DEPARTMENT OF TRANSPORTATION

Hot Shots for Cold Climates -- Evaluating Treatment of the Hardest Icy Spots

Stephen J. Druschel, Principal Investigator
Center for Transportation Research Implementation Minnesota State University, Mankato

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Nineteen state highway locations around south-central and southwestern Minnesota were evaluated during winter 2019-20 for the application of deicer “hot shots,” extra levels of salt or other chemical treatments used to deice roadways and maintain roadway driving levels of performance. Locations were selected based on previous recordkeeping that indicated difficult winter driving conditions including drifting, blow ice formation, ice fog (black ice formation), roadway shading, and exposed bridge decks. Highways selected were representative of low-traffic-volume roadways classified as rural commuter, primary, and secondary roads. Deicer application amounts were gathered from AVL measurements made onboard plow trucks. Local and regional weather conditions were measured. A total of 909 application passes by plow trucks were found for the nineteen locations of study for winter 2019-20. Hot-shot treatments were observed to comprise 28% of the total treatments.

Hot-shot treatments were observed, but neither at the proportions nor in the patterns expected for the studied situations of winter roadway difficulty. Operator judgment appeared to be much more important than any other defined factor. In the balance of winter driving level of service and costs, with costs not only measured in money but also in labor, equipment and environmental impact, perhaps the best investments will be in enhanced operator training and the sharing of experience; roadway and weather information systems; and public education and the management of expectations.

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Hot Shots for Cold Climates – Evaluating Treatment of the Hardest Icy Spots

FINAL REPORT

Prepared by:

Stephen J. Druschel
Minnesota State University, Mankato
Center for Transportation Research Implementation
Trafton Science Center 205 East
Mankato, MN 56001

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EXECUTIVE SUMMARY

Nineteen state highway locations around south-central and southwestern Minnesota were evaluated during winter 2019-20 for the application of deicer “hot shots,” extra levels of salt or other chemical treatments used to deice roadways and maintain roadway driving levels of performance. Locations were selected based on previous recordkeeping that indicated difficult winter driving conditions including drifting, blow ice formation, ice fog (black ice formation), roadway shading, and exposed bridge decks. Control locations were also identified. Highways selected were representative of low-traffic-volume roadways classified as rural commuter, primary, and secondary roads.

Instruments at the site locations recorded highway level air temperature, dewpoint, and light intensity, while regional weather stations were used for measurements of precipitation amount and type, and wind speed and direction. Onsite time-lapsed photography was also gathered to verify roadway conditions. Deicer application amounts were gathered from automatic vehicle location (AVL) measurements made onboard plow trucks; a total of 909 application passes by plow trucks were found for the nineteen locations of study for winter 2019-20. Hot-shot treatments were observed to comprise 28% of the total treatments.

Hot-shot treatments were evaluated across the five “bad road” conditions and the control locations for patterns of treatment; few patterns were found, and none found were strong. Drifting, which seems to be a condition of difficulty related mostly to the middle- to late-winter months, did not appear to require hot-shot treatments but rather more broadly based treatments. Blow ice formation, also a middle- to late-winter occurrence, also received broadly based treatments rather than hot-shot treatments. Ice fog locations at which black ice can form seemed to be treated through a reliance on traffic and anti-icing rather than localized salt treatment such as by hot shots. Bridge decks exposed to wind and roadways experiencing mid-day shading were treated with hot-shot approaches in substantial proportions; both situations had temperature differentials that could create significant differences in roadway deicing. Control locations illustrated that a wide variation in treatment levels could exist even between similar sites in similar geographies.

Traffic affected deicer operations in what seemed to be two opposing directions: higher levels of traffic brought greater managerial and policy expectations for roadway service level, increasing the motivation to use larger amounts of deicer, yet higher levels of traffic provided greater effectiveness of applied deicer through greater mixing and churning of snow/ice compaction. Because of these divergent factors, no patterns of traffic level and use of hot-shot treatments were consistently observed for the study locations.

In summary, hot-shot treatments were observed, but neither at the proportions nor in the patterns expected for the studied situations of winter roadway difficulty. Operator judgment appeared to be much more important than any other defined factor, as substantial differences were noted even at a location pair treated by the same operator on the same route, just 10 miles apart on the same highway.

Therefore, when balancing winter driving level of service and costs, with costs not only measured in money but also in labor, equipment and environmental impact, perhaps the best investments will be in enhanced operator training and the sharing of experience; roadway and weather information systems; and public education and the management of expectations.

CHAPTER 1: INTRODUCTION

Roadway deicing and snow removal (Figure 1) is a balance between achieving a winter driving “level of service” and cost. However, costs are not only measured in money but also in labor, equipment, and environmental impact. If only we could put out a sign saying, “Cost Savings Ahead – Reduce Speed.” However, public safety and perhaps bad driving demand a certain level of expense. Recent optimizations in deicer application by weather conditions have helped reduce costs and improve environmental impacts, and these optimizations have become the standard in winter roadway maintenance.

Figure 1: Typical MnDOT winter maintenance truck, circa 2016, outfitted with front, right wing and underbody plows, brine saddle tanks and rear deicer distribution system.

However, every roadway has trouble spots: wind blow, shading, cold air capture, refreeze, or perhaps just awkward cross slopes on curves. When icy conditions develop on these trouble spots, state patrol shouts for more salt as vehicles slide sideways, crashes multiply, and people potentially get hurt. In times like these, consideration of environmental protection can be neglected, and much of the good work done on deicer optimization can be negated.

In this study, roadway sections of known deicing difficulty have been compared to nearby “normal” sections of roadway, using automatic vehicle location (AVL) and maintenance decision support software (MDSS) records of MnDOT deicer applications, augmented by onsite photographic records and weather measurement. Sites were selected in consultation with MnDOT winter maintenance personnel, based on their experience. Sites were outfitted with weather measurement and logging devices plus time-lapse cameras to produce a time-based characterization of the site and roadway conditions.

Figure 2: Winging the roadway shoulder to improve safety and prepare for additional snow storage of future storm events.

1.1 HISTORY OF ROADWAY DEICING

Description of previous studies regarding the history of roadway deicing taken from Druschel (2017):

> 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 regarding deicing and anti-icing performance taken from 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.

Additional descriptions of previous studies regarding deicing and anti-icing performance taken from Druschel (2017) (selected passages, and updated):

> 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.
>
> 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).
- Sullivan, et al (2015) considered factors for strategically locating satellite salt facilities to gain efficiencies in roadway snow and ice control.
- Miller, et al (2018) and Blandford, et al (2018) evaluated the economic benefits gained through reduced demands on labor, equipment and deicer material that occur when optimizing snowplow routes at the Ohio Department of Transportation and the Kentucky Transportation Cabinet, respectively.

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.

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).

Anti-icing performance measures were evaluated in four publications. Snow-pavement bond strength, bond failure temperature and friction of pavement after snow removal were evaluated by Cuelho and Harwood (2012). Fjaerestad, et al (2020) evaluated the freezing process for anti-iced salted roadway surfaces during conditions of ice fog or hoar frost formation. Experiments indicated that a relationship could be developed between amount of precipitation and the protection time provided by an anti-icing application. Fu, et al (2012) was a field test of anti icer compounds derived from beet molasses that focused on friction of the pavement through nine snow events. Shi and Cui (2015) considered the economic, environmental and social benefits attributable to the proactive nature and environmentally responsible performance of anti-icing and pre-wetting.

Environmental damage done by roadway deicers was described in several publications. Dudley, et al (2014) evaluated the effects of roadway deicers on the germinations rate of native grasses and forbs. Rossi, et al (2016) characterized the effect of roadway deicers on soil-mineral interactions at roadside locations. Herb (2017) evaluated the transport and accumulation of chloride from road deicers through surface water runoff and soil infiltration in an urban area watershed. Results suggested a greater infiltration of chlorides into soil and subsurface waters than was previously assumed.

CHAPTER 2: SITES SELECTED FOR EVALUATION

2.1 SITE SELECTION LOGIC

Working with members of the Technical Advisory Panel, both collectively and individually, locations have been nominated for study around the question: "Where are your trouble spots for black ice formation, refreeze and drifting; the locations where maintenance is difficult and safety is most difficult to protect?"

Beyond winter maintenance anecdotal information, MnDOT high wind mapping and snow trap inventory reports have been consulted to develop general roadway areas for study.

