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Optimizing Anti-icing Operation for Winter Roadway Treatment Using A Decision-Making Tool

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OPTIMIZING ANTI-ICING OPERATION FOR WINTER ROADWAY TREATMENT USING A DECISION-MAKING TOOL

by

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ABSTRACT

Managing winter roadway treatment can be a challenge where winter is not severe, but snowfall is experienced a few times a year. Winter weather makes the road dangerous and challenging to travel. Most US states have approached and implemented different winter road maintenance practices to make transportation of goods, services, and people uninterrupted. However, the state of Georgia has always struggled to deal with winter weather. Recently, there has been some progress. The Georgia Department of Transportation prepared a winter road treatment plan in 2019, and they are still working on improving it. Increasing emphasis on pre-treating the road rather than relying heavily on snow plowing and other post-treatment is the current trend in winter road maintenance. Pre-treatment reduces chemical use and has several other benefits. In this research, a pre-treatment requirement model was developed to calculate the amount of brine required to melt different snow and ice amounts. In the last three years, Georgia faced a few snow events; three were selected for analysis using the developed model. The study revealed that adjusting the pre-treatment amount at smaller snow events can eliminate the need for post-treatment. The model suggests that different parts of a route require different amounts of pre-treatment. The application of the brine amount can be adjusted based on snow accumulation prediction by the model. The model sensitivity analysis showed that more snow is accumulated at lower temperatures, and the effectiveness of brine in melting snow diminishes. Higher wind speed increases snowmelt resulting in lowered brine application requirements. The decision-making tool can optimize the amount of brine used by suggesting location and pre-treatment amount. The output of the model can be used in better decision making on winter road pre-treatment.

INDEX WORDS: Winter road maintenance, Winter road treatment, Anti-icing, De-icing, Pre-treatment, Winter operation.

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DEDICATION

To my mother who never worried about my research, rather worried if I had eaten anything.

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CHAPTER 1: INTRODUCTION

1.1 Background

More than 70 percent of the US population lives in snowy regions. Roads in these regions receive more than 5 inches of average snowfall annually. Snow and ice reduce friction between the pavement and the vehicle, which results in the slow-speed drive and reduces the capacity of roadways (Federal Highway Administration, 2017). Winter weather conditions are associated with an increase in crash frequency, and maintenance operations can help mitigate several harmful impacts (Zhang et al, 2019). Winter road maintenance (WRM) operations are the strategies applied to improve the level of service (LOS) on roadways. Strategies undertaken include plowing, de-icing, anti-icing, sanding, and snow fencing or a combination of these (Du et al., 2019). Research has shown that weather maintenance operations can also reduce the frequency of fatal crashes (Hanbali and Kuemmel, 1992).

Before World War II, local governments in most US cities used to plow ice from the roads. To increase traction on roads, they would spread abrasives like sands and cinders. People commonly accepted that roads were not accessible during snowstorms (Plumer, 2015). After World War II, the highway system expanded, and as it became more critical to the economy, people needed to travel in every condition. Most of the cities and suburbs started making policies to make their roads ice-free right after the snow events. Strategies included anti-icing (applying salts on the road before snowfall) and de-icing (applying chemicals during and after a snowfall so plows can efficiently remove snow) (Du et al., 2019). Until the 1970s, salt use increased rapidly, and then adverse effects of deicers on the environment were recognized (Transportation Research Board, 1991). Currently, common chemical products used include freezing point depressants (sodium chloride – $NaCl$, calcium chloride – $CaCl_2$, and magnesium chloride – $MgCl_2$), non-chloride products (potassium acetate – KAc and calcium magnesium acetate – CMA, etc.) and agro-based byproducts (Du et al., 2019). The state Department of Transportation (DOT) spends 20 percent of its maintenance budget on winter road maintenance nationally. According to the Federal Highway Administration, the annual expense on ice control operations is more than $2.3 billion (NBC News, 2015).

1.2 Problem Statement

Different states in the US have winter conditions of different severities, and hence they require different levels of preparedness. Figure 1.1 shows that Georgia has a low winter severity index. The northern part of Georgia has moderate winter severity during winters. Winters are brief, and the average temperature is around 40°F. Northern parts get snow several times a year, but snowfall events in the southern parts are rare (Georgia Department of Economic Development, 2019).

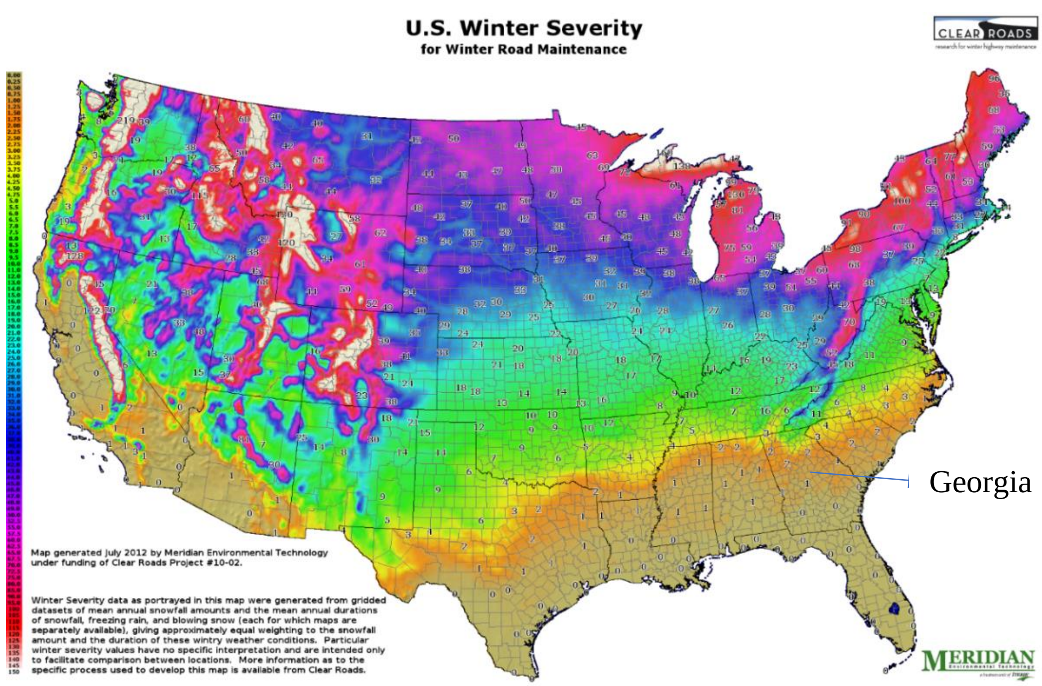

Figure 1.1: State-wise winter severity index map (Source: Clear Roads, 2019).

