic effects. Prewet rates of 5 – 6 gal/ton and 10 – 12 gal/ton were found minimal but effective for prewetting on the spinner and in the truck bed, respectively, although recommendation was given to increase the rate by 50% for greater effectiveness and reliability of method. Magnesium chloride was evaluated and found to be an effective anti-icing material as a liquid or prewet on sodium chloride. Anti-icing techniques were found to be ineffective or even detrimental if used during freezing rain or drizzle events, or on compacted snow.

Ketcham et al. (1998) is a follow on study to Blackburn et al. (1994) using eight of the sites previously studied and adding eight new sites. Fifteen states were involved in the study (IA, KS, MA, NH, OR and WI were added), although results were only reported from twelve sites in eleven states addressing average daily traffic of 3000 – 40,000 vehicles. The goal of this study, similar to the previous study, was to evaluate new techniques of anti-icing in comparison with conventional practices of the particular state, with the objective to further encourage development and implementation of the new anti-icing practices. As before, performance was measured with friction tests and pavement observations, while perceptions of passenger vehicle handling after treatment were added. Results were graphed across the storm times then evaluated with statistical evaluations of friction values by pavement conditions and treatment approach (either conventional or anti-icing based). Two to fourteen storms per year were evaluated for each site. A wide range of treatment materials were evaluated including rock salt, fine salt, calcium chloride, magnesium chloride, potassium acetate, and abrasives.

In the study by Ketcham et al. (1998), friction was found to be reduced by lower air temperatures (greatest effect), higher precipitation rates and decreasing traffic volume (least effect). Snowfall intensity was also particularly identified, as packed snow was observed to occur after an upturn in intensity, although the results were not quantified. Friction was consistently worse with "snow" conditions than with "light snow" conditions. Cost analyses of five highway sections were inconclusive, as anti-icing techniques resulted in both lower and higher costs. Reasons for the costs to increase included higher priced chemicals being used, test operations not being completely typical, and anti-icing not being "tuned" to achieve the full potential of ice prevention and removal. Additionally, clean up of abrasives (when used) was identified as a significant cost.

Anti-icing performance factors identified by Ketcham et al. (1998) as needing further evaluation included:

- Lower levels of service being incorporated as a flexible storm response;
- Rural versus urban roadway treatments;
- Abrasives as a complementary strategy to anti-icing;
- The effective application of solids and prewet solids for anti-icing;
- Persistence of anti-icing treatments between storms;
- The optimum timing of anti-icing treatments ahead of storms;
- Interaction of anti-icing with open graded pavement courses; and,
- Effective anti-icing techniques for freezing rain conditions.

Recent work by Blomqvist et al. (2011) shows that anti-icing and deicing operations could be negatively affected by the roadway wetness as traffic removes salt through splash and spray as well as run off:

> "Road surface wetness, as shown from the wheel tracks, related positively to the rate of residual salt loss. The wetter the surface, the faster the salt left the wheel tracks. On a wet road surface, the salt in the wheel tracks was almost gone after only a couple of hundred vehicles had traveled across the surface, whereas on a moist road surface, it would take a couple of thousand vehicles to reach the same result."

Blomqvist et al. (2011) suggests that, while road wetness has a significant impact, it is first and foremost traffic that appears to reduce deicer persistence. This finding matches the conclusions of Raukola et al. (1993) and Stotterud and Reitan (1993), noted previously. However, this finding appears different than the finding noted by Ketcham et al. (1998) that decreasing traffic reduces friction; in essence, that traffic is helpful to anti-icing. It may be these two findings are describing two different behaviors within anti-icing:

- Vehicle as breaker of ice, perhaps by dislodging undercut ice; and,
- Vehicle as remover of salt chemical, perhaps by mobilizing salt water spray or splash.

Shi et al. (2013) connects the two-phase behavior of Trost et al. (1987) to observations of time being a highly significant factor in roadway ice melting: melting occurred within 30 minutes of application for magnesium chloride and calcium chloride, but within 60 minutes for sodium chloride.

Druschel (2014) quantifies the salinity response of pavements treated with anti-icer to precipitation. Salinity in pavement drainage typically started high then declined with flow, reaching a consistent residual value. Most of the change in salinity values would occur within 0.30 inches of precipitation or less. Little difference was seen in salinity response whether the pavement consisted of asphalt concrete or Portland cement concrete. Differences caused by differences in anti-icer materials were observed, although were generally modest.

4.2 TEST METHOD

4.2.1 Method Design

For this evaluation of anti-icing persistence, measurements of flow and deicer concentration over time were made of storm drainage runoff from defined highway pavement areas. Comparison of the deicer concentration in the runoff to the timing and amount of precipitation events can be assessed by factors including temperature and precipitation intensity. Comparison between different pavement areas can allow evaluation of traffic factors including traffic rate, direction, truck proportion plus allow consideration of replicates for improvement of evaluation strength.

Additionally, an evaluation was made of plow cast during a storm plowing event. Snow catching bins were staked out in two lines perpendicular to the defined highway areas being evaluated in the main experiment. Snow cast by the plowing effort was caught along with the storm precipitation; captured precipitation was melted then measured for volume and salinity.

4.2.2 Field Site

Pavement areas were defined by the contributing drainage area of individual scupper collection points on an elevated section of US 169 in Mankato, Minnesota (Figure 19), part of the Minnesota River crossing. This location was selected because: (1) the elevated highway is an active highway with known anti-icing and deicing procedures; (2) the drainage system is easy to access from below, with no exposure to highway traffic nor any potential confined space entry as can occur with catch basins; and, (3) weather at this location was both sufficiently wintery and well defined through use of the National Oceanic and Atmospheric Agency (NOAA) weather system coverage.

Access agreements with MnDOT were negotiated and agreed upon on November 26, 2013, during a meeting with the District 7 Maintenance, Bridge and Hydraulics departments, the bridge managers. Safety procedure review was received at the bridge site on December 11, 2013, and project personnel were approved for site operations as proposed.

Bridge drainage follows the profile and crown slopes of the bridge deck, draining from south to north and from a crown line between the right and left lanes for both northbound and southbound directions. Drainage is collected from the pavement in scupper inlets, then flows downward through 8-inch ductile iron down chutes to discharge through an open bend to just above a concrete gutter on the ground surface that leads to a catch basin and a subsurface drainage system (Figure 20). Scuppers are located in sets of four located along a single bridge deck joint and coming down a single bridge pier line.