Logic used in selection of study locations is described in the following tables (Tables 1 to 6).

Table 1: Blow ice location logic.

Condition of Study	General Characteristics of Sites
Blow Ice	• State highway with MnDOT plow and deicing route • Located between 4 – 10 miles east of Buffalo Ridge, typically in southwest Minnesota ○ Area known for very dry snow, high wind and daytime sun • East-west oriented roadway • Highway of lower traffic volume • Combination or transitions of roadway above surrounding grade/low height of fill and roadway below grade in a shallow cut • Long views to see varying conditions • Demarcation as special spot on MnDOT Snow Trap Index but perhaps not long/continuous demarcation • At least 1 mile from zone of lower speed limits • Location of safe turnoff from main roadway/state highway • Away from residences by approximately 1000 feet or more • Exposed without adjacent trees or structures • Wide space beyond ditch line with height sufficient to post camera for view of pavement • Location representative of highways in local region

Table 2: Drifting snow location logic.

Condition of Study	General Characteristics of Sites
Drifting Snow	• State highway with MnDOT plow and deicing route • Located south or west of Mankato, typically in south central Minnesota o Area known for low winds, moist or moderately dry snow • North-south oriented roadway • Highway of lower traffic volume • Lengthy demarcation as special section on MnDOT Snow Trap Index • Typically a location with adjacent trees or structures • Long views to see varying conditions • At least 1 mile from zone of lower speed limits • Location of safe turnoff from main roadway/state highway • Away from residences by approximately 1000 feet or more • Wide space beyond ditch line with height sufficient to post camera for view of pavement • Location representative of highways in local region

Table 3: Bridge decks freezing before surrounding road location logic.

Condition of Study	General Characteristics of Sites
Bridge Decks Freezing Before Surrounding Road	• State highway with MnDOT plow and deicing route • Longer bridge with main highway on bridge • Exposed bridge deck, away from trees, raised above local topography or water body if possible • North-south oriented roadway • Highway of lower traffic volume • Not necessary/unlikely to be indicated as special section on MnDOT Snow Trap Index • Separated from zones of lower speed limits • Location of safe turnoff from main roadway/state highway • Access to safe zone outside of guard rails to post camera for view of pavement; access without crossing highway travel lanes • Location representative of highways in local region

Table 4: Afternoon shading location logic.

Condition of Study	General Characteristics of Sites
Afternoon Shading	• State highway with MnDOT plow and deicing route • Roadway section with trees close to travel lanes on west side; trees should be tall and thick, likely to create shade and prevent sun warming of pavement • North-south oriented roadway • Highway of lower traffic volume • Not necessary/unlikely to be indicated as special section on MnDOT Snow Trap Index • Separated from zones of lower speed limits • Location of safe turnoff from main roadway/state highway • Instrument location to be near trees and record relative light reading of similar condition to light on roadway • Access to instrument location without crossing highway travel lanes • Location representative of highways in local region

Table 5: Ice fog location logic.

Condition of Study	General Characteristics of Sites
Ice Fog	• State highway with MnDOT plow and deicing route • Located south or west of Mankato, typically in south central Minnesota ○ Area known for low winds • Highway of lower traffic volume • Topographic low section, likely associated with former/current lake or wide river bottom • May or may not be indicated as special section on MnDOT Snow Trap Index, as ice fogging not likely to be mapped as it is an unusual and temporal occurrence • Nearby trees or structures but perhaps 300 – 500 feet away from roadway on downhill side; few trees or structures on uphill side as want no blocks to sinking cold air • Large catchment area of higher ground leading to study area • Long views to see varying conditions • At least 1 mile from zone of lower speed limits • Location of safe turnoff from main roadway/state highway • Away from residences by approximately 1000 feet or more • Wide space beyond ditch line with height sufficient to post camera for view of pavement • Location representative of highways in local region

Table 6: Control location logic.

Condition of Study	General Characteristics of Sites
Control	• State highway with MnDOT plow and deicing route • Located south or west of Mankato, typically in south central Minnesota ○ Area known for low winds • Highway of lower traffic volume • Topographic low section, likely associated with former/current lake or wide river bottom • May or may not be indicated as special section on MnDOT Snow Trap Index, as ice fogging not likely to be mapped as it is an unusual and temporal occurrence • Nearby trees or structures but perhaps 300 – 500 feet away from roadway on downhill side; few trees or structures on uphill side as want no blocks to sinking cold air • Large catchment area of higher ground leading to study area • Long views to see varying conditions • At least 1 mile from zone of lower speed limits • Location of safe turnoff from main roadway/state highway • Away from residences by approximately 1000 feet or more • Wide space beyond ditch line with height sufficient to post camera for view of pavement • Location representative of highways in local region

2.2 SELECTION OF SITES

Locations selected for study are listed in Table 7. Nineteen total locations were selected.

Table 7: Study Locations

Location Name (Township)	Roadway (Travel Directions)	Location (County)	Coordinates	AADT[1] (vehicles/day) and Pavement Surface
Florence Bridge (Shelburne)	US 14 over MN 23 (east-west)	Mile 21.5, approximately a quarter mile northeast of Florence MN (Lyon)	N44° 14.425' W096° 02.805'	1350 Concrete deck and approach slab; asphalt roadway
Fort Ridgeley	Incorporated into Sleepy Eye Bridge site; no separate measurements			
Garden City (Garden City)	US 169 (north-south)	Mile 39, approximately one mile south of Garden City, MN (Blue Earth)	N44° 02.360' W094° 10.475'	2800 Concrete
Ivanhoe (Royal)	MN 19 (east-west)	Mile 13.4, approximately two miles east of Ivanhoe, MN (Lincoln)	N44° 27.602' W096° 12.006'	1200 Asphalt
Jeffers (Amboy)	MN 30 (east-west)	Mile 72, approximately one and a half miles east of Jeffers, MN (Cottonwood)	N44° 03.010' W095° 09.653'	1250 Asphalt
Judson Control (Cambria)	MN 68 (east-west)	Mile 132, approximately two miles west of Judson, MN (Blue Earth)	N44° 11.755' W094° 13.638'	1750 Asphalt
Judson Ice Fog (Judson)	MN 68 (east-west)	Mile 134.5, approximately one quarter mile south of Judson, MN (Blue Earth)	N44° 11.565' W094° 12.022'	1750 Asphalt

Lake Benton (Lake Benton)	US 14 (east-west)	Mile 12, approximately three and a half miles east of Lake Benton, MN (Lincoln)	N44° 16.204' W096° 13.138'	2000 Asphalt
Maple River (Sterling)	MN 30 (east-west)	Mile 138, approximately six miles west of Mapleton, MN (Blue Earth)	N43° 53.755' W094° 03.592'	1150 Asphalt
New Richland (New Richland)	MN 30 (east-west)	Mile 169.7, approximately 2 miles east of New Richland (Waseca)	N43° 53.504' W093° 27.800'	1300 Asphalt
Pemberton (Freedom)	MN 83 (northwest-southeast)	Mile 11, approximately one mile southeast of Pemberton, MN (Blue Earth & Waseca)	N43° 59.852' W093° 46.082'	990 Asphalt
Pipestone. (Gray)	MN 30 (east-west)	Mile 12, approximately four miles east of Pipestone, MN (Pipestone)	N43° 59.628' W096° 13.556'	1900 Asphalt
Rice Lake (Winnebago)	MN 109 (east-west)	Mile 2.5, approximately two and a half miles east of Winnebago, MN (Faribault)	N43° 45.619' W094° 06.373'	750 Asphalt
Sanborn (Germantown)	US 71 (north-south)	Mile 46, approximately six miles south of Sanborn, MN (Cottonwood)	N44° 07.305' W095° 07.231'	2350 Concrete
Searles (Cottonwood)	MN 15 (north-south)	Mile 50, approximately one mile south of Searles, MN (Brown)	N44° 12.875' W094° 25.940'	2100 Asphalt

Sleepy Eye Bridge (Ridgely, Home, Fairfax)	MN 4 over Minnesota River (north-south)	Mile 73, approximately nine miles north of Sleepy Eye, MN (Brown & Nicollet)	N44° 25.975’ W094° 43.075’	1850 Concrete deck and approach slab; asphalt roadway
Springfield (Charlestown, North Star)	US 14 (east-west)	Mile 68.5, approximately six and a half miles west of Springfield, MN (Redwood)	N44° 14.312’ W095° 06.517’	2150 Asphalt
Waldorf (Vivian)	MN 83 (north-south)	Mile 1, approximately two miles south of Waldorf, MN (Waseca)	N43° 54.383’ W093° 41.837’	1250 Asphalt
Wells Bridge (Foster)	MN 22 over I 90 (north-south)	Mile 12, approximately six miles south of Wells, MN (Faribault)	N43° 39.442’ W093° 43.698’	1200 Concrete deck and approach slab; asphalt roadway
Willow Creek Bridge (Pleasant Mound)	MN 30 over Willow Creek (east-west)	Mile 127, approximately five miles west of Amboy, MN (Blue Earth)	N43° 53.696’ W094° 15.869’	530 Asphalt-topped concrete deck; concrete roadway and approach slab
Notes: [1] Annual Average Daily Traffic (AADT) as estimated in 2018 by MnDOT				

2.3 SAFETY PROCEDURES FOR SITE VISITS

The safety procedures (as approved by the Minnesota State University, Mankato Safety Officer) followed for site location visits are provided in Appendix A.