Different states in the US have their method of dealing with winter weather events. Mitigation measures taken by different states fall into three major types: advisory (providing information on weather conditions to both motorists and transportation managers), control (regulate road traffic permission and restriction), and treatment (supply resources to deal with weather impacts). The Alabama DOT has a low visibility warning system to reduce fog-related crashes. Along with a low visibility warning, the California DOT deployed pavement sensors to detect ice on the pavement and dynamically activated signage to warn motorists of icy conditions. The Iowa Department of Transportation (Iowa DOT) has a salt use dashboard to compare actual salt use and what was estimated. This tool allows them to control salt use more efficiently. Moreover, the Iowa DOT offers real-time weather information to travelers through their "Weatherview" website. The Maryland DOT has implemented an emergency park and ride lots for trucks to take shelter during heavy snow events. The Pennsylvania DOT restricts speed, and sometimes vehicles, on interstates temporarily during snowstorms (FHWA, 2012).

Most cold region US state DOTs have either a winter weather preparedness plan or a winter road maintenance plan. For example, Maryland has a statewide salt management plan, Minnesota has a snow and ice control guidebook, Colorado has levels of service (LOS) manual, New York has snow and ice guidelines, South Dakota has a winter highway maintenance plan, and Texas has a snow and ice control operations manual. On January 29, 2014, several cars were abandoned on the road (Figure 1.2) due to only two inches of snow in Atlanta. On the same day of 2019, Governor Kemp announced the closure of state offices on Tuesday, January 29, 2019, and expected a severe winter storm. Nevertheless, the event never arrived except for some areas receiving light dusting and rain. Gray News reported this as "Atlanta shuts down city for a winter storm that never comes," and people again mocked the event on Twitter and Facebook, calling it "Snowpocalypse 2019" (Payne, 2019).

Figure 1.2: Abandoned cars on I-75 near the Chattahoochee river after a winter snowstorm (Source: Payne, 2019).

There has been recent improvement in winter weather response from the Georgia Department of Transportation (GDOT). Georgia has a "Winter Weather Response Plan," which briefly describes a few initiatives and a list of resources to fight winter weather events. According to the state winter maintenance data and statistics of clear roads, Georgia spent a total of $8,569,613 on winter operations to maintain 39,919 Lane-Miles for the 2017-18 winter (Clear Roads, 2019). Considering the cost per lane-miles, Georgia spent more than New Mexico and Texas, where winter is more severe (Figure 1.1). Considering differences in winter weather between other northern states and Georgia, the response plan needs to be improved and tailored for weather specific to Georgia.

1.3 Objective of the Study

This study evaluates the impact of anti-icing procedures to optimize the overall winter maintenance operation. Specific objectives include:

1. to develop a decision-making tool for roadway pre-treatment during winter events based on weather forecast data.
2. to analyze the feasibility of using the decision-making tool to optimize winter road treatment.

1.4 Significance

As a part of the Georgia DOT preparedness effort, GDOT has set 55 Road Weather Information System (RWIS) sensors around the state of Georgia to improve the ability to predict weather conditions on roads such as ice, temperature, precipitation, and wind (GDOT, 2019). Georgia winter weather preparedness resources include 1,938 employees on-call covering 39,919 lane miles, 54,030 tons of salt, 65,460 tons of gravel, 426 snow removal equipment units (one plow + hopper + truck = one equipment unit), the capacity to store 550,000 gallons of brine, and the capacity to store 30,000 gallons of calcium chloride (GDOT, 2019).

The Georgia winter weather preparedness program focuses more on preventive efforts. The winter weather response plan prioritizes maintaining two lanes of interstates first and then the state’s highest-volume roads. If the temperature drop is above 25 degrees, a mixture of small ’89 stone’ and sodium chloride salt is used. If the temperature drop is below 25 degrees, calcium chloride is added to the mixture (GDOT, 2013). During the winter storm Helena in 2017, statewide, Georgia DOT was ready with approximately 1,900 employees on call with 54,030 tons of salt, 65,460 tons of gravel, 450,000 gallons of brine, and more than 380 pieces of snow removal equipment (Dale, 2017).

All this information suggests that Georgia has the equipment and the capacity to fight the winter storms. However, the “Georgia Winter Weather Response Plan” was adopted in October 2019, which is still under review and does not include some critical issues like material application guidelines and a decision-making process. This study proposes suggestions on how to optimize resources and make a decision on the application of road treatment materials, make a more rational decision regarding different maintenance operations, and how to minimize the cost of maintenance.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Terms related to WRM

Winter road maintenance (WRM) is the method that is effective in countering the increased accident risk during winter conditions (Norrman et al., 2000). Modern WRM constitutes of different winter maintenance activities, aiming at either snow and ice removal, or friction control. Snow removal aims at maintaining the accessibility of the roads and keeping them open to traffic, while the friction control aims mostly at maintaining the safety and friction between the tires of the vehicle and the road surface. The most common winter maintenance activity in the Scandinavian countries is friction control, which is typically done by spreading either one or both, of the following: (a) a freezing point depressant like sodium chloride (salt) or (b) an abrasive like sand (Klein-Paste, 2008; Lysbakken, 2013). Although using salt and abrasives in WRM has been proved to be effective in reducing the risk for accidents, the use of salt is questioned. A more environmentally friendly approach is to use thermal methods for local winter road maintenance. Thermal methods imply the addition of thermal energy to the pavement using a surface heating system, thereby melting ice and snow on the road. The method is suitable for both friction control and snow and ice removal since it creates a bare road surface (Lysbakken, 2013).