Two sets of four scupper/down chute drainage features were selected for study, shown on Figure 21 and detailed in Table 40. The two sets are replicates, draining adjacent areas with the same traffic and thermal conditions. Each set of four scuppers represents four distinct areas of the bridge: northbound right lane, ramp and shoulder; northbound left lane with shoulder; southbound left lane with shoulder; and southbound right lane, ramp and shoulder. The are denoted in that order as Locations A to D and E to H for the north and south sets, respectively. As viewed from the ground level, the north set is along the Minnesota River flood protection levee and the south set is near to Sibley Avenue.

a) Side view, view west.

b) Northbound lanes, view south.

Figure 19 North Star Bridge, US 169 over the Minnesota River at Mankato, Minnesota.

a) Scupper.

b) Down chute piping, outside lane.

c) Down chute piping, inside lanes.

d) Outlet to concrete drainage gutter.

Figure 20 North Star Bridge drainage.

The traffic on the bridge was characterized for the project by Scott Thompson of MnDOT District 7:

> *The last time traffic counts were done on the bridge was 2011. At that time, the bridge had 32,500 AADT (Average Annual Daily Traffic). Of the 32,500 vehicles, 2,450 would be heavy commercial vehicles.*
>
> *Traffic volumes in our area have been relatively flat. In order to inflate to 2014 values, I would use a straight 1% annual increase in volumes. Regarding directionality of the volumes, I would assume a 50/50 split. It should also be assumed that 10% of the daily traffic volume occurs during the peak AM rush hour and another 10% occurs during the peak PM rush hour.*

It may be noted that the heavy commercial (truck) proportion is about 7.5% of the total traffic. Figure 22 provides several views of traffic on the bridge.

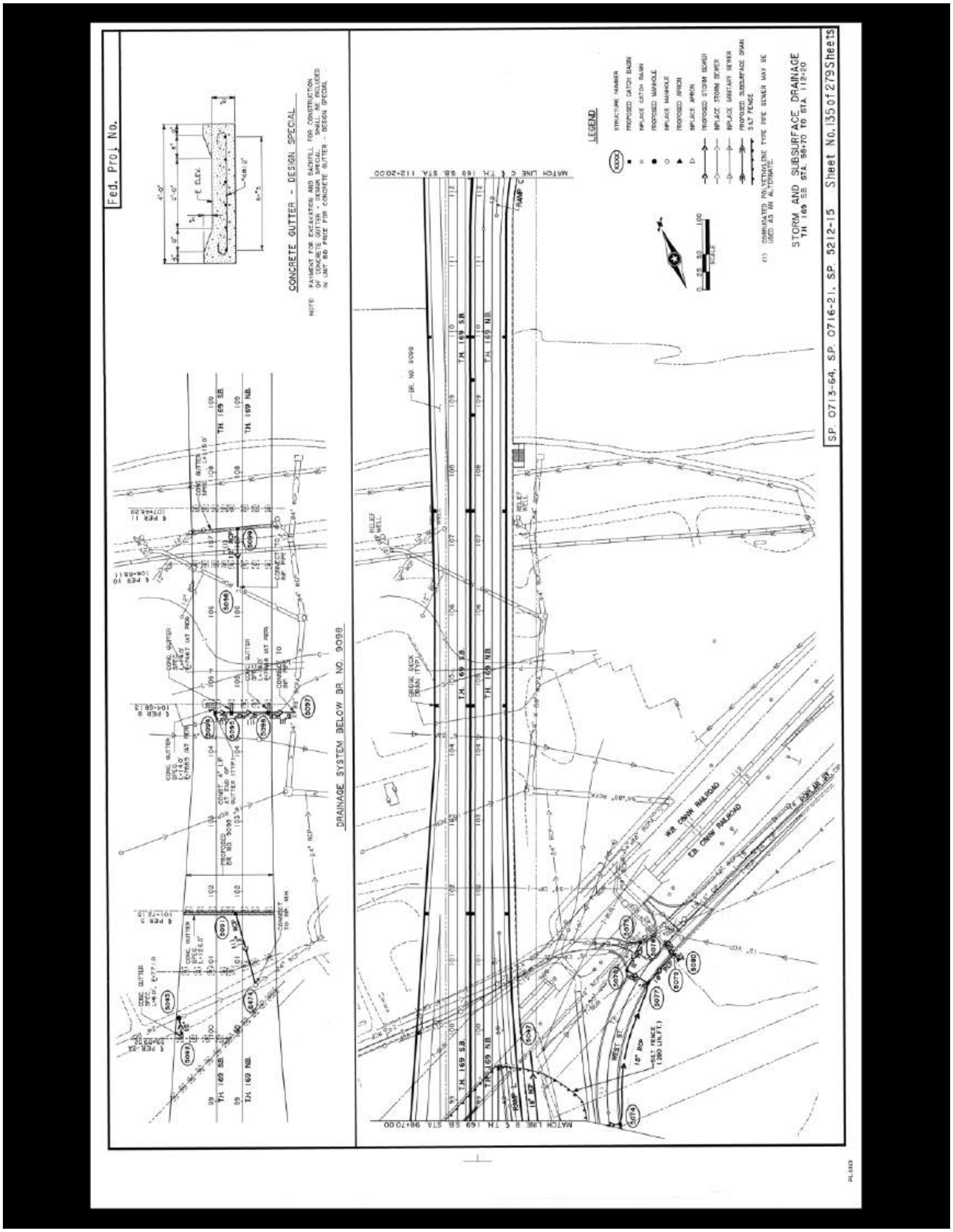


Figure 21 North Star Bridge plan showing drainage inlet locations.

Table 40 Storm drainage locations used in measurements.