CHAPTER 3: DATA COLLECTION AND ANALYSIS

3.1 INSTRUMENTATION PLAN FOR SITE INSTALLATION

Table 8 lists the measurements and data gathered for each site. The instrument installation/post placement procedures are provided in Appendix B.

Site-specific weather information was measured and recorded using two data logging devices installed near the roadway and at approximately roadway elevation:

- Kestrel DROP D2 Wireless Temperature and Humidity Data Logger (Nielsen-Kellerman, Boothwyn, PA), operated with measurements on a 10-minute recording period.
- HOBO Pendant MX Temperature/Light Data Logger (Onset Computer Corporation, Bourne, MA), also operated with measurements on a 10-minute recording period.

The Kestrel and HOBO instruments were placed on posts located in the right of way outside of the ditch line or behind a guard rail or other vehicle barrier. Additional weather information representing regional wind and precipitation data were obtained from on-line databases of weather instrument readings at the nearest MnDOT-operated or airport weather station, listed by study site in Table 8.

Field conditions were documented through photography using two different camera systems. Handheld, high resolution photographs during site visits were taken using a Nikon D3000 camera with a 70-300 mm telephoto lens (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 post mounted at approximately a 6-ft height and enclosed in a wooden birdhouse-like structure.

Roadway pavement temperatures were measured in both point and area (graphical) format using a FLIR E6 (FLIR Systems, Inc., Wilsonville, Oregon) infrared camera (Figure 5). The FLIR is a non-contact device that measures heat, converts the heat measurement into an electronic signal, then displays the measurement on the screen in a color tapestry that correspond to temperature. The FLIR model E6 used in this experiment offers a 19,200 (160 x 120) pixel resolution, fine enough to see temperature differentials across one inch on proximal roadways and pavements. Concurrent photographs (visible light image) and thermographs (thermal signal image) are made to record the FLIR measurements (Figure 6).

Figure 3: Time-lapse cameras located in birdhouses and post mounted; Kestrel and Hobo meters being raised above snow drift level. Posts were eventually raised an additional five feet to remain above snow level. Searles location.

Figure 4: Time lapse camera being switched out for one with fresh batteries (left), and Kestrel and Hobo instruments being downloaded using iPad for communication (right). Ivanhoe location.

Figure 5: Measurement of roadway temperatures using FLIR E6.

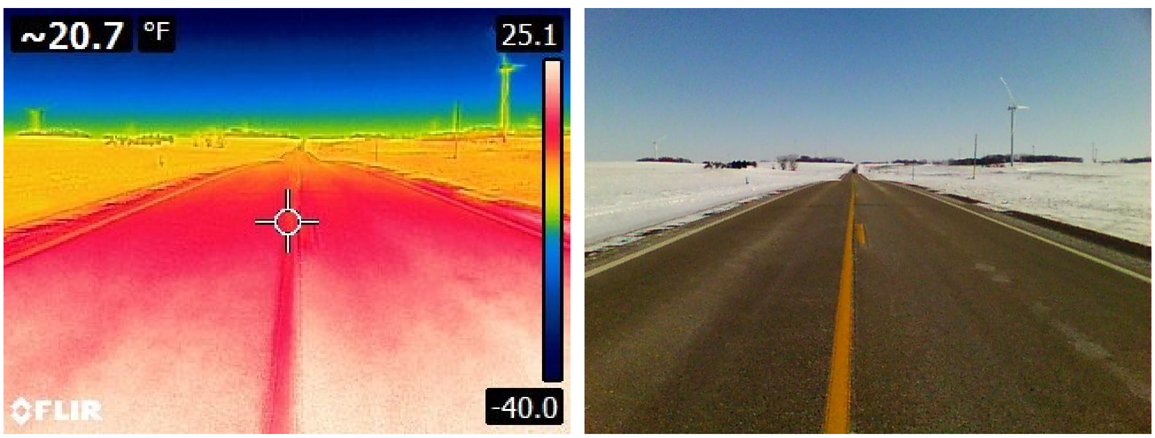

Figure 6: FLIR thermograph and concurrent photograph from measurement process shown in Figure 5. Ivanhoe location, 2/20/20: Air 10◦ F, sun 5615 lumens/ft2. Roadway temperature is value (20.7 ◦F) shown in upper left corner of thermograph; measurement is at point represented by circle in center for thermograph.

Deicer application was obtained through the Automated Vehicle Location (AVL) system operated by AmeriTrak (http://www.ameritrak.biz) for MnDOT. Deicer distribution systems record amounts of deicer distributed per lane mile, which is uploaded to the AVL database along with the vehicle location and speed, roadway and air temperature measurements. Figure 7 shows a typical output in Google Earth format for an operating truck; once truck operational time and location are known, deicer distribution information can be obtained.

Figure 7: Example AVL output in Google Earth format. Rice Lake location.

Table 8: Measurements made at locations

Location Name (Township)	On Site Measurements	Representative Weather Station	Primary Salt Distributing Truck(s) (Distribution Control System[1])	Truck Station Maintaining Site (MnDOT District)
Florence Bridge (Shelburne)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera	US 14 @ MP 6.59 (Lake Benton)	217577 (FA)	Marshall (8a)
Garden City (Garden City)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 60 @ MP 86.13 (Madelia)	216585 (FA)	Mankato (7a)
Ivanhoe (Royal)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	TH 19 @ MP 1.82 (Hendricks)	213562 (FA)	Marshall (8a)

Jeffers (Amboy)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 71 @ MP 43.48 (Jeffers)	204580 (DJ)	Storden (7b)
Judson Control (Cambria)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 60 @ MP 86.13 (Madelia)	206581 (DJ)	Mankato (7a)
Judson Ice Fog (Judson)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 60 @ MP 86.13 (Madelia)	206581 (DJ)	Mankato (7a)
Lake Benton (Lake Benton)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 14 @ MP 6.59 (Lake Benton)	217577 (FA)	Marshall (8a)
Maple River (Sterling)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 60 @ MP 86.13 (Madelia)	205582 (DJ)	Mapleton (7a)
New Richland (New Richland)	No on site measurements	US 14 @ MP 160 (Waseca)	217571 (FA)	Owatonna (6b)
Pemberton (Freedom)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 14 @ MP 160 (Waseca)	217509 (FA)	Mankato (7a)
Pipestone (Gray)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	Pipestone Municipal Airport	207524 (DJ)	Pipestone (8a)
Rice Lake (Winnebago)	Air Temperature, Dew Pt, Light	I-90 @ MP 118.6 (Blue Earth)	212577 (FA)	Wells (7a)

	Intensity, Roadway Camera (2)			
Sanborn (Germantown)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 71 @ MP 43.48 (Jeffers)	217572 (FA)	Windom (7b)
Searles (Cottonwood)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	New Ulm Municipal Airport	211563 (DJ)	Courtland (7a)
Sleepy Eye Bridge (Ridgely, Home, Fairfax)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	New Ulm Municipal Airport	212567 (DJ)	Sleepy Eye (7b)
Springfield (Charlestown, North Star)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 71 @ MP 43.48 (Jeffers)	216588 (FA)	Sleepy Eye (7b)
Waldorf (Vivian)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 14 @ MP 160 (Waseca)	217509 (FA)	Mankato (7a)
Wells Bridge (Foster)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera	I-90 @ MP 118.6 (Blue Earth)	212577, 213560, 215581, 218577 (all FA)	Wells (7a)
Willow Creek Bridge (Pleasant Mound)	Air Temperature, Dew Pt, Light Intensity, Roadway Camera (2)	US 60 @ MP 86.13 (Madelia)	205582 (DJ)	Mapleton (7a)
Notes: [1] Distribution control systems: (DJ) Dickey John Control Point system; (FA) Force America Spreader Control system				

3.2 RESULTS

Results of the 2019-20 winter measurements are presented in the following appendices:

- Appendix D – AVL Salting Events. Presents all found truck passes with deicer spreading, sorted by study location.