The following sub-sections briefly illustrate the methods used to treat roads in the process of WRM.

2.1.1 Mechanical Methods

Mechanical methods focus on the removal of snow through plowing and friction enhancement through sanding. Regardless of the specific means, the use of mechanical methods is generally reactive and seeks to address winter precipitation, which has already bonded to the roadway surface to some degree.

The mechanical removal of snow and ice involves the removal of accumulated material by physically plowing, brooming, or blowing without the use of snow and ice control chemicals (Blackburn et al., 2004). Varying equipment and configurations of plowing include snowplow trucks, V plows, reversible plows, tandem or echelon vehicle formations, wing plow, and snow blowers. The V plows are used for deep snow or heavy drifts; reversible plows are used to move snow to the left side, or the right side of the truck; tandem or echelon vehicle formations are used to clear multiple lanes simultaneously; wing plows are used to clear shoulders or sides of roadways; and snow blowers are used to clean up snow accumulation (Center for Transportation Research and Education, 2006; Transport Association of Canada, 2003). The plow's location and angle may vary between trucks and road conditions, as well as the type of blade (Ketcham et al., 1996).

Increasing the coefficient of friction or friction enhancement is a method in which abrasives, or a mixture of abrasives and chemicals, are applied to the plowed or scraped roadway surface that may have a layer of compact snow or ice already bonded to the pavement surface (Transportation Research Board, 2007). The most common technique for enhancing friction is to apply abrasive materials such as sand, cinders, ash, tailings, and crushed stone/rock (Blackburn et al., 2004). This strategy provides an increased level of friction for vehicular traffic, even though this increase may be short-lived. Abrasives only increase the friction coefficient and do not act as ice-control chemicals in and of themselves.

Abrasives can be applied straight or with varying amounts of liquid or solid snow and ice control chemical in a mixture. The addition of chemicals to abrasives is thought to help them stick to the road better and therefore last longer on the road. Solid chemicals can be mixed directly into the abrasive stockpiles, and liquid chemicals can be sprayed onto the abrasives as they are being applied to the road, or while the stockpile is being created (Blackburn et al., 2004). Warm water can also be applied to abrasives to help them stick to the road.

Application recommendations for abrasives reported in the NCHRP Report 577 for pre-wet, dry, or salt/sand blends range from 500 to 6,000 pounds per lane-mile (lbs/l-mi). When using pre-wet versus dry abrasives, there appear to be no temperature constraints; on the other hand, salt/sand blends are limited to use when temperatures range from 0° to 32°F (Wisconsin Transportation Information Center, 1996).

2.1.2 Chemical Methods

Chemical methods of snow and ice removal disperse chemicals on the roadbed so that, through their reaction with the winter precipitate and roadbed, the pavement surface condition is improved. To generate the right chemical reaction, it becomes more necessary to know the roadway environment's current and future conditions, including pavement temperature and chemical concentration. As such, the use of chemical methods will generally require a higher level of precision and accuracy concerning weather information sources.

2.1.2.1 De-icing

De-icing is a reactive measure of snow and ice control that is taken after precipitation has reached the roadway. This method entails removing compacted snow or ice already bonded to the pavement surface by chemical means (Blackburn et al., 2004; Transportation Research Board, 2007). De-icing generally involves the application of solid chemicals or pre-wet solid chemicals.

De-icing as a snow and ice control measure works in most weather and traffic conditions and locations. Application rates for de-icing reported in NCHRP Report 577 for solid and pre-wet solids range from 200 to 700 lbs/l-m with a working temperature range of 32° to 0°F (Blackburn et al., 2004). These are general guidelines with application rates varying based on meteorological and pavement surface current conditions and trends, and available resources. The practice of de-icing can begin once precipitation has reached the roadway, but it may continue until after the weather event has ended until satisfactory pavement conditions are reached. De-icing usually will require more chemicals than anti-icing to produce the same LOS (Blackburn et al., 2004).

2.1.2.2 Anti-icing

Anti-icing is a proactive treatment method for snow and ice on roads, which can be initiated before the weather event begins or just as the precipitation begins falling. Anti-icing can help to prevent black ice and prevents or weakens the bond that could form between the pavement and ice, ultimately allowing for easier removal of snow and ice using plowing techniques. Anti-icing can be done with liquid, solid, and pre-wet chemicals. Application rates for anti-icing are typically 3 to 5 times lower than those used in de-icing (Transportation Research Board, 2007).

Application rates for anti-icing reported in NCHRP Report 577 for liquid, solid, and pre-wet solids range from 65 to 400 lbs/l-m with a working temperature range of 10° to 32°F (Blackburn et al., 2004). These are general guidelines with application rates varying based on meteorological and pavement surface current conditions and trends, and available resources.

The use of anti-icing has been particularly successful as a liquid pretreatment for forecasted frost and icy locations. It can be used in most weather and traffic conditions and locations with a few exceptions. First, anti-icing with a liquid chemical is not a good strategy when the pavement temperatures are below the working temperature of the product at the onset of a snowfall event, or at any freezing pavement temperatures when the snowfall event is forecast to be followed by rain. Second, anti-icing with liquid chemicals is not recommended during freezing rain or sleet events (Blackburn et al., 2004).

2.1.2.3 Pre-wetting

Pre-wetting involves spraying liquid de-icing chemicals onto solid de-icing chemicals or abrasives to increase their effectiveness and help them stick to the road (Transportation Research Board, 2007).