Notation	Direction, Station and Offset	Lanes Drained	Approximate Drainage Area
A (Alfa)	TH 169 NB Sta 107+40 32 ft right	Right through lane Ramp lane Shoulder	8,800 sf
B (Bravo)	TH 169 NB Sta 107+40 20 ft left	Left through lane Shoulder	5,500 sf
C (Charlie)	TH 169 SB Sta 107+40 20 ft right	Left through lane Shoulder	5,500 sf
D (Delta)	TH 169 SB Sta 107+40 32 ft left	Right through lane Ramp lane Shoulder	8,800 sf
E (Echo)	TH 169 NB Sta 104+65 32 ft right	Right through lane Ramp lane Shoulder	9,440 sf
F (Foxtrot)	TH 169 NB Sta 104+65 20 ft left	Left through lane Shoulder	5,990 sf
G (Golf)	TH 169 SB Sta 104+65 20 ft right	Left through lane Shoulder	5,990 sf
H (Hotel)	TH 169 SB Sta 104+65 32 ft left	Right through lane Ramp lane Shoulder	9,440 sf
Notes: Station lines match to lines shown on plan of Figure 5. Locations A-D are at the north end of the elevated highway near the flood levee. Locations E-H are at the middle of the elevated highway near the north side of Sibley Parkway located below the highway. Names in parentheses beneath the notations were used during field operations to verbally distinguish locations; names may appear in field notes and calculations.			

a) Northbound – cold day.

b) Northbound – rain day.

c) Southbound – dry day.

d) Southbound – rain day.

Figure 22 Traffic on the North Star Bridge.

4.2.3 Drainage Measurement

To measure flow and deicer concentration as a function of time, drainage from each scupper/down chute assembly selected for study was routed through a flow through cell, consisting of a butyl rubber pipe boot, a PVC stub pipe and a 55-gallon polyethylene drum oriented horizontally (Figure 23). The drum provided a reservoir in which water conductivity, a surrogate strongly correlated to deicer concentration, could be measured. Flow was obtained by measurement of depth over a weir; two weirs were cut into the discharge end of the drum: a broad weir 4 inch x 16 inch extending across the whole width of the drum end, and a 22.5° V-notch weir cut beneath the broad weir. The V-notch weir provided sensitivity in low flow measurements and the broad weir provided large capacity discharge.

Water level, conductivity and temperature were all measured using LTC Levelogger Junior in-water measurement probes (Solinst Canada, Ltd, Georgetown, ON), selected for both measurement ability and resistance to salt water. The probes were lowered into the drum and rested horizontally on the drum bottom until being removed for reading/downloading. PVC coated wire rope 1/8th inch diameter was used to attach the Leveloggers to a U-bolt installed in the top crown of the horizontal drum. The drums were chained and locked in place, with the chain attaching to the ductile iron down chute above the lowest anchor point. The chain was also wrapped circumferentially around the drum and through an adjacent 8 inch x 8 inch x 16 inch concrete masonry unit used to help level the drum and prevent the drum from rolling towards the center low point of the concrete gutter.

The weirs of each drum were calibrated for flow by pumping a known flow through the drum then measuring the depth over the weir (Figure 24). A weir coefficient was obtained particular to each drum using a best fit method (Appendix F). Calibration was done for flows ranging from 0.2 gpm to 4 gpm. Additional evaluation was done for flows up to 50 gpm.

Conductivity calibration of each Levelogger was done using solutions made with sodium chloride (rock salt) at nine concentrations from 0 to 150 g/L (Figure 25 and Appendix G). Leveloggers were rinsed with deionized (DI) water, placed in the solution and read at four time intervals. The order of the solutions was randomized, and 36 total solution mixtures were evaluated. Results were evaluated and found to bifurcate with a lower range of 0 – 60 g/L and a higher range of 60 – 150 g/L best representing the measured conductivities. However, during the course of the 2015-16 winter season, no field measurements reached to the high range for the conductivity measurement.

Depth measurement was done by the Leveloggers using total pressure measured at pressure membrane location. Total pressure consists of atmospheric (barometric) pressure plus water pressure. To calculate water pressure, barometric pressure must be subtracted. Two barometric pressure loggers (Solinst Edge 3001 Barologger) were used in the project: a main Barologger locked to the flow through cell at Location C and a backup Barologger kept in the vehicle typically used to support the project (this vehicle was typically parked within ½ to 1½ miles of the North Star Bridge). Pressure and depth calibrations were done at the manufacture and provided with the instruments.

Clogging in the flow through cells was frequently observed, typically consisting of cigarette butts, agricultural materials such as corn or soybeans, miscellaneous vegetative matter (Figure 26) or ice (Figure 27).

Because of the potential for ice to damage the pressure transducer within the Leveloggers, when temperatures were expected to be consistently below 20°F, flow through cells were taken out of the drainage pathway and locked in place adjacent to the drainage gutter and down chute (Note: extreme pressures on several Leveloggers were observed during the February 29 to March 7th, 2016 time period, due to subfreezing temperatures creating ice around the Levelogger pressure membranes; flow through cells had not been removed during this period as temperatures had been forecast to remain above 20°F; the ice formation was likely due to drainage water not having significant chloride content to cause freeze point depression).

a) End view showing plastic drum with V-notch weir, broad weir, manual measurement tape, leveling chain/concrete masonry unit, and security chain.

b) Side view showing down chute piping, boot, PVC stub, plastic drum, leveling chain/concrete masonry unit, and security chain.

Figure 23 Flow through cells

a) Flow through V-notch weir into receiving sump.

b) Measurement of water level at known flow.

Figure 24 Calibration of flow measurement in weirs of plastic drum.

Figure 25 Calibration of conductivity measurement in ten total data loggers (Leveloggers). Solutions of various concentrations contained in beakers. Leveloggers being rinsed with deionized water and toweled dry between placement in solutions.

4.2.4 Weather Measurement

A Kestrel 4000 handheld weather station (Nielsen-Kellerman, Boothwyn, PA), capable of determining temperature, relative humidity, dew point and wind speed, was used to guide assessment of conditions during field operations. Weather measurements were determined with documentation from weatherunderground.com, used for interpreting National Weather Service data obtained from Mankato Regional Airport, located 6 miles northeast of the field site (Appendix H).

Figure 26 Debris clog at Location A, March 27, 2014.

4.2.5 Cameras and Photography

Field conditions were documented through photography using two different camera systems. Handheld, high resolution photographs were taken using a Nikon D3000 camera with a 55-300 mm telephoto lens, occasionally alternating with a 20-55 mm wide angle lens. Additional handheld photographs were taken with an Apple iPhone 5 camera. Time-lapse photographs were attempted, but two camera installations were vandalized and the cameras stolen so time-lapse photography was discontinued.

a) March 27, 2014, Location F, ice level above broad weir.

b) April 3, 2014, Location F, debris and ice damming flow through V-notch weir.