- Appendix E – Site Visits by Location and by Date. Listing of all visits to study locations by field personnel when obtaining measurements or taking photographs, sorted both by date and by study location.

- Appendix F – Light Intensity and Temperature/Dew Point Graphs for Each Site. Graphs present data for period November 1, 2019 to March 20, 2020.

- Appendix G – Pavement Temperature Measurements (FLIR Thermographs). Presents thermograph and roadway pavement measurements made during study location visits. Bridge sites include measurements of bridge deck, approach slab, adjacent roadway, and underlying roadway or landscape.

Regarding temperature and dew point data, there are some missing segments as a result of meter damage. Kestrel DROP D2 meters cease to function below about -17° F, and do not automatically restart when temperatures recover. Measurements restarted when the stopped meter was replaced.

Weather station (MnDOT or NOAA airport) databases were developed from on-line instrument history databases. Time lapse photographs were gathered and organized by date and time, and also developed into a working database. Due to the sizers of these databases, neither of these sources are included within this document.

3.3 ANALYSIS

Timelines and weather conditions of each deicer application day are provided in Appendix H, organized alphabetically by site location. Deicer passes were evaluated for application uniformity using the time span from 5 minutes before the time passing a site location to 5 minutes after, or about 2.5 miles before and 2.5 miles after, at 30 mph. Application uniformity is described using the following terms (note that lbs/LM is the abbreviation for pounds per lane mile):

- Same: +/- 25 lbs/LM, e.g., if 400 lbs/LM, varying between 375 – 425 lbs/LM
- Similar: +/- 25%/ LM, e.g., if 400 lbs/LM, varying in range of 300 – 500 lbs/LM (actually between 300-375 lbs/LM or 425 – 500 lbs/LM)
- More: +25-50%/ LM, e.g., if 400 lbs/LM, between 500 – 600 lbs/LM
- Less: -25-50%/ LM, e.g., if 400 lbs/LM, between 200 – 300 lbs/LM
- Significantly More: >50%/ LM, e.g., if 400 lbs/LM, greater than 600 lbs/LM

- Significantly Less: <50%/ LM, e.g., if 400 lbs/LM, less than 200 lbs/LM
- Hot Shot Treatment: spot treatment with adjacent areas being treated with zero deicer.
- Hot Shot Negative Treatment: spot gap in treatment between adjacent areas that are treated with deicer.

Deicing events, Appendix D, AVL Salting Events, were further studied during the analysis. Deicing event summaries are presented in a series of tables provided in Appendix I. Table I1 in Appendix I presents the number of passes when deicer was applied by day of month and by study location, presented in sub-tables a-e representing months from November to March. Passes include spreading rock salt, treated rock salt, liquid deicer, and salt:sand blends.

Treatment passes were further delineated by type and presented with rates in pounds per lane mile as a daily total deicer amount, organized by day of month and by study location, presented in sub-tables a-e representing months from November to March, also in Appendix I. Four separate tables are presented, organizing the study locations by geographic association or by as bridge sites:

- Table I2: Salting Events by Date – Southeast Project Area
- Table I3: Salting Events by Date – South Central Project Area
- Table I4: Salting Events by Date – Southwest Project Area
- Table I5: Salting Events by Date – Bridge Sites

Appendix J presents a table of generalized weather broken out by project area (Southeast, South Central, Southwest), developed from the Minnesota Public Radio Updraft blog (https://www.mprnews.org/weather-and-climate/updraft) using a combination of posts representing both storm forecast and day-after reflection.

CHAPTER 4: EVALUATION

4.1 DEICER APPLICATION POLICY

Determining a hot shot or extra deicing efforts requires first establishing a baseline deicing level. MnDOT's Maintenance Manual addresses removal of snow and ice from trunk highways in Minnesota in Chapter 2. By both law (Minnesota Statute Chapter 160.215) and policy, snow and ice removal operations are to emphasize plowing to a most practicable degree then use chemical treatments for deicing. In the law, it is explicitly stated that plowing is preferred in order to:

- Minimize the harmful or corrosive effects of salt or other chemicals upon vehicles, roadways, and vegetation;
- Reduce the pollution of waters; and
- Reduce the driving hazards resulting from chemicals on windshields.

From the Maintenance Manual Section 2-8.0 regarding chemical management:

> *The type and amount of each chemical to be used in snow and ice control operations should correspond to such variable factors as pavement temperature (rising or falling), type and amount of precipitation, wind velocity, wind direction, traffic volume, likelihood of trapping subsequent snowfall, amount and type of accumulation, weather forecasts, etc. Supervisors should make an effort to reduce chemical usage wherever possible. Chemical application should be restricted to amounts necessary to meet level of service requirements…*
>
> *This statute* (Minnesota Statute Chapter 160.215) *does not arbitrarily prohibit the use of chemicals on the roadway. Chemicals and chemicals with abrasives may be used under the conditions specifically outlined in the law.*
>
> *When, where or the amount of chemicals to be placed on a roadway cannot be predetermined precisely. Each circumstance involving a hazardous condition and the particular need for vehicle traction must be judged on its own merits with consideration for safety of the traveling public using that particular roadway at that particular time.*

The guidance of this section specifically encourages supervisors and operators to adjust application rates as needed in their judgement, based on their training, experience and knowledge of physical chemistry/deicer thermodynamics. Base line application rates, provided as a starting point, are addressed in Section 2-8.01.01 of the Maintenance Manual:

> *Chemical and sand application rates are determined by the operator or as recommended by the maintenance supervisors. Operators must be trained to consider weather and road conditions when determining rates. Application rate guidelines are provided in Table 2-8.01.01A;* ***rates found in this table are not fixed numbers and can/should be adapted to meet the roadway***

classification, weather conditions and experience of each district. (emphasis included in original text)

Table 2-8.01.01A of the Maintenance Manual uses pavement temperature and trend plus weather condition as factors to guide maintenance actions and deicer/abrasive application rates.

The establishment of a standard of care for snow and ice removal for roadway maintenance is a critical component to the determination of application rate. Two aspects comprise a standard of care: the pavement clearance quality level and the post-storm time to achieve (regain) this quality level. In Minnesota, this policy standard is defined in the Maintenance Manual Section 2-3.02 with the following provisions:

- Snow and ice removal operations begin when conditions, or forecasted conditions, may result in the loss of "bare lane." Bare lane is defined as: driving lanes will be free of ice and snow between the outer edges of the wheel paths and have no greater than 1 inch accumulation on the center of the roadway.
- Bare Lane Regain Time or "Regain Time" is the time from the end of the event until bare lane is obtained… The Bare Lane description is the same for all routes. The Target Regain Time is dependent on the classification of roadway.

Study locations used in this evaluation are classified by AADT into three levels of bare lane regain time targets:

- Rural commuter highways (2,000-10,000 AADT) – target regain time 4 – 9 hours
- Primary highways (800-2,000 AADT) – target regain time 6 – 12 hours
- Secondary highways (Under 800 AADT) – target regain time 9 – 36 hours

Shorter bare lane target regain times can influence additional deicer use, as deicer action can be emphasized in order to encourage plowing effectiveness, particularly in preventing and removing compaction.