Adding liquid chemicals to solid chemicals reduces bounce and scatter and accelerates the formation of brine. Once this occurs, the material is more likely to stay on the roadway than be displaced by traffic. Applying liquid de-icing chemical to abrasives adds weight and cushions the fall of the abrasives as they hit the roadway and may help it stick to the road (Fu and Usman, 2012).

2.1.3 Thermal Methods

Thermal energy storage used in local winter road maintenance involves the utilization of any sources of renewable energy. This type of energy storage can be divided into different categories depending on their usage and characteristics, while the time between charging and discharge of thermal energy storage separates the storage methods into short term and long term (Johnsson, 2017). Thermal energy storage can be divided into two main categories, namely, sensible and latent heat storage technologies (Dincer and Rosen, 2011; Cabeza, 2014). A third thermal energy storage technology is thermochemical storage technologies (Cabeza, 2014).

Research on hydronic pavements has been performed since the introduction of the technology in 1948, Oregon, US (Adlam, 1950; Pan et al., 2015). The hydronic pavement consists of a pipe network embedded in the pavement, in which a warm fluid is circulated to facilitate the transport of thermal energy into the pavement (Pan et al., 2015). Frequently used energy systems are boilers or district heating, which restricts the sites suitable for hydronic pavement systems, and reductions of the environmental impact can be achieved if these systems use renewable energy sources (Johnsson, 2017).

2.2 Benefits of Winter Road Maintenance

Some studies that have been conducted to investigate different benefits of winter road maintenance are reviewed as follows.

An observation was made on the benefits of winter road maintenance through a modeling approach on the roads of Canada (Usman et al., 2010). The authors investigated the linkage between the accident frequency during a snowstorm event and some factors controlling traffic exposure, such as road surface conditions, and visibility. The results can be applied for evaluating different maintenance strategies using safety as a performance measure. This research introduced a road surface condition index as a measure of the commonly used friction measures to capture different road surface conditions. Important data from various data sources, such as weather, road condition observations, traffic counts, and accidents, were integrated and used to test three event-based models, including the negative binomial model, the generalized NB model, and the zero-inflated NB model. These models were compared for their capability to explain differences in accident frequencies between individual snowstorms. It was revealed from the results that the generalized NB model best fits the data and is most capable of capturing heterogeneity other than excess zeros. It was also found that the road surface condition index was statistically significant, influencing the accident occurrence.

WRM activities were beneficial due to their critical roles in maintaining the mobility and safety of highway networks during winter seasons in Canada (Fu et al., 2012). However, there was no robust methodology available for quantifying these benefits, which were needed for a comprehensive cost-benefit analysis of all WRM decisions. The authors introduced a set of collision and mobility prediction models that could address this need. The models were developed using detailed hourly records of road weather and surface conditions, traffic counts, and collisions for several Ontario highway routes. Some case studies were used to analyze the applications of these models for evaluating alternative winter maintenance policies and operations, such as changing bare pavement recovery time, changing maintenance operation deployment time, and changing the level of service standards.

The benefits of a multi-level solution for intelligent winter road maintenance management were described based on monitoring and forecasting weather conditions and the road surface conditions in Slovakia (Kociánová, 2015). In this system, an automatic data collection and transmission were ensured by road weather stations, which provided early warnings of dangerous situations on the road, such as frost, ice, mist, wet or snow-covered surfaces. Important data from these weather stations, together with weather forecasting models and dates from weather radars and satellites, were processed, presented, and used for prediction of the pavement surface state and temperature. The result provided information support for the right maintenance decision and the effective and timely treatment of roads in the winter. Another part of the system was the winter maintenance dynamic dispatching that provided online fleet monitoring and management. Additionally, variable message signs were in the system for ensuring information for drivers or even for traffic control on dangerous road sections to improve traffic safety.

Snow and ice on the road surface can cause the drivers to reduce vehicle speeds or to switch to high gears, and thus decrease fuel combustion efficiency. WRM was found to be beneficial in reducing vehicular air emissions and fuel consumption (Min et al., 2016). However, there was minimal information about the underlying relationship, which is essential for quantifying this particular benefit of a winter road maintenance program. This research was focused on establishing a quantitative relationship between winter road surface conditions and vehicular air emissions. In this study, some speed distribution models were developed for the selected Ontario highways in Canada. The vehicular air emissions under different road surface conditions were calculated by coupling the speed models with the engine emission models integrated into the emission estimation model - MOVES. It was found that a 10% improvement in road surface conditions could result in approximately 0.6–2% reduction in air emissions, on average.

Winter transportation operations were found to be essential and beneficial to the public and the economy of the northern US and other cold-climate areas, in which transportation operations rely on various winter maintenance activities, such as plowing and salting to ensure the safety, mobility, and productivity of transportation systems (Shi and Fu, 2018). Transportation agencies have continually been challenged to deliver an effective maintenance program so that a high level of service (LOS) and a degree of safety and mobility can be kept in a fiscally and environmentally responsible manner. More agencies are exploring the impacts of winter road maintenance operations, including voluntary and regulatory controls to reduce their impacts.

2.2.1 Economic Benefits of Winter Road Maintenance

Some studies that have been performed to investigate the economic benefits of winter road maintenance are reviewed as follows.

An assessment of benefit-costs for weather information in winter road maintenance for Iowa, Nevada, and Michigan in the US was carried out (Ye et al., 2009). The benefit-cost analysis showed that the use of weather information brought more benefits than costs. The benefits and costs associated with weather information are summarized in Table 2.1. The highest benefit-cost ratio was achieved in the case of Michigan due to low costs in weather service. However, the percentage of benefits over total winter road maintenance costs was 5.6 percent for Iowa, with a rate of 6.5 percent for Nevada, and 0.9 percent for Michigan. Although the Michigan case had the highest benefit-cost ratio, the percentage of benefits over total winter maintenance costs was the lowest. For this reason, benefit-cost numbers in this research study could not illustrate the overall situation. The benefit-cost ratios of the Iowa and Nevada cases were more representative because the costs associated with weather information in those two states were based on statewide numbers, while the Michigan case was not.