Figure 27 Ice blocking.

4.2.6 Plow and Deicer Spreading Operations

Plowing and deicer spreading (distribution) were done by maintenance personnel from MnDOT District 7 Headquarters location in Mankato. Typical equipment was a Sterling tandem axle, automatic transmission dump truck with front, right wing and underbody plows (Figure 28). Side mounted (saddle) tanks were used to carry brine materials used for prewetting granular deicer. Typical deicer material applied was rock salt pretreated with calcium chloride at a rate of 6 gal/ton then prewet at 15 gal/ton with 10% RG8 - 90% salt brine (sodium chloride, 23.3%, in tap water). Application typically is off the left rear corner of an application truck, so placed to use traffic for pavement distribution. Based on discussion with maintenance personnel, the North Star Bridge was treated with deicer at about 400 lb/LM as an anti-icing treatment prior to storm events if the pavement temperature is below freezing, plus application of 200 – 800 lb/LM during storm event plowing. Application rates were automatically adjusted for vehicle speed.

Figure 28 Typical MnDOT winter maintenance truck, circa 2016, outfitted with front, right wing and underbody plows, brine saddle tanks and rear deicer distribution system.

4.3 RESULTS

Data was collected in 5-minute increments by the Leveloggers then supplemented with manual measurements to provide a check. Results from each measurement location at the North Star Bridge are presented in Appendix I by location, grouped with Fall 2015 results first, then Spring 2016 results. Results are presented in two graphs on a page: water level and temperature graphed to separate scales on the top graph, water level and conductivity similarly graphed to separate scales on the bottom graph (water level is used as a marker for comparison between the two graphs). No Spring 2016 results were obtained for Locations B and E due to equipment malfunction.

Calculation of chloride concentration and flow at each location was done, with results presented graphically in Appendix J by location (same organizational structure and graphing system as Appendix I). Chloride concentration was calculated using the Levelogger specific conductivity and the calibration relationship developed as shown in Appendix G. Flow was calculated using values for the height of water over a flow through cell weir, obtained from the Levelogger depth less a zero-flow depth representing the submersion level of the logger. Zero-flow depths were determined manually from the graphs of water depth in Appendix I for periods of no flow. Zero-flow depths were reassessed for time periods after Levelogger download or adjustment (e.g., cleaning), or for periods following obvious icing. Note that all flows for the time period of February 29th to March 7th were made to be zero due to ice jamming, determined by the substantial level increase without concurrent precipitation, caused by the ice pressure.

Calculation of mass flow, defined as the amount of mass passing a drainage location in a period of time, was calculated from the results of Appendix J by the formula:

Mass Flow = Mass/Time = Concentration x Flow (Equation 1)

Mass flow was determined in units of lb/LM/minute to show a running level related to the application of deicer and anti-icer.

Cumulative mass flow, defined as the sum of all the mass flow that had passed through a drainage location, was determined in units of lb/LM/week to show a running level related to the application of deicer and anti-icer.

Both mass flow and cumulative mass flow are presented graphically in Appendix K by location (same organizational structure and graphing system as Appendices I and J). Ideally, these values would be accompanied by automatic vehicle locator (AVL) system results that include the deicer application rates. However, AVL results were apparently not recorded for the North Star Bridge treatments during the study period.

The results of the plow cast evaluation are provided in Appendix L. Snow catching bins were staked out in two lines perpendicular to the defined highway areas being evaluated in the main experiment (Figure

29, top left and top right). Snow cast by the plowing effort was caught along with the storm precipitation (bottom left); captured precipitation was melted then measured for volume and salinity (bottom right).

Figure 29 Plow cast experiment for the storm of February 3, 2016.

4.4 EVALUATION

4.4.1 Flow

Fall results all show same general shape, responding to five major precipitation events and three smaller events. Locations G & H show substantial "tails" in which the flow level does not come down after the peak with the same rate of decline as the other locations; the tails suggest back flooding by clogged drainage outlets, and result in flow quantities artificially raised after storm peaks. Locations B and F (both US 169 NB left lane) appear to be lower in flow levels than Locations A and E (both US 169 NB right lane and ramp) in proportion to the relative catchment area of the drainage locations (Table 1). Locations C and G (both US 169 SB left lane) also appear to be lower in flow levels than Locations D and H (both US 169 SB right lane and ramp). However the proportion for Location C seems too low for the only factor to be catchment area; perhaps blockage at the inlet is to blame.

Spring results show similar shape in the flow levels among the six functioning locations, with twelve discernable peaks plus several minor responses. Location H shows clear impact by a blocked outlet causing back flooding; the level of back flooding being of a magnitude to obscure several peaks. Magnitudes of the remaining five locations appear similar, although a few selected individual peaks appear substantially higher suggesting brief blockages from debris.

4.4.2 Concentration

Fall results have the same general response across all eight locations, with no chloride application being measured until November 21st, then chloride concentrations in the 100 to 350 g/L range for six days, when the levels appear to wash down to zero or near zero, then rebound to about level lower than the previous level. These results are interpreted as no deicer was placed on the bridge pavement until an icing event of November 21st (little to no drainage flow was measured concurrently), then the deicer material was washed off during the precipitation of November 26th but replaced with new material. These results match the AVL data that indicated a single pass of deicing both northbound and southbound around 5 pm on November 21st (none earlier as apparently the bridge pavement temperature was not cold enough).

Spring results have similar response for Locations A, C, D, F and G (Location H is disregarded because of being compromised by the back flooding; Locations B and E did not record results because of equipment failure). Concentrations range from 50 to 200 g/L. An initial response was measured on February 20th that appears to be washed through quickly, then new deicer was applied on March 2nd that appears to be related to an icing event as it is associated with no significant precipitation. A wash through occurs on March 13th, with reapplication of deicer on March 19th that stays through April 1st (flow through cell removal). Note that Location A shows a muted parallel to these trends, but that the amounts are substantially lower than the other locations.