4.2 DEICER HOT SHOT APPLICATIONS

Hot shots are defined as a significant increase in deicer application, in either a single location or over a short distance of snowplow operation. Hot shots may be seen in the context of a deicing continuum (Figure 8), ranging from salt nowhere to salt everywhere, and including spot treatment and partial treatment as middle levels. Hot shots can certainly be spot treatment, but their opposite also exists as a "hot shot negative" or a gap in treatment, also in either a single location or over a short distance of snowplow operation. Hot shots or hot shot negatives can be applied by a trained and experienced operator for many reasons if change is created or observed in short distances along the roadway:

- Location factors
    - Topographic features that accentuate snowfall or drifting

  - Structural features such as buildings or trees that direct drifting onto the roadway or create shaded spots
  - Roadway geometric features that trap more precipitation, or have insufficient drainage
  - Past accident locations
  - Traffic amount and pattern
- Weather factors
  - Pavement temperature and direction of change
  - Sunlight amount, angle and direction
  - Precipitation form and amount
  - Air temperature and direction of change
  - Wind speed and direction
  - Weather forecast for current route
- Environmental factors
  - Sensitivity of receiving waterways
  - Sensitivity of roadside vegetation
  - Aquifer quality and use
- Management factors
  - Level of service and standard of uniformity
  - Available staff
  - Available deicing equipment
  - Equipment capability
  - Staff training
  - Deicer quality and composition
  - Deicer price
  - Routes for snowplows and deicer distribution equipment
  - Plow route cycle time
  - Public acceptance

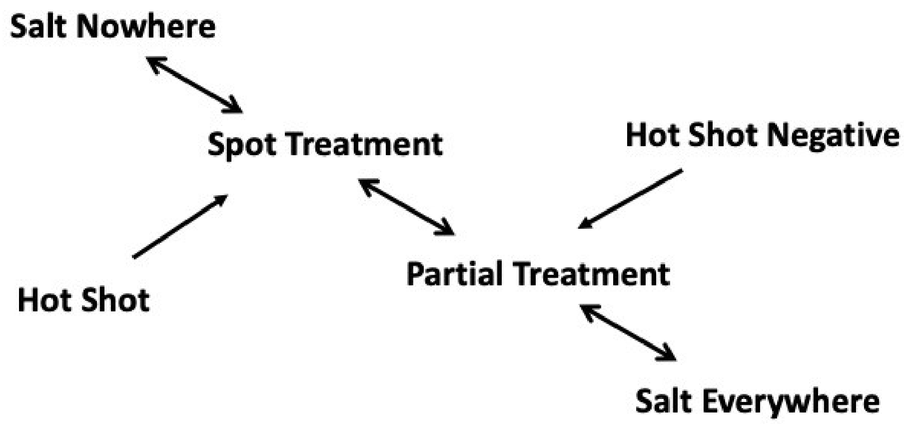

Figure 8: Deicing continuum.

An additional method was used to identify hot shots in the deicing records of the study locations. The season long, cumulative salt loading was developed for each location by summing up all treatments through the winter season to a given date. This cumulative salt loading was graphed (Appendix K) and evaluated for unusual jumps in salt application by day (storm event). The cumulative salt loading was then compared with the cumulative salt loading for both similar sites and control sites. Hot shots were identified by atypical jumps in the cumulative salt loading, while troublesome locations may show season-long higher levels of deicer application.

4.3 CONTROL SITE EVALUATIONS

Control sites (Judson Control, Jeffers, Sanborn, Springfield) were effectively reduced by one because AVL deicing data could not be located for the Sanborn location, as discussed in Task Report 4. Proportions of hot shot applications are listed by month and by whole winter season for control sites in Table 9. Hot shot application proportions varied widely across the three remaining sites, from limited application of 5% of the total treatments being hot shots at Judson Control, to Jeffers receiving an application proportion of 25% hot shots, to Springfield receiving an application proportion of 43% hot shots. The high frequency use of hot shots at Springfield was not matched by hot shot applications at any other non-bridge location in this study.

Total amounts of deicer placed, ranked from lowest to highest, were 12,300, 19,620 and 23,450 lbs/LM for Jeffers (AADT 1250), Springfield (AADT 2150) and Judson Control (AADT 1700), respectively. Jeffers would have even been less except for a significant storm event on November 7th when 2,300 lb/LM of salt was applied. These amounts are not completely explained by AADT, as Springfield has 26% more traffic but received 16% less salt than Judson Control (contrary to a trend of more salt with more AADT) while Jeffers, with 26% less traffic received 48% less salt than Judson Control (matching a trend of more salt with more AADT).

Overall, the seasonal forms of the cumulative salt load graphs for each site (Appendix K) are highly similar, even though amounts differ, suggesting uniform procedure across a range of geography representing a 50-mile center of the whole study region (135 miles total breadth). As is appropriate to winter in Minnesota, even control locations experience difficult weather conditions such as clear-day drifting and roadway snow compaction (Figure 9).

Table 9: Deicer treatment comparison for control study locations

Date	Judson Control (MN 68)	Jeffers (MN 30)	Sanborn (US 71)	Springfield (US 14)
November	9 (9S+0HS)	4 (3S+1HS)	did not record	9 (5S+4HS)
December	13 (13S+0HS)	0	did not record	1 (0S+1HS)
January	33 (29S+4HS)	8 (6S+2HS)	did not record	22 (18S+4HS)
February	21 (21S+0HS)	4 (3S+1HS)	did not record	20 (7S+13HS)
March	0	0	did not record	4 (2S+2HS)
Winter Total Treatments	76 (72S+4HS)	16 (12S+4HS)	did not record	56 (32S+24HS)
Hot Shot Proportion of All Treatments	5%	25%	did not record	43%
Winter Total Cumulative Salt Loading	23,450 lbs/LM	12,300 lbs/LM	did not record	19,620 lbs/LM
AADT	1700	1250	2350	2150

Figure 9: Drifting on roadway, with compaction developing due to vehicle transit through drifting snow at a control site on a clear day. Sanborn location, February 20, 2020.

4.4 DRIFTING SITE EVALUATIONS

Drifting sites (Pemberton, Waldorf and Searles, all with a north-south roadway orientation) seem to have needed hot shots mostly during the later months of the winter of study (Table 10), as only two hot shots total were used across the three sites in November and December. Note that Searles site appears to have no AVL salting data recorded between December 13 and February 8, a period of about 8 weeks in length. Besides loose snow and wind, it appears a consistent snowpack may need to be developed on land adjacent to a highway before drifting may occur. Dry (dew point temperatures below 15 °F) conditions may also increase the occurrence of drifting.

Review of specific storm day records (Appendices H and I) provided much insight. Mid-January showed hot shots applied 3 to 5 times each at Pemberton and Waldorf, while February 9-10 had 7 hot shot applications at Pemberton but none at Waldorf (only 10 miles to the south of Pemberton), an unusual difference that may be a reflection of specific conditions of roadway/wind directions. February 18-21 showed significant hot shot applications at all three sites: 7 applications at Pemberton, 4 applications at Waldorf and 2 applications at Searles. These heavy applications reflect that February had two periods of severe cold and very dry conditions with blowing snow; heavy compaction formed that required significant deicer application to remove (Figure 10, from about 15 miles south of Waldorf).

Table 10: Deicer treatment comparison for drifting study locations

Date	Pemberton (MN 83)	Waldorf (MN 83)	Searles (MN 15)
November	1 (1S+0HS)	1 (1S+0HS)	7 (6S+1HS)
December	1 (0S+1HS)	0	1 (1S+0HS)
January	21 (15S+6HS)	21 (18S+3HS)	did not record
February	21 (7S+14HS)	11 (8S+3HS)	11 (9S+2HS)
March	0	0	0
Winter Total Treatments	44 (23S+21HS)	33 (27S+6HS)	19 (16S+3HS)
Hot Shot Proportion of All Treatments	48%	18%	16%
Winter Total Cumulative Salt Loading	12,550 lbs/LM	8,600 lbs/LM	10,350 lbs/LM
AADT	990	1250	2100

Figure 10: Compaction on roadway. TH 22, 0.5 mile north of Wells Bridge location, February 13, 2020.

Hot shots were not used much at Searles (4 total hot shots for the entire winter); this was an unexpected result. The Seales location is on the east side of a hill with significant medium height tree structure and shrubbery associated with a cemetery. The road is clearly in the lee of the hill, protected from westerly and northwesterly winds typical of winter at the location (Figure 11); the vegetation and the hill lee clearly create a trap zone for snow as drifts built up to significant depths during the study winter. However, the hill may be set back sufficiently to create drifting protection (Figure 12) of the roadway so that hot shot negatives were more likely than hot shot applications, even on the flanks of the hill where wind streams and drifting would be expected.

Comparison of the cumulative salt loadings between the three drifting sites (Table 10 and Appendix K) showed total season values of between 12,550, 8,600 and 10,350 lbs/LM for Pemberton, Waldorf and Searles, respectively, although Searles appears to be missing about 8 weeks of data as noted previously. That there is about a 50% difference between Waldorf and Pemberton, even though they are on the same highway with the same truck/operator personnel and only 10 miles apart, was striking. Pemberton has lower AADT than Waldorf (990 versus 1250), so the higher amount at Pemberton is inversely correlated with traffic level. Geographies and vegetation features appear similar. Perhaps the difference is simply a reflection of typical deicer application variation; no other factor was identified.