Table 2.1: Summary of benefit-cost analysis (Ye et al., 2009).

Case study state	Winter season	Winter maintenance cost ($ 000s)	Benefits ($ 000s)	Weather information cost ($ 000s)	Benefit-Cost Ratio	Benefits/ Maintenance Costs (%)
Iowa	2006-07	14,634	814	448	1.8	5.6
Nevada	2006-07	8,924	576	181	3.2	6.5
Michigan	2007-08	31,530	272	7.4	36.7	0.9

Observation of direct and indirect benefits of public winter highway maintenance activities in terms of return was performed (Ye et al., 2013). However, the cost of such activities demands scrutiny. There was a need to understand better and quantitatively estimate the benefits of winter road maintenance. Therefore, the work was undertaken to quantitatively assess the benefits of winter highway operations at the state level. The authors developed methodologies to estimate the significant benefits of WRM, including safety improvements, travel time savings, and fuel savings.

A case in Minnesota was used to demonstrate the methodologies and quantify those benefits. Results of that case study showed the benefits of WRM achieved by the Minnesota Department of Transportation was found to be $227 million per winter season, with $168 million of safety benefits, $11 million of mobility benefits, and $48 million of fuel savings. The benefit-cost ratio of WRM in Minnesota was found to be 6.2.

2.3 Costs and Environmental Impact of Winter Road Maintenance

Annually, the US spends approximately $2 billion on winter road maintenance (Fu and Usman, 2012). In contrast, Canada expends $1 billion per year, which includes the application of five million tons of salts (Transport Association of Canada, 2003). This salt commonly ends up in the environment along the road, causing damage to vegetation (Zítková et al., 2018), saltification of freshwater, and facilitates leaching toxic heavy metals (Fay and Shi, 2012). The saltification of freshwater streams increases the risk for slippery road conditions (Norrman et al., 2000). The abrasives used are mainly sand or crushed rocks, which are finite resources. The use of abrasives is associated with environmental issues like the increase of fine PM10 particles in the air (Zítková et al., 2018). The fine particles originating from abrasives and traffic-related emissions are also associated with health risks (Valavanidiset al., 2008).

2.3.1 Environmental Requirements on Winter Maintenance Guidelines

Most of the winter maintenance guidelines/manuals do not mention the environmental impacts of winter operations. There is no clear guidance on environmental requirements in winter maintenance guidelines by the Federal Highway Administration. Some of them mention the negative impact of salt use on soil, groundwater, surface water, and biology. A few of them encourage environment-friendly practices. The Arizona DOT is developing an Environmental Management System (EMS). EMS is monitoring the impacts of winter operations on soil, water, vegetation, etc. The results will be used to determine the environmental fate of the chemicals and to measure the potential impact of the chemicals on the ecosystem (Arizona DOT, 2014).

The Maine DOT uses a liquid blend to pre-wet the rock salts. The liquid blend consists of Magnesium Chloride with sugars (molasses), high fructose corn syrup, or carbohydrate-based products. There are a few industry names for these mixes, such as “Ice-B’Gone” or “Ice Ban” or “70/30 blend”. “Ice-B’Gone” is recognized by the EPA under Design for the Environment (DfE) program (Maine DOT, 2015). The Ohio DOT provides a salt usage awareness spreadsheet to its maintenance garage so that they can track salt use, and their plow drivers are more aware of the usage of salts per lane mile (Ohio DOT, 2011). The Oregon DOT is also committed to promoting the efficient use of salts and other winter operation materials to minimize environmental impacts. They maintain environmental Best Management Practices (BMP) for salt purchase, storage, handling, application, and disposal. As they learn more about the best practices, they implement these practices and train their staffs and managers (Oregon DOT, 2018).

2.4 Benefits of Anti-icing Operation

A typical anti-icing operation is done on the dry pavement by using streamer nozzles before a predicted frost or snow event. Anti-icing is commonly performed with liquid materials, although it is possible to use dry and pre-wet solid granular materials (Transport Association of Canada, 2003). This is because liquids can attach to dry pavement better, while solid materials will be dispersed by traffic action (CTC & Associates LLC, 2009). Once applied, chemicals will remain on the pavement to work through the next storm event until they are diluted out by precipitation. In contrast to an anti-icing operation, the traditional de-icing practice involves plowing and chemical treatment after an inch or more of snow have accumulated and is often already compacted and bonded to the pavement. As a result, anti-icing leads to an improved level of service (LOS), reduced need for chemicals, cost savings, and benefits in safety and mobility relative to de-icing and sanding (Ketcham et al., 1996; CTC & Associates LLC, 2009).

2.4.1 Traffic Safety

The safety benefits of anti-icing strategies over de-icing have been reported in several states. During a twelve-year study involving anti-icing strategies on the interstate system in the Denver metro area, Colorado saw an average decrease of 14% in snow and ice-related crashes (Du et al., 2009). The anti-icing benefits include achieving bare pavement quickly and making snowplowing much easier (CTC & Associates LLC, 2009). Connecticut's study shows that such a reduction in statewide crashes did occur in Connecticut after a decision in 2005 to 2006 to eliminate the use of sand and abrasives and implement anti-icing practices, including pretreating roadways, pre-wetting deicers, and upgrading to state-of-the-art winter maintenance equipment (Du et al., 2009).

2.4.2 Cost Saving

An analysis of implementation in New Hampshire, Minnesota, and Colorado found reduced material use, improved safety and mobility, and cost savings with resulting benefit-cost ratios of 1.33 to 8.67 (Ye et al., 2009).

2.4.3 Effectiveness

An obvious benefit of anti-icing (as opposed to sanding and de-icing) is the reduction in snowy, slushy, and icy surface conditions. That means the amount of time when snow, slush, or ice occurs on the pavement during each weather event, as well as the total amount over the entire year, should be significantly reduced by anti-icing efforts, and this reduction could be the single biggest factor in the reduction of crashes. The anti-icing strategy leads to less snow or ice bonding to the road surface and the easier removal of snow by plowing (CTC & Associates LLC, 2009).