4.4.3 Mass flow rate & cumulative mass

Fall results indicate cumulative chloride masses that are reasonable for the flow and concentration conditions at Locations B plus D through F, in which the chloride mass accumulates after the deicer application on November 21st, reaching a plateau of between 2,000 and 6,000 pounds per lane mile. These values seem reasonable given that most deicer applications during storm conditions are around 400 pounds per lane mile, so these plateau values would represent five to fifteen passes over two days; note that these passes may not have occurred directly in the drainage area but may represent material carried in by vehicles from deicer application on nearby roadway sections (supported by AVL results).

Location A has a plateau value of over 9,000 pounds per lane mile, which would represent twenty-two passes over two days, possible but a value that seems high.

Location C appears influenced by the low chloride concentration previously noted and resulted in a plateau of less than 500 pounds per lane mile, far too low for the conditions. Locations G and H have cumulative mass amounts that appear to rise continually once chloride is applied, interpreted as being influenced by the back flooding and not representative of the actual conditions.

Spring results show a series of plateau values reached after deicer mass flows begin in earnest as of March 8th; earlier dates do not have significant drainage flows at most locations. The plateaus are reached as chloride washes through the system, with deicer applications to the bridge pavement being washed through the drainage system location by precipitation flows. Plateaus step up at Locations C, D, F and G at step increments of about 400 pounds per lane mile, suggesting moderate treatment during spring cold mornings or snow squall events. Total values of between 2,500 and 6,000 pounds per lane mile, representing six to fifteen passes total, appear reasonable.

Location A reached a plateau of 2,000 pounds per lane mile on February 21st, a date that does not match the other data, then holds steady with no further increase through February and March. This behavior matches the chloride concentration observations for the logger at Location A, noted above. It appears that the logger for Location A may have failed for conductivity measurements, or at least lost sensitivity, negating the value of the results for Location A in the spring analysis period.

4.4.4 Plow cast results

Plow cast results from the storm of February 3rd suggest that the greatest concentration of salt contained within the plow cast landed about five feet away from the bridge parapet, and that the total salt cast off the bridge totaled about 5,000 pounds per lane mile (assuming 10.75 square feet of catchment area per foot of bridge length from the 12 bins, with an average total mass of 66.7 g per foot of bridge length). Salt was cast up to 60 feet away from the parapet, though the majority of the salt mass fell within 30 feet of the parapet. The total salt cast from the bridge represents about six passes of deicer treatment for each of two lanes, an amount quite in line or perhaps even low for the conditions of that particular storm. (R. Glaser, personal communication).

Note that AVL results were not available for all the trucks performing deicer distribution at the North Star Bridge during the spring analysis period.

4.5 CONCLUSIONS AND RECOMMENDATIONS

Chloride from deicer application can be tracked from application through the drainage system by analyzing drainage flow and chloride concentration. While selected locations were impacted by equipment failure, many of our monitored locations performed well. Total chloride mass was evaluated and compared to application rates and found to match well.

Chloride in plow cast was analyzed during one storm event in early February when drainage was frozen and not flowing. Cast was found to contain considerable chloride in the zone from the parapet to about 30 feet away, a distance specific to the geometry of the North Star Bridge; additional chloride was found in the cast farther away from the bridge but at lesser amounts. Chloride depositional zones were found to match in two replicate locations.

In summary, chloride appears to migrate from the point of roadway application through a combination of storm drainage and plow cast in significant amounts but dependent upon the temperature and moisture conditions at the time of the application. Additional chloride migration is likely from spray caused by vehicle tire tracking and carry through, neither of which was directly analyzed in this study. In particular, the moisture condition appears to be the main factor in determining the pathway of the chloride.

Specific timing of chloride placed on the roadway and chloride moving through the drainage locations was not evaluated because of the non-uniform application of deicer during the fall analysis period and the gaps in the truck distribution monitoring during the spring analysis period.

CHAPTER 5: PAVEMENT STUDY

Under MnDOT Agreement 02829, work was conducted by the Principal Investigator that studied the salinity response of pavements treated with anti-icer to precipitation (Druschel, 2014). Salinity in pavement drainage typically started high then declined with flow, reaching a consistent residual value. Most of the change in salinity values would occur within 0.30 inches of precipitation or less. Little difference was seen in salinity response whether the pavement consisted of asphalt concrete or Portland cement concrete. Differences caused by differences in anti-icer materials were observed, although were generally modest.

An additional laboratory study was therefore done to further characterize and define the pavement and treatment material compositional factors of anti-icing by performing laboratory tests of anti-icer persistence at temperatures representative of service conditions. Different deicer/anti-icer chemicals were evaluated in response to application of artificial precipitation. Pavements were prepared by application of deicer chemical in brine form, dried to replicate service conditions, then chilled and held at temperatures below the freeze point of water but within the range of effective ice melt capacity. Measurements of chloride content were made to see how long the deicer chemical stuck to the pavement in relationship to the precipitation amount.

5.1 TEST METHOD

5.1.1 Method design

For this evaluation of anti-icing persistence, measurements of storm drainage (runoff) flow and anti-icer concentration were made in relation to amounts of artificial precipitation from defined areas on highway pavement specimens at temperatures representative of winter service conditions. Pavement and treatment material compositional factors were compared. Pavements were prepared by application of deicer chemical in brine form, dried to replicate service conditions, then chilled and held at temperatures below the freeze point of water but within the range of effective ice melt capacity. Measurements of chloride content by determination of total dissolved solids were done to see how long the deicer chemical stuck to the pavement in relationship to the precipitation amount.

In a related set of experiments, rock salt was evaluated for melt initiation and expansion as a function of rock salt grain size, prewet condition, and temperature. The goal of these observations was to assess deicer factors that would contribute to increased undercutting of ice on pavement. Evaluation was done using comparisons of ionic disassociation as expressed by thermal behavior and measured through infrared measurements (thermographs).

5.1.2 Controlled Temperature Chambers

Chambers to provide controlled temperature conditions were needed to achieve stable thermal conditions in the range of 0 to 32°F, the range too warm for standard freezer technology and too cold for standard refrigerator technology. Selected temperatures were achieved by freezing a brine solution of a concentration targeted at a specific freeze point (depressed from the 32°F freeze point of pure water by the addition of salt).