Searles value of 10,350 lbs/LM was midway between the values for the other two drifting sites, but if data is indeed missing the result could be perhaps 25% or more higher. A value of 15,000 lbs/LM would perhaps be reflective of higher AADT at the Searles site, challenging the trend of higher traffic levels being inversely correlated with the salt amount.

Figure 11: Drifts formed at Searles study location, February 20, 2020, view south.

Figure 12: Drifting gap at Searles study location, February 7, 2020, view south.

Note that the season-long cumulative salt load amounts for drifting sites (Table 4) are about half the level of the two higher values observed for the control sites (Table 10), although the highest drifting site value (from Pemberton) more nearly matches the lowest control site value (from Jeffers). At least some of this reduced application is likely due to the lower traffic levels for the drifting sites, but this relationship certainly does not reflect a drifting location-specific “bad road” condition that would necessitate additional salting.

4.5 ICE FOG SITE EVALUATIONS

Ice fog locations (Rice Lake, Maple River, Willow Creek, and Judson Ice Fog) were sites monitored for hot shot application due to the formation of ice fog as roadway frost or black ice conditions (Figure 13). While there was no doubt that these locations experienced conditions conducive to ice fog-deposited roadway ice many times through the winter season of study, the question is whether hot shot deicing was done to combat the ice effects.

Figure 13: Ice fog-deposited roadway ice visible outside of wheel tracks. Waldorf location, December 19, 2019.

Table 11 lists the proportions of hot shot treatments for the ice fog study locations. The Judson Ice Fog location (1750 AADT) received only 6 total hot shot treatments through the whole winter (9% of all treatments), mostly applied during January. Conversely, the Rice Lake location (750 AADT) received 7 hot shot treatments in November alone, another in December, 5 more in January, and 2 more in February for 15 total hot shot treatments (29% of total treatments as hot shots) for the entire winter. The Willow Creek location (530 AADT) received 1 hot shot treatment in December and 3 more in February for a winter total of 4 hot shot treatments (8% of total treatments as hot shots). The Maple River location (1150 AADT) received 1 hot shot treatment in November, 1 in December, 4 in January, and 1 in February for a winter total of 7 hot shot treatments (13% of total treatments as hot shots).

No pattern for hot shot treatments was observed other than to address likely drift snow conditions. Hot shots were placed most times when winds were greater than 10 mph and snowing, unlikely to create frost on roadways which typically requires quiescent conditions.

Table 11: Deicer treatment comparison for ice fog study locations

Date	Rice Lake (MN 109)	Maple River (MN 30)	Willow Creek (MN 30)	Judson Ice Fog (MN 68)
November	9 (2S+7HS)	5 (4S+1HS)	8 (8S+0HS)	6 (6S+0HS)
December	1 (1S+0HS)	5 (4S+1HS)	6 (5S+1HS)	7 (7S+0HS)
January	22 (17S+5HS)	30 (26S+4HS)	23 (23S+0HS)	33 (28S+5HS)
February	22 (20S+2HS)	11 (10S+1HS)	12 (9S+3HS)	19 (18S+1HS)
March	0	1 (1S+0HS)	0	0
Winter Total Treatments	51 (36S+15HS)	52 (45S+7HS)	49 (45S+4HS)	65 (59S+6HS)
Hot Shot Proportion of All Treatments	29%	13%	8%	9%
Winter Total Cumulative Salt Loading	12,250 lbs/LM	19,900 lbs/LM	15,250 lbs/LM	20,000 lbs/LM
AADT	750	1150	530	1750

No obvious pattern was found attributable to low traffic volume either (4, 15, 7, and 6 hot shot treatments for highway traffic volumes of 530, 750, 1150 and 1750 AADT, respectively); the very low volume roadway of 750 AADT for the Rice Lake location received double the hot shot treatments of the other roadways, while the similarly very low volume roadway of 530 AADT for the Willow Creek location received the lowest number of hot shot treatments.

There was a large variation in total applied salt ranging from 12,250 lbs/LM for the Rice Lake location to 20,000 lbs/LM for the Judson Ice Fog location. The Maple River location almost matched the group high amount with 19,900 lbs/LM, with the Willow Creek location being in the middle of the distribution at 15,250 lbs/LM. As with other attempts at pattern discernment for this group, there was no pattern identified as to the cumulative salt loading observed over the season of study as related to traffic volume.

It appears that ice fog is not a condition that warrants hot shot treatments to any significant degree, at least on primary and secondary highways. Perhaps anti icing treatments that leave residual deicer on roadways prior to storms (Figure 14) is a more common approach than hot shot treatment related to specific points of geography.

Figure 14: Salt residual on pavement. Rice Lake location, February 25, 2020.

4.6 BLOW ICE SITE EVALUATIONS

Sites studied for blow ice (Pipestone, Lake Benton, Ivanhoe) are all in southwestern Minnesota, a region known for persistent high wind conditions related to the topographic high known as Buffalo Ridge that is oriented from northwest to southeast. Pipestone is west of the Ridge, Lake Benton is on the Ridge, and Ivanhoe is just east of the Ridge. The National Weather Service in Sioux Falls, South Dakota has written about the high winds of up to 60 mph caused in localized areas around the Ridge, wind speeds that may not be observed even just 20 miles away, depending upon specific conditions (https://www.weather.gov/fsd/news_buffaloridgewind). The blow ice locations certainly experienced such high winds during the course of the study winter.

However, blow ice formation also requires two other conditions: dry air conducive to the erosion of previously fallen snow, and warm roadways for the capture of the eroded and then blowing snow. Such warm roadways create conditions supportive of “refreeze”, in which the deposited snow will first melt then refreeze as the conditions cool. Refreeze can also occur when salt brine waters become more dilute through additional melt of deposited snow; the dilution shifts the melt point upward leaving an ice-forming mixture at a given temperature. Figures 15 and 16 present observations of blow ice formed on a roadway east of the Pipestone study location site.

Figure 15: Blow ice on roadway, formed by dry snow drifting across sunlight-warmed pavement, melting then refreezing during deposition. TH 30, 2 miles east of Currie, MN, February 20, 2020

Figure 16: Dry snow drifting across sunlight-warmed pavement forming blow ice on roadway. TH 30, 2 miles east of Currie, MN, February 20, 2020

These necessary conditions may be reflected in the salting records summarized in Table 12 for the site locations. While deicing was prevalent during both early and late November periods, only one pass was a hot shot out of 26 total treatments on the three sites.

Table 12: Deicer treatment comparison for blow ice study locations

Date	Pipestone	Lake Benton	Ivanhoe
November	8 (8S+0HS)	8 (3S+5HS)	10 (8S+2HS)
December	0	0	8 (8S+0HS)
January	4 (4S+0HS)	12 (7S+5HS)	18 (12S+6HS)
February	7 (6S+1HS)	11 (4S+7HS)	3 (1S+2HS)
March	2 (2S+0HS)	4 (3S+1HS)	1 (1S+0HS)
Winter Total Treatments	21 (20S+1HS)	35 (21S+14HS)	40 (32S+8HS)
Hot Shot Proportion of All Treatments	5%	40%	20%
Winter Total Cumulative Salt Loading	13,800 lbs/LM	14,800 lbs/LM	18,900 lbs/LM
AADT	1900	2000	1200

December had only a single storm sequence which needed treatment at Ivanhoe only, none at the other locations; no December treatments were hot shots. However, in January and February approximately one third to one half of all treatments were hot shots (11 of 34 and 10 of 21 in January and February, respectively, totaled across all three blow ice locations). There were differences between the sites, as the Pipestone location received only 1 hot shot for the whole year (5% of total treatments as hot shots) while Lake Benton location received 14 hot shots (40% of total treatments as hot shots) and Ivanhoe 8 hot shots (20% of total treatments as hot shots).

The cumulative salt loading (Appendix K) had a unique pattern: at all three sites, two storms accounted for over half of the total season salt load, but they aren't the same storm days at each site. At Pipestone, the two significant storms of early November and early February required 4600 and 4200 lbs/LM, respectively. At Lake Benton, the two significant storms of early January and early February required 2600 and 6100 lbs/LM, respectively. At Ivanhoe, the two significant storms were in early December and early January required 6300 and 5500 lbs/LM, respectively. At each site, other storm events typically required perhaps 1000 – 1500 lbs/LM.