The chemicals applied before or in the early stages of a winter weather event make ice formation below the snow layer less likely. The reduction in ice formation provides more traction (less-slippery road conditions), leading to fewer motor vehicle crashes (Du et al., 2009).

2.4.4 Environmental Benefits

All de-icing chemicals have potential negative issues, such as adverse environmental impacts, high costs, or the corrosion of certain materials used in infrastructure and motor vehicles (Du et al., 2009).

2.5 Decision Making Process on Winter Treatment

The decision to initiate the treatment process depends on the availability of a reliable weather forecast. The Federal Highway Administration (FHWA) suggests weather forecast from the National Weather Service (NWS) and suggests information gathered from the Road Weather Information Systems (RWIS). Route specific weather information, such as precipitation, air temperature trend during and after a storm, wind direction, and speed; real-time knowledge of pavement surface condition, such as pavement temperature, state (wet or dry), etc. are required to make a decision on when to start what treatment to apply (Federal Highway Administration, 1996). Most of the states rely on NWS and RWIS for weather information, as suggested by FHWA. The Alaska DOT has developed a Maintenance Decision Support System (MDSS), a computer-based tool that collects data from NWS and RWIS and comes up with maintenance recommendations for DOT personnel (Alaska DOT, 2012). Minnesota also has MDSS to help to make better decisions regarding winter operations (LRBB, 2012). The Connecticut DOT gets weather forecasts from the Division of Emergency Management and Homeland Security of the Department of Emergency Services and Public Protection during major storm events. Along with RWIS information, pavement condition data are monitored by a truck-mounted sensor (Connecticut Transportation

Institute, 2015). Some states rely on private services for weather information. South Dakota gets weather service from Iteris Inc. (South Dakota DOT, 2019). Northwest Weathernet provides area-specific weather forecast to Washington DOT maintenance personnel (Washington SDOT, 2016).

Although most of the states follow a maintenance guideline for winter operations, most of the time, deciding whether or not to treat the roads depends on weather information. DOTs make the decision based on experience and personal judgment of the maintenance personnel. The Arizona DOT follows a schematic management strategy (Figure 2.1) to decide on the application of different anti-icing and de-icing agents (Arizona DOT, 2014).

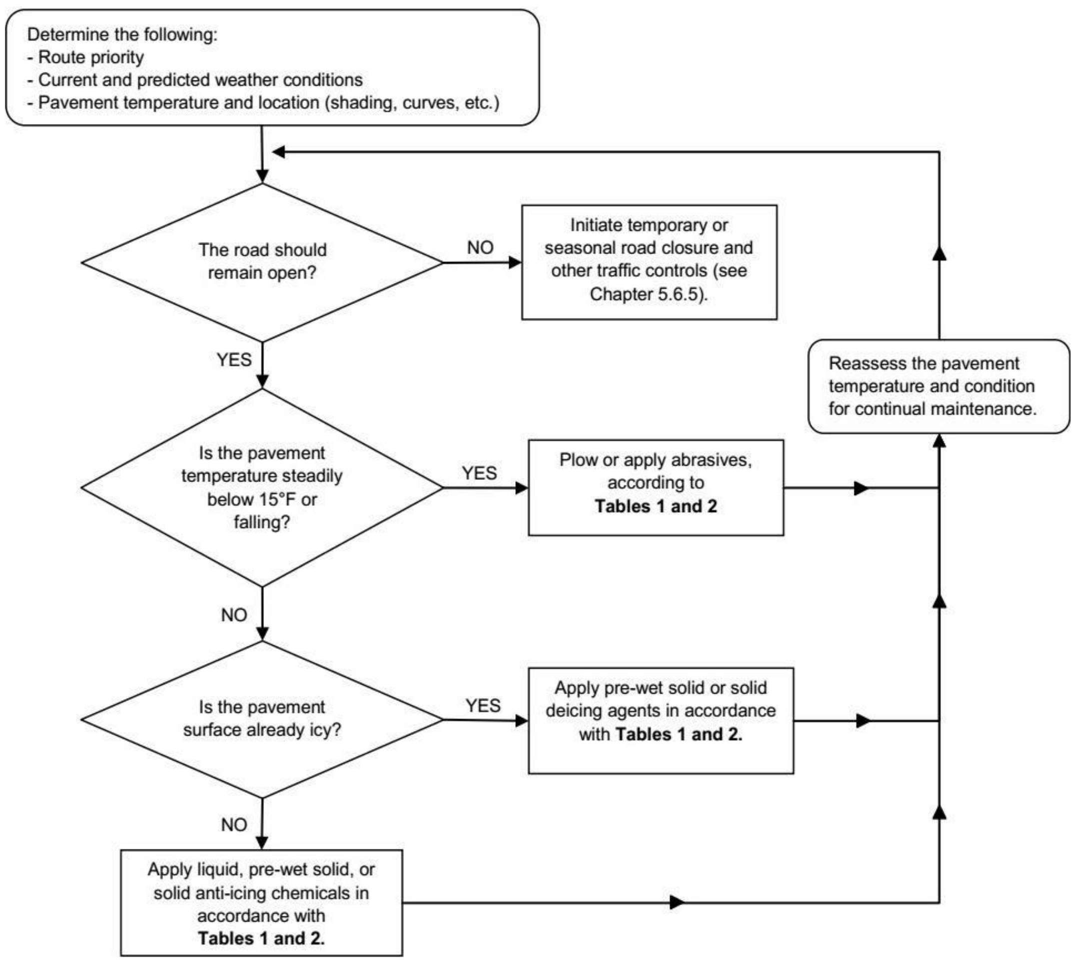

Figure 2.1: Winter storm management strategy (Arizona DOT, 2014).