The controlled temperature chambers were built with an inside dimension of 40 inches by 40 inches by 16 inches deep, a size large enough to accommodate four pavement specimens or six ice sheet containers, with room under and between specimens or containers such that the ice brine solution could circulate. All sides, top and bottom were insulated with 2 inches thick expanded polystyrene ("blueboard") with an R-value of 10. The chambers were double lined with 6 mil high density polyethylene sheeting, separated by additional foam board, and reinforced to resist the hydraulic pressures using twisted wire cable as hoop reinforcement.

5.1.3 Pavement Samples

Pavement samples were obtained from Blue Earth County and the City of Mankato, rather than MnDOT, as by the time this research work had been authorized, excavated state highway pavements had been removed from maintenance and construction operations (pavements are typically ground or crushed in preparations for material reuse). Figure 30 shows student workers collecting a concrete pavement sample.

Collected pavement samples included:

- Limestone aggregate concrete pavement, approximately 60 years old, Blue Earth County (Minnesota) State Aid Highway (CSAH) 17 (referred to as "Concrete 1");
- Asphalt concrete pavement, approximately 20 years old, Carney Avenue, Mankato, Minnesota ("Asphalt 2");
- Granite aggregate concrete pavement, unknown age and location, Cannon Falls Truck Station, MnDOT District 4 ("Concrete 3"); and,
- Asphalt concrete pavement, approximately 1 year old (temporary pavement), CSAH 17 ("Asphalt 4").

Test sections of 8 inches by 8 inches (20 cm by 20 cm) were defined using weather stripping and silicone caulk to create hydraulic isolation on the pavement area of interest.

5.1.4 Deicers

Deicer chemicals used in this study (Table 41) were furnished by MnDOT from operational stocks. Salt brine used for anti-icer testing was mixed by MnDOT District 7 using rock salt originating from the

Blanche Mine in Louisiana in municipal drinking water. Additional rock salt was furnished by MnDOT Metro District from the Chaska Truck Station for non-anti-icer uses on this project.

Deicers were evenly distributed over the pavement section as 10 mL volumes from a transfer pipet (Figure 31).

Table 41 Deicers considered in this study, listed with active components as provided by the vendor.

Deicer	Form	Main Component	Secondary Component(s)	Company/ Manufacture
Rock Salt	Solid	NaCl	none	North American Salt
Salt Brine	Liquid	NaCl (23.3%)	none	North American Salt
FreezGard CI Plus	Liquid	26-34% $MgCl_2$	2% Corrosion Inhibitor, 1% Sulfate	Compass Minerals
Road Guard Plus-8 (RG8)	Liquid	27% $CaCl_2$, 3% $MgCl_2$, 1% NaCl, 1% KCl	8% Sugar Beet Molasses	Green Touch Systems, LLC
Apex (Meltdown Apex)	Liquid	25-35% $MgCl_2$	<1% Corrosion Inhibitor, <1% Performance Additive	EnviroTech Services, Inc.

Additional materials were used for comparison of effects, including molasses (Grandma's Original (unsulphered) Molasses, B&G Foods, Parsippany, NJ), corn syrup (Garden Club Light Corn Syrup, Clements Foods Co., Oklahoma City, OK) and denatured ethanol (Jasco Denatured Alcohol, W.M. Barr & Co., Inc., Memphis, TN).

5.1.5 Precipitation and Drainage

Artificial precipitation was applied to each pavement section in 10 mL or 25 mL increments; precipitation consisted of deionized water created by reverse osmosis treatment. The precipitation was measured with a 10 mL or 50 mL transfer pipet and gently released to the treated pavement. Drainage was then collected from along the pavement test section perimeter using a glass syringe, measured and placed in a 75-mL aluminum foil weigh dish.

Drainage was evaluated for deicer compounds using total dissolved solids analysis, in which collected liquid is massed and evaluated for volume, then evaporated in a 105°C oven and massed again for residual solids. Residual solids are interpreted as effectively all being dissolved, although some particulate solids would also be included; particulates are considered to be minor components as the dissolved compounds must be of high levels to be effective in deicing applications.

Figure 30 Pavement specimen collection, CSAH 17 project.

5.1.6 Ice Sheets

Ice sheets were formed by freezing deionized water in a covered 9-inch by 13-inch metal pan. An average depth of 0.5 inch was found sufficient to achieve a uniform surface in the pan. Ice sheets in the pans were floated in an ice/brine mixture in the controlled temperature chambers and allowed to equilibrate for two hours or more at the ice/brine freeze point temperature so that the ice sheet temperature matched the ice/brine mixture temperature.

Figure 31 Anti-icer application to defined pavement area.

5.2 RESULTS

Twelve different anti-icer mixtures were used in the various analyses; the total dissolved solids concentrations of each anti-icer mixture is provided in Appendix M.

Results of the analyses for anti-icer persistence in pavement drainage (Table 42) are provided for each pavement, anti-icer, and temperature combination in Appendix N. Both numeric and graphical results are given. The numerical results provide: application rate; precipitation volume and equivalent impingement depth (precipitation in inches); volume recovered and equivalent runoff depth; total dissolved solids concentration measured in milligrams per liter (mg/L); and the cumulative dissolved solids (salt equivalent) in both total mass (grams) and mass per pavement area calculated in pounds per lane mile. The graphs are of total dissolved solids concentration, cumulative drainage, and cumulative dissolved solids graphed by precipitation.

Table 42 Pavement anti-icing tests.

Date	Pavement Surface Temperature	Pavement	Anti-icing
May 10th	28°F	Concrete 1	RG8 10%, Salt Brine 90%
		Asphalt 2	RG8 10%, Salt Brine 90%
May 13th	34°F	Concrete 1	RG8 10%, Salt Brine 90%
		Asphalt 2	RG8 10%, Salt Brine 90%
		Concrete 3	RG8 10%, Salt Brine 90%
		Asphalt 4	RG8 10%, Salt Brine 90%
May 16th	18°F	Concrete 1	Apex 100%
		Asphalt 2	RG8 100%
		Concrete 3	Freezegard 100%
		Asphalt 4	RG8 10%, Salt Brine 90%
May 17th	24°F	Concrete 1	Salt Brine 50%, Molasses 50%, DI Water 0%
		Asphalt 2	Salt Brine 50%, Molasses 0%, DI Water 50%
		Concrete 3	Salt Brine 50%, Molasses 12.5%, DI Water 37.5%
		Asphalt 4	Salt Brine 50%, Molasses 25%, DI Water 25%
May 19th	24°F	Concrete 1	Salt Brine 50%, Molasses 25%, DI Water 25%
		Asphalt 2	Salt Brine 50%, Ethanol 25%, DI Water 25%
		Concrete 3	Salt Brine 50%, DI Water 50%
		Asphalt 4	Salt Brine 50%, Corn Syrup 25%, DI Water 25%
Notes: All anti-icers were mixed then applied at a rate of 376 gal/LM. Precipitation was added in 10 mL increments for 10 steps, then 25 mL increments for 8 steps, for a total of 300 mL, equivalent to an applied precipitation of 0.26 inch.			