The whole winter salt load totals were 13,800, 14,800 and 18,900 lbs/LM for Pipestone, Lake Benton, and Ivanhoe locations, respectively. The difference in magnitude for the Ivanhoe location relates to how much was placed in the two big storm events, discussed above. Otherwise the salt loading graphs are generally similar if one accepts that the cumulative salt curves are dominated by the big storm applications for each site.

Like drifting and ice fog, blow ice does not seem to be a significant driver of hot shot treatments; rather, the region of blow ice appears to require broad treatments of occasional high intensity to combat adverse winter roadway conditions.

4.7 BRIDGE STUDY LOCATION EVALUATIONS

Four bridges were studied: Florence Bridge (US 14 over MN 23), Sleepy Eye Bridge (MN 4 over the Minnesota River), Wells Bridge (MN 22 over I90) and Willow Creek (MN 30 over Willow Creek). Willow Creek bridge was also a study location for drifting evaluation. Monthly breakdowns of non-hot shot and hot shot treatments, and season totals of treatments and cumulative salt loadings are listed in Table 13 by bridge study locations, with complete daily loadings listed in Appendix I.

Bridge study locations received hot shot treatments at a high proportion of all treatments, but not uniformly so.

- Willow Creek Bridge, a short (76 ft length, east-west orientation) and low single span bridge supporting a low volume secondary highway over a small watercourse, had only 8% of all treatments as hot shots;
- Both Florence Bridge (300 ft length, east-west orientation) and Wells Bridge (324 ft length, north-south orientation), multi-span high bridges supporting primary highways over another primary highway plus a railroad and an interstate highway, respectively, had nearly 60% of all treatments as hot shots; and,
- Sleepy Eye Bridge (490 ft length, north-south orientation), a multi-span low bridge supporting a primary highway over a wide river had only 15% of all treatments as hot shots.

Bridge length does not seem to determine hot shot proportion, as Sleepy Eye Bridge is the longest of the bridges studied but had few hot shot treatments similar to the shortest bridge of the study, Willow Creek Bridge. Bridge orientation also does not seem to determine hot shot proportion, as Sleepy Eye Bridge and Wells Bridge are both north-south oriented bridges of similar length that had widely dissimilar proportions of hot shot treatments.

Table 13: Deicer treatment comparison for bridge study locations

Date	Florence Bridge (US 14 over MN 23)	Sleepy Eye Bridge (MN 4 over Minnesota River)	Wells Bridge (MN 22 over I 90)	Willow Creek Bridge (MN 30 over Willow Creek)
November	3 (2S+1HS)	20 (20S+0HS)	8 (2S+6HS)	8 (7S+1HS)
December	3 (2S+1HS)	17 (17S+0HS)	3 (0S+3HS)	6 (6S+0HS)
January	23 (11S+12HS)	44 (33S+11HS)	36 (18S+18HS)	23 (23S+0HS)
February	8 (1S+7HS)	21 (17S+4HS)	17 (8S+9HS)	12 (9S+3HS)
March	5 (2S+3HS)	0	3 (0S+3HS)	0
Winter Total Treatments	42 (18S+24HS)	102 (87S+15HS)	67 (28S+39HS)	49 (45S+4HS)
Hot Shot Proportion of All Treatments	57%	15%	58%	8%
Winter Total Cumulative Salt Loading	18,400 lbs/LM	46,080 lbs/LM	20,510 lbs/LM	15,250 lbs/LM
AADT	1350	1850	1200	530

Similarly, total deicer application for the winter season shows a lack of uniformity related to Sleepy Eye Bridge; the other three bridges vary across a moderate 35% range. Sleepy Eye Bridge total deicer is almost 300% the value of the least treated bridge, and over 200% the value of the next most treated bridge. Likely much of this difference is related to geographic setting, as Sleepy Eye Bridge approach roadways are curved, tree-surrounded declines with high levels of shading and cold air trapping potential. These highway sections are likely difficult to deice, and the bridge appears to be treated at high levels without hot shot treatment therefore at the same level as the approach highway sections. The three other bridges are all in open areas with few if any trees.

Note that the pattern of salting suggested by the cumulative salt load graph for bridge locations (Appendix K) is quite similar for each of the four studied bridges; only the magnitude of treatment at Sleepy Eye Bridge is unusual and high compared to the other studied bridge locations.

The overall lack of patterns in hot shot treatments suggests that plow operators are making independent decisions about bridge deck treatment amounts based on observed conditions of temperature, wind and light. The warning sign "Bridge Deck Freezes Before Roadway" is a familiar feature around bridges and strongly connotes that temperature differentials of bridge decks to adjacent roadways is a well-known occurrence. Figure 17 illustrates the difference from a site visit at Florence Bridge location.

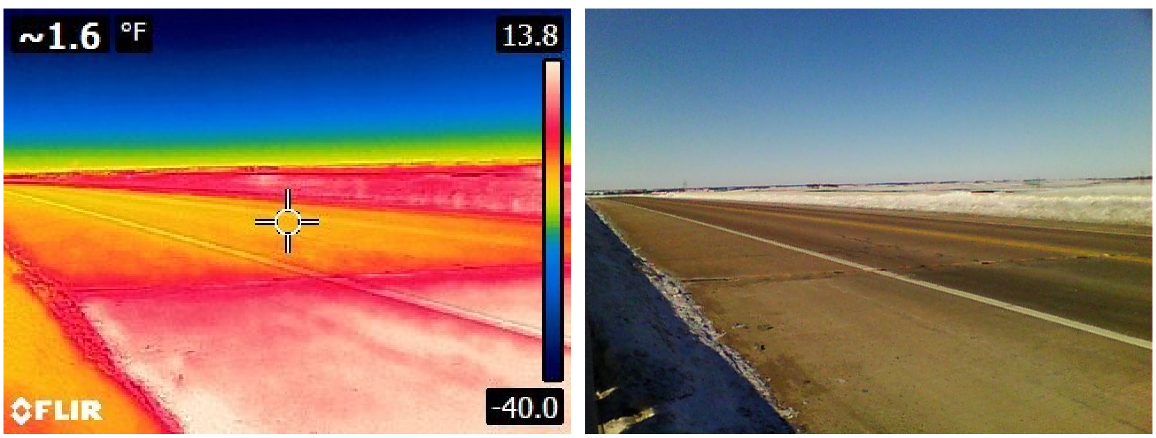

Figure 17: Bridge deck temperature difference of 12◦ F compared to temperature of adjacent approach slab. Differential occurs over a roadway travel distance of approximately 6 feet and is a typical or even a low value from what was observed during windy conditions on other days. Florence Bridge location, February 20, 2020.

Roadway temperatures were measured during instrument tending visits through the winter season of study. Appendix L, Table L1 presents a summary of all bridge deck, approach slab and adjacent roadway measurements made during the winter study season. Tables L2, L3, L4 and L5 in Appendix L list the temperature measurements alongside air temperature, wind and light measurements for Florence Bridge, Sleepy Eye Bridge, Wells Bridge and Willow Creek Bridge locations, respectively. Temperature differentials of 10° F or more were often observed, generally associated with cooler air temperatures with at least some wind.

Such temperature differentials are important in the consideration of deicer performance, as ice melt capacity (IMC) of a deicer can be greatly reduced by a 10° F or more temperature difference. From previous work (Druschel, 2012), IMC was found to be halved if the temperature changed from 28° F to 20° F, and went to zero (unable to melt ice) at 12° F. These temperature ranges could be found on bridge decks; in such situations a driver could assume one level of deicing consistency on an open road then find a much reduced or non-existent level of deicing on a bridge deck within a travel time of less than 0.1 s if traveling at highway speed.

4.8 ROADWAY SHADING SITE EVALUATIONS

Two sites were specifically evaluated for the effects of shading on deicer application amount: Garden City location (US 169, AADT of 2800, oriented north-south with a high bank and shading trees on the west side) and New Richland location (MN 30, AADT of 1300, oriented east-west with shading trees on the south side). Salting applications were remarkably different on these two sites (Table 14). The Garden City location had 24 total deicer passes for the whole winter season, with 8,350 lbs/LM total applied; 9 passes were hot shot (38% of total treatments as hot shots). This season total is the lowest amount observed across all locations in the whole study (excepting one location where applications did not record). The New Richland location had 68 total deicer passes for the whole winter season, with 22,550 lbs/LM total applied; for 62% hot shot treatment proportion. Over 50% of the total deicer applied at New Richland location was associated with one storm sequence in late November.