2.6 Choice of an Appropriate Anti-icing Agent

The selection of an effective anti-icing material depends on its performance, cost, availability, performance, impact on the environment, etc.

2.6.1 Comparison between Different Anti-icing Agents

2.6.1.1 Ice Melting Capacity

As shown in Figure 2.2, chlorides and acetates/formats outperformed agro-based deicers and abrasives. The ice-melting capacity is measured at 23°F and 26.6±6.6% relative humidity. Reagent based solid deicers melted more ice in the first 30 minutes, which subsided afterward. This is because of the dilution effect. In the case of the commercially available deicers, more ice melting occurred in the first 10 minutes. The chloride-based deicers, agro-based products, and CMA products have shown similar ice-melting with CB2 being the exception (Fay et al., 2008).

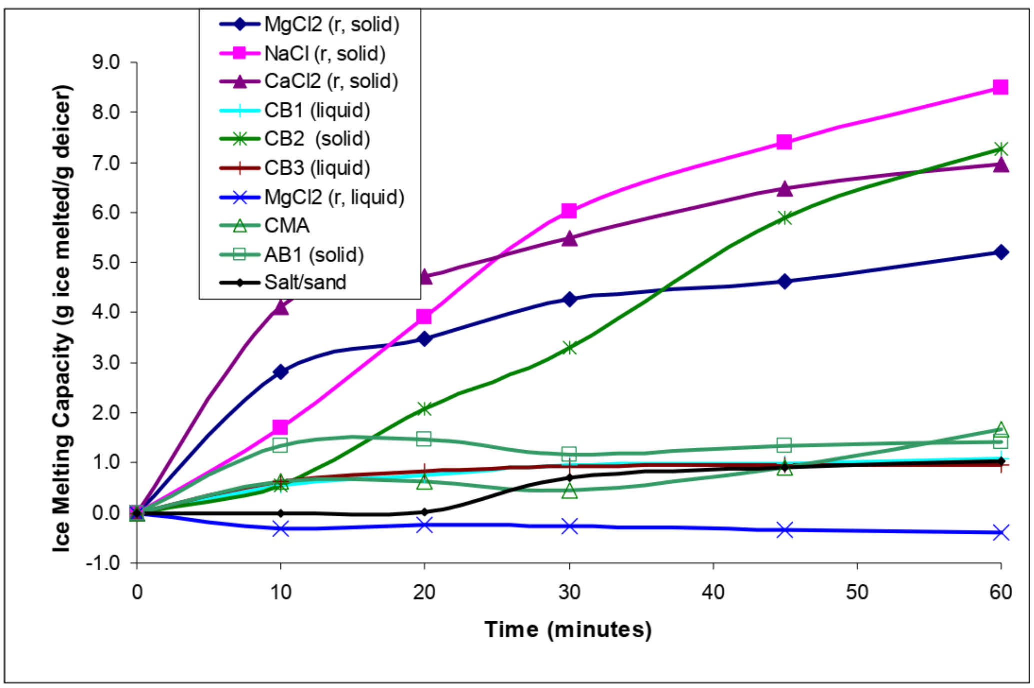

Figure 2.2: Ice-melting capacity of deicers measured at 23°F for reagent-based chlorides, chloride-based (CB), and agro-based (AB) deicers. Deicers not listed as reagent grade are commercially available products. Salt-sand blend is 10% salt by weight.

2.6.1.1 Eutectic Temperature

The phase diagram of different salt solutions in Figure 2.3 shows the relation between freezing point and concentration. The freezing point of the whole solution goes down as the concentration of solution increases until a certain point and then goes up again. The lowest temperature on the formed curve is called eutectic temperature, and the concentration at that point is called eutectic composition. Above the curve, the salt is in solution, which means melting occurs.

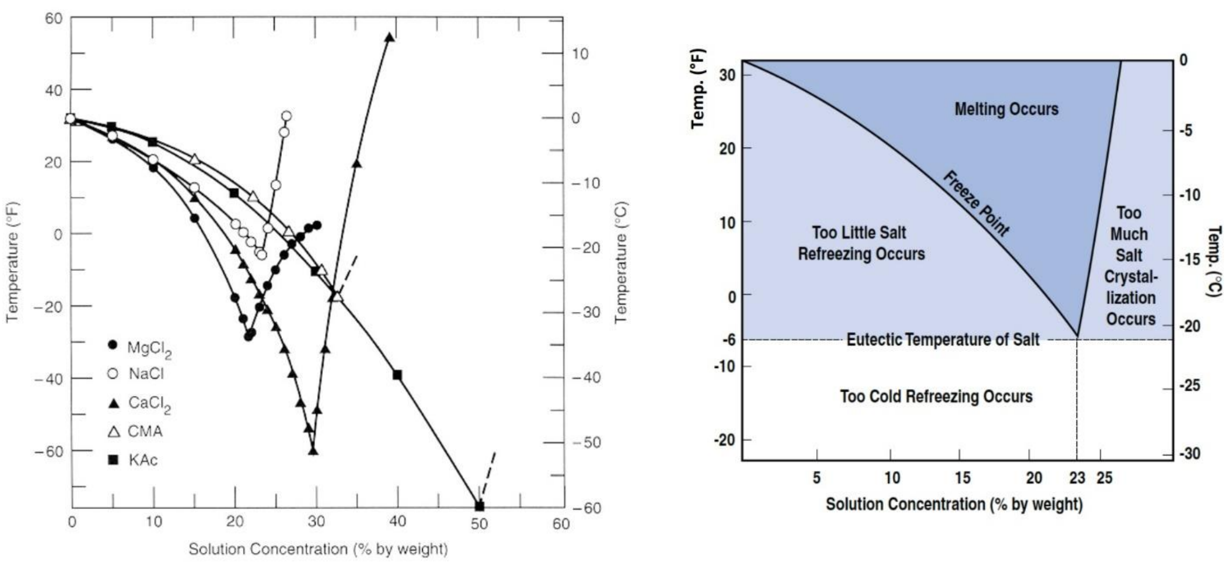

Figure 2.3: (Right) Description of eutectic temperature of a salt solution (Du et al., 2019), (Left) comparison on eutectic temperatures of different solutions (Ketcham et al., 1996).