Comparisons of anti-icer persistence by temperature condition, pavement type, anti-icer mixture, organic content, and organic composition are contained on individual graphs in Appendix O.

Results of the melt initiation and expansion tests (Table 43) are provided in Appendices P and Q for 28°F and 13°F, respectively. Results are provided in a series of thermographs (infrared photographs) taken at listed times after application of deicer to the ice surface, organized by deicer/prewet treatment. Comparisons within each series is made for both grain size by prewet treatment and prewet treatment by grain size.

Table 43 Melt initiation and expansion tests.

Date	Temperature	Prewet	Deicer
May 5th	28°F	none	#4 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	#4 Rock Salt
		none	4-10 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	4-10 Rock Salt
		none	#10 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	#10 Rock Salt
May 12th	13°F	none	#4 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	#4 Rock Salt
		none	4-10 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	4-10 Rock Salt
		none	#10 Rock Salt
		RG8 10% Salt Brine 90% at 15 gal/ton	#10 Rock Salt
Notes: Rock salt designation in accordance with standard terms of granular products: #4 Rock Salt is retained on a #4 (4.75 mm mesh) sieve, #10 Rock Salt is retained on a #10 (2.00 mm mesh) sieve, and 4-10 Rock Salt is passing a #4 sieve but retained on a #10 sieve. US Standard sieve sizes per ASTM F1195.			

5.3 EVALUATION

5.3.1 Anti-icer Persistence Tests

General trends of precipitation runoff (drainage) were similar for all of the anti-icer persistence tests, as seen in the graphs provided in Appendix N. Runoff amounts initially are lower than the applied precipitation, as some of the water wets the surface and likely absorbs into the pavement structure. Runoff then increases in amounts concurrent with but slightly lower than the applied precipitation. Runoff coefficients, defined as runoff amount divided by precipitation amount, ranged between 0.77 and 0.95, with lower coefficients being associated with colder temperatures, interpreted as meaning that some precipitation froze to the pavement. No pattern of behavior was observed to be correlated with pavement type, as both asphalt and concrete pavements had similar runoffs for a given temperature condition. Similarly, age of pavement did not seem to be a correlating factor.

The two pavements tested on May 10th (C1 051016 and A2 051016) returned runoff at levels in excess of the applied drainage, unlike all the other tests. This difference is interpreted as the runoff being impacted by the temperature control brine surrounding the pavement; these two tests are therefore disregarded and not included in further analyses.

Total dissolved solids concentrations in the anti-icer persistence tests using the standard anti-icer mixture of 10% RG8 and 90% salt brine were similar across all evaluated tests, starting at relatively high levels of 50,000 mg/L at 0.01 inches precipitation, then rising up sharply to a peak concentration of around 80,000 mg/L (8% concentration) typically by 0.02 inches precipitation, then declining quickly to a residual concentration of below 2,000 mg/L by perhaps 0.12 inches precipitation where the concentration would remain steady with increasing precipitation. The decline is interpreted as flushing out the chloride and other dissolved materials, and would likely result in a runoff that would freeze near the pure water freeze point of 32°F.

Cumulative dissolved solids in the anti-icer persistence tests were also similar across all evaluated tests using the standard anti-icer mixture of 10% RG8 and 90% salt brine. Cumulative dissolved solids were observed to increase quickly during the initial precipitation, then slowing the increase and settling into a maximum of about 1000 pounds per lane mile.

Tests performed with other anti-icer mixtures and variations on organic content and composition suggested that the total dissolved solids and the cumulative dissolved solids have similar behaviors no matter what the mixture, only the magnitudes differed. Increasing the organic content but holding the chloride level constant did provide a greater persistence of deicer, doubling the amount of precipitation exposure (approximately 0.23 inches) before the concentration in the runoff reduced to the flushed out level.

These results are consistent with the findings presented in Druschel (2014), but the characterization of the anti-icer release from the pavement is at a much finer scale, and can be seen to occur even quicker than previously observed. Moisture condition on the pavement surface may well be a substantial factor in determining anti-icing success, supporting the hypothesis presented by Blomqvist et al. (2011).

5.3.2 Melt Initiation and Expansion Tests

Finer sized deicers appear to initiate melt faster than coarser sized deicers of the same material. This difference is interpreted as melt initiating over a broader area for the finer sized deicers related to the greater amount of total grain-to-ice contact area for smaller particles of the same overall deicer mass; a greater surface area of the deicer equals a greater amount of ionic disassociation (the first step of melting ice by salt application for freeze point depression). Finer sized deicers had the melt signature of individual grains blended into a general area melt by 2 minutes 30 seconds after application at 28°F. Medium sized deicers had the individual grain melt signature blended into a general area melt by 9 minutes after application at 28°F, while coarse sized deicers did not achieve general area melt but remained as individual grain melt throughout the test period at 28°F.

Given that at 28°F the ice melt capacity is about 9 mL/g of deicer, for the same mass of deicers, it seems that deicer with grains smaller than 2.00 mm works primarily by surficial melting, while deicer with grains larger than 4.75 mm works primarily by penetration melting (and perhaps undercutting, if the pavement surface is not too deep). This behavior is likely governed by the relationship between grain mass, which controls the amount of ice melted by the grain, and grain surface area, which controls melt initiation by ionic disassociation into the water/ice matrix.