Table 14: Deicer treatment comparison for roadway shading study locations

Date	Garden City (US 169)	New Richland (MN 30)
November	5 (5S+0HS)	13 (2S+11HS)
December	1 (1S+0HS)	34 (17S+17HS)
January	4 (2S+2HS)	4 (1S+3HS)
February	14 (7S+7HS)	17 (6S+11HS)
March	0	0
Winter Total Treatments	24 (15S+9HS)	68 (26S+42HS)
Hot Shot Proportion of All Treatments	38%	62%

Winter Total Cumulative Salt Loading	8,350 lbs/LM	22,550 lbs/LM
AADT	2800	1300

Perhaps the truck traffic or the additional overall traffic at Garden City decreases the need for deicing. Hot shots were used predominantly in February at Garden City, when half of the treatments were applied as hot shots, likely associated with compaction removal influenced by limited late-winter sun (described in Section 4.4 for nearby drifting study locations).

The high proportion of hot shot treatments at New Richland is uniform throughout the winter season, with every month having hot shots as the majority treatment method. Apparently, the shading of the roadway from the south side necessitates extra treatment all winter long; this location was the only place in the entire study that had winter-long uniform hot shot proportion. Excepting the one significant storm requiring salting in late November, the total amount of treatment at New Richland approximated the amounts at the drifting study locations nearby; just the hot shot proportion of treatment was different, meaning non-shaded roadway sections at New Richland were salted less than the nearby drifting sites.

As discussed previously regarding bridge deck cooling, temperature differentials can have significant effects on deicer effectiveness. Observed here, roadway shading can cause significant temperature differentials. Figure 18 displays a temperature difference of 28° F measured over a roadway length of 4 feet. With cold spots occurring in this pattern, it is no wonder that hot shot treatments are used on shaded roadways.

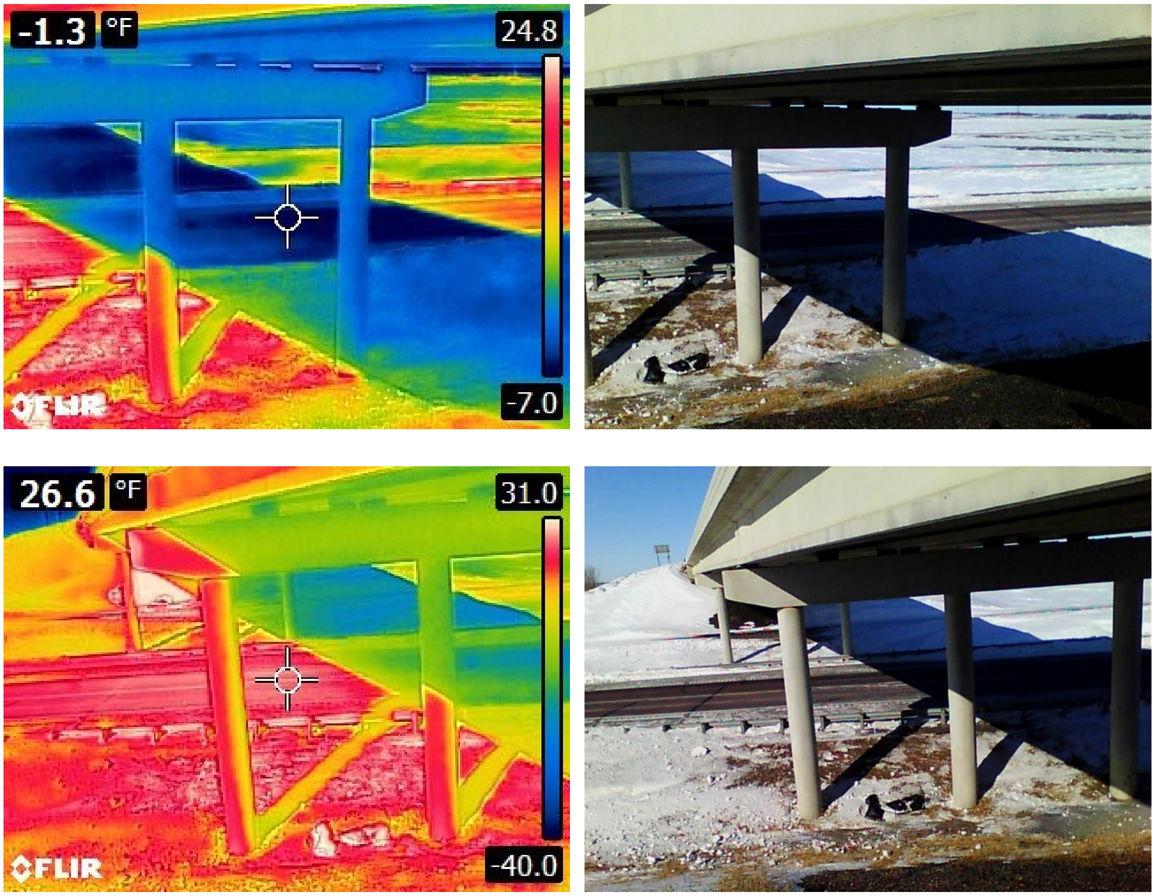

Figure 18: Pavement temperature differential of 28◦ F caused by shadow under bridge. Differential occurs over a roadway travel distance of approximately 4 feet. MN 23, Florence Bridge location, February 20, 2020. Air temperature 7◦ F, light intensity 5198 lumen.

CHAPTER 5: CONCLUSIONS

Nineteen state highway locations around south-central and southwestern Minnesota were evaluated during winter 2019-20 for the application of deicer "hot shots," extra levels of salt or other chemical treatments used to deice roadways and maintain roadway driving levels of performance. Locations were selected based on previous recordkeeping that indicated difficult winter driving conditions including drifting, blow ice formation, ice fog (black ice formation), roadway shading, and exposed bridge decks. Control locations were also identified. Highways selected were representative of low-traffic-volume roadways classified as rural commuter, primary, and secondary roads.

Instruments at the site locations recorded highway level air temperature, dewpoint, and light intensity, while regional weather stations were used for measurements of precipitation amount and type, and wind speed and direction. Onsite time-lapsed photography was also gathered to verify roadway conditions. Deicer application amounts were gathered from AVL measurements made onboard plow trucks; a total of 909 application passes by plow trucks were found for the nineteen locations of study for winter 2019-20. Hot-shot treatments were observed to comprise 28% of the total treatments.

Hot-shot treatments were evaluated across the five "bad road" conditions and the control locations for patterns of treatment; few patterns were found, and none found were strong. Drifting, which seems to be a condition of difficulty related mostly to the middle- to late-winter months, did not appear to require hot-shot treatments but rather more broadly based treatments. Blow ice formation, also a middle- to late-winter occurrence, also received broadly based treatments rather than hot-shot treatments. Ice fog locations at which black ice can form seemed to be treated through a reliance on traffic and anti-icing rather than localized salt treatment such as by hot shots. Bridge decks exposed to wind and roadways experiencing mid-day shading were treated with hot shot approaches in substantial proportions; both situations had temperature differentials that could create significant differences in roadway deicing. Control locations illustrated that a wide variation in treatment levels could exist even between similar sites in similar geographies.

Traffic affected deicer operations in what seemed to be two opposing directions: higher levels of traffic brought higher managerial and policy expectations for roadway service level, increasing the motivation to use greater amounts of deicer, yet higher levels of traffic provided greater effectiveness of applied deicer through more mixing and churning of snow/ice compaction. Because of these divergent factors, no patterns of traffic level and use of hot-shot treatments were consistently observed for the study locations.

In summary, hot-shot treatments were observed, but neither at the proportions nor in the patterns expected for the studied situations of winter roadway difficulty. Operator judgment appeared to be much more important than any other defined factor, as substantial differences were noted even at a location pair treated by the same operator on the same route, just 10 miles apart on the same highway.

Therefore, when balancing winter driving level of service and costs, with costs not only measured in money but also in labor, equipment, and environmental impact, perhaps the best investments will be in enhanced operator training and the sharing of experience; roadway and weather information systems; and public education and the management of expectations.

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