Prewet with finer sized deicers caused the material to clump and act like coarse sized deicer; otherwise deicer prewet made no apparent difference in observed melt initiation and expansion at 28°F. It was noted that the experiments conducted used ice that was deeply frozen and without many observable air bubbles or pockets; if the ice matrix had less water content (i.e., more air bubbles or a consistency of compacted snow), perhaps prewet would have a greater effect on the melt initiation and expansion.

Temperature does not seem to be a factor in the speed of melt initiation nor of expansion, other than as caused by the change in ice melt capacity (at 13°F, the ice melt capacity is about 1 mL/g of deicer).

5.4 CONCLUSIONS

Pavements were studied for dissolved solid response in runoff during precipitation events after applications of different deicer materials. Total dissolved solids concentrations were similar across all evaluated tests, starting at relatively high levels, rising up sharply to a peak concentration of around 8% concentration typically by 0.02 inches precipitation, then declining quickly to a low residual concentration by perhaps 0.12 inches precipitation where the concentration remained steady with increasing precipitation. The decline was interpreted as flushing out the chloride and other dissolved materials, and would likely result in a runoff that would freeze near the pure water freeze point of 32°F.

Cumulative totals of dissolved solids were also similar across all evaluated tests, increasing quickly during the initial precipitation, then slowing the increase and reaching to a deicer-specific maximum level. Tests performed with other anti-icer mixtures and variations on organic content and composition suggested that the total dissolved solids and the cumulative dissolved solids have similar behaviors no matter what the mixture, only the magnitudes differed.

Moisture condition on the pavement surface may well be a substantial factor in determining anti-icing success, supporting the hypothesis presented by Blomqvist et al. (2011). Some persistence benefit was observed to be derived from increasing organic content within the anti-icer mixture.

Deicers were also studied for melt initiation and expansion characteristics. Finer sized deicers appeared to initiate melt faster than coarser sized deicers of the same material, interpreted as melt initiating over a broader area related to the increased amount of total grain-to-ice contact area for the finer-sized deicers. Melt expansion appeared to have differing mechanisms for the fine and coarse deicers, as coarse particles penetrated far into the ice sheet, while fine particles acted predominantly on the surface of the ice sheet.

Temperature did not seem to be a factor in the speed of either the melt initiation or the melt expansion, other than as caused by the change in ice melt capacity between different temperatures. Prewetting the deicer did not appear to affect the melt initiation, although the lack of behavioral difference may be caused by the high moisture content of the ice sheet used for testing, rather than the lower moisture content associated with some compacted snow material.

CHAPTER 6: CONCLUSIONS

Three research approaches were used to study winter roadway maintenance. First, a deicer and anti-icer test facility was set up and procedures were established. Eight drainage locations of US 169 were routed through flow cells for measurements of chloride content and flow. Comparisons suggested good experimental behavior in the method, except for anomalous readings caused by instruments frozen in ice and effects caused by debris blockage. Efforts to protect and clean gear during deployment increased reliability. Of the measurements, it was observed that:

- Temperature makes a good variable to check on instrument operating conditions;
- Conductivity and therefore chloride concentration were only affected by a lack of mixing due to ice or sedimentation in the flow-through cells; and,
- Depth and therefore flow measurement were sensitive to ice buildup and debris blockage.

Chloride mass amounts passing through the drainage locations were calculated at levels substantially below the likely roadway application levels. This observation was consistent through the study area, regardless of traffic condition or direction. This finding agrees with observations by previous researchers that the majority of deicer loss occurs through traffic-induced spray or dust combined with plow "throw." It is recommended that future efforts incorporate atmospheric sampling and off-roadway drainage measurement to assess chloride migration through such effects. Some evidence was observed of possible wind effects in the pathway of chloride on the roadways of the study site.

Results of two closely spaced storms suggested little to no persistence in chloride after a storm event. This result was intriguing, as it indicates that anti-icing could be detrimentally affected by any antecedent moisture prior to the anticipated icing event. Additional evaluation of this effect will occur during the upcoming Task 4 Pavement Study of this contract.

Second, a plowing and deicing test facility was set up and procedures were established. Six and three parallel 1,000-foot-long lanes were created at two facilities offering a range of snow conditions. Time-lapse photography worked well to document plowing and melting conditions, at least during daylight hours. Ice base creation procedures were developed but remain somewhat difficult to do in winter conditions without a ready supply of cold water.

Similar plowing results were obtained across six different lanes at one facility, suggesting strong replication of performance. Results appeared consistent over the length of the lanes, based on the photographs. Similar results were also seen when plowing was compared between two sites with slightly different snow conditions, suggesting uniformity in results from a single truck, plow and driver combination. Plowing results followed expectations for differences in speed, in that snow rises higher in the curvature of the plow in response to higher speeds, and higher speeds create a broader spray off the plow ends, with an accompanying greater distribution distance of the dislodged snow.

Deicing results followed the expectations developed in laboratory studies for temperature, with warmer temperatures providing more melt from the deicer. Little melt was observed below about 10° F unless sunlight provided warming. Additional work is needed to evaluate deicing behaviors when faced with changing temperatures, i.e., formation of refreeze when temperatures drop but the roadway is still wet with brine, activation of deicing when temperatures rise from a cold application temperature, etc. Time of the melting process did not appreciably change with temperature, and any changes noted may be more related to the increased ice melt capacity with increased temperature. However, additional work could be done to fine-tune the melt time characteristics, perhaps with closer photography at more rapid increments.

No significant difference was observed in deicer performance by whether prewet was used or not. Benefits reported by maintenance personnel of better roadway adherence during windy conditions and quicker initiation of melt were not observed during this study and could warrant further evaluation if deemed important. Traffic, specifically truck traffic, was found to cause a significant improvement in deicer performance, with both wider and quicker melt occurring. The interaction of tire pressure and deicer was clearly observed to create the improved melting, as compared to the effect of the tire pressure alone.

Third, pavements were studied for salinity response during precipitation events after applications of different deicer materials. Salinity in pavement drainage typically started high then declined with flow, reaching a consistent residual value. Most of the change in salinity values would occur within 0.30 inches of precipitation or less. Little difference was seen in salinity response whether the pavement consisted of asphalt concrete or Portland cement concrete. Differences in deicer materials were slight, although greater variability in results was observed for salt brine, and salinity of Apogee deicer registered at higher levels than chloride-based deicers.

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