Below eutectic temperature (and below the dashed line), no melting occurs, ice and salt both stays solid. The same thing happens because there is too little salt to the left of the solid curve and above the dashed line. On the right of the solid curve and above the dashed line, a mixture of salt solution and solid salt exists (Ketcham et al., 1996).

A chemical with lower eutectic temperature has a higher solubility in water. If the difference between ambient temperature and the eutectic temperature is larger, snow melts faster (Du et al., 2019). Thus, the choice of an anti-icing or de-icing chemicals can be made based on the temperature of a specific location. Moreover, the choice of concentration can be made from the phase diagram. Concentration at the eutectic temperature is the optimum concentration of salt that can provide the best result in snow melting. For example, NaCl solution works best at 23% concentration (Figure 2.3).

2.6.2 Current Anti-icing Practices and Recommendations

According to NCHRP report 526, both dry and liquid chemicals can be applied for anti-icing. Dry solid chemicals are recommended when traffic speed and volume are below 30 mph and 100 vehicles per hour. Because fine graded salts are diluted faster and hence have to be reapplied often, coarse graded salts are recommended to ensure chemical effectiveness. NaCl solution has proven to be most effective as a liquid anti-icing agent. A 23% NaCl solution or brine applied at a rate of 40 to 60 gallons per lane mile provides the best protection when there is no precipitation. Brine operation is an excellent way of dealing with black ice and frost. If there is no precipitation, liquid chemicals are effective for three to five days. Letting the liquid chemical dry before the event makes it more effective (Blackburn et al., 2004).

If the temperature of pavement is below 20°F at the onset of a snowstorm event, anti-icing is not recommended (Blackburn et al., 2004). FHWA suggests an even conservative temperature of 15°F below which anti-icing is not recommended (Ketcham et al., 1996). Anti-icing with liquid chemicals is not a good strategy during freezing rain or sleet events. Crosswind speed of more than 15 mph can cause snowdrift, eliminating the need for anti-icing (Blackburn et al., 2004; Ketcham et al., 1996).

According to NCHRP Project 25-25, Task 4, the first application of anti-icing materials is desired to be completed two hours before the anticipated event. Before the second application, the pavement should be cleared of snow, slush, or ice as much as possible to increase effectiveness (Venner Consulting, 2004).

According to an FHWA report (Federal Highway Administration, 1996), NaCl is the most commonly used chemical for anti-icing. $CaCl_2$ can be used, or in some instances, a mix of solid NaCl and $CaCl_2$ also is used by some agencies. $CaCl_2$ has an advantage over NaCl as it absorbs moisture from the environment when relative humidity is higher than 42%. The Utah LTAP center found liquid chemicals to be more effective than dry solid chemicals. Also, during heavy frost and freezing fogs, anti-icing is the most cost-effective strategy (Utah LTAP Center, 2008). The salt institute found NaCl to be the most effective anti-icer above 15°F. NaCl solution or brine is effective to -6°F when the mixture contains 23.3% salt. $CaCl_2$ and $MgCl_2$ are both effective to -6°F, but they are found to be more than six times costlier than NaCl (Salt Institute, 2007). Brine with higher or lower salinity has a lower freezing point and is less effective.

Due to their effectiveness at low-temperature, the Connecticut DOT commonly uses $CaCl_2$ and $MgCl_2$ for anti-icing. Colorado uses two forms of $MgCl_2$ for different temperatures. To be used at a temperature lower than 15°F, $MgCl_2$ is mixed with corn by-products. This anti-icing mixture has little or no environmental impact (Connecticut Academy of Science and Engineering, 2006). Despite the detrimental impact on the environment, anti-icers can reduce sand use and cost less (Staples et al., 2004). NaCl is less toxic to the environment compared to $CaCl_2$ and $MgCl_2$. Also, $CaCl_2$ and $MgCl_2$ are expensive and difficult to handle. As they attract moisture from the air, the road may become slippery and dangerous (Staples et al., 2004). The Road Salt Management Guidebook (Transportation Association of Canada, 2013) mentions that the liquid anti-icing chemicals can temporarily reduce surface friction and therefore, safety. However, using the proper application method can minimize this temporary effect. They suggest the application of liquid at 8 to 15.5 inch spacing on the road (Transportation Association of Canada, 2013).

Considering the negative environmental impacts of chlorides, chloride-free chemicals like acetates and agro-based products have recently been introduced. The disadvantages are high cost, and sometimes quality control issues (Du et al., 2019). Calcium Magnesium Acetate (CMA) requires 50% more application rate chloride salts to achieve a similar level of service (Wegner and Yaggi, 2001). Potassium Acetate (KAc) can melt snow or ice faster and at a lower temperature (Staples et al., 2004). But researches have shown that acetates have much more negative impacts than customarily assumed. They increase the emulsification risk of asphalt concrete and reduce oxygen levels in water (Fay et al., 2008).

The optimum application rate for salt concentration in brine is found to be 23.3%. It is never recommended to go beyond 25% (FHWA, 2012). Brine with higher or lower salinity has a lower freezing point and is less effective (Minnesota Department of Transportation, 2009). Too much NaCl is applied, and the freezing point goes up; too little and the freezing point also goes up (IOWA DOT, 2019).

CHAPTER 3: METHODOLOGY

3.1 Selection of Study Area

Winter is more prevalent on the northern side of Georgia. According to the Georgia Winter Weather Response Plan, interstate routes receive the highest priority for the winter operation. Most of the Road Weather Information System (RWIS) sensors are set up along interstates. Considering the traffic volume and the length of the road, 23 RWIS stations, all along interstates in Georgia, were selected in this study (Figure 3.1). Information about the selected weather stations is listed in Table 3.1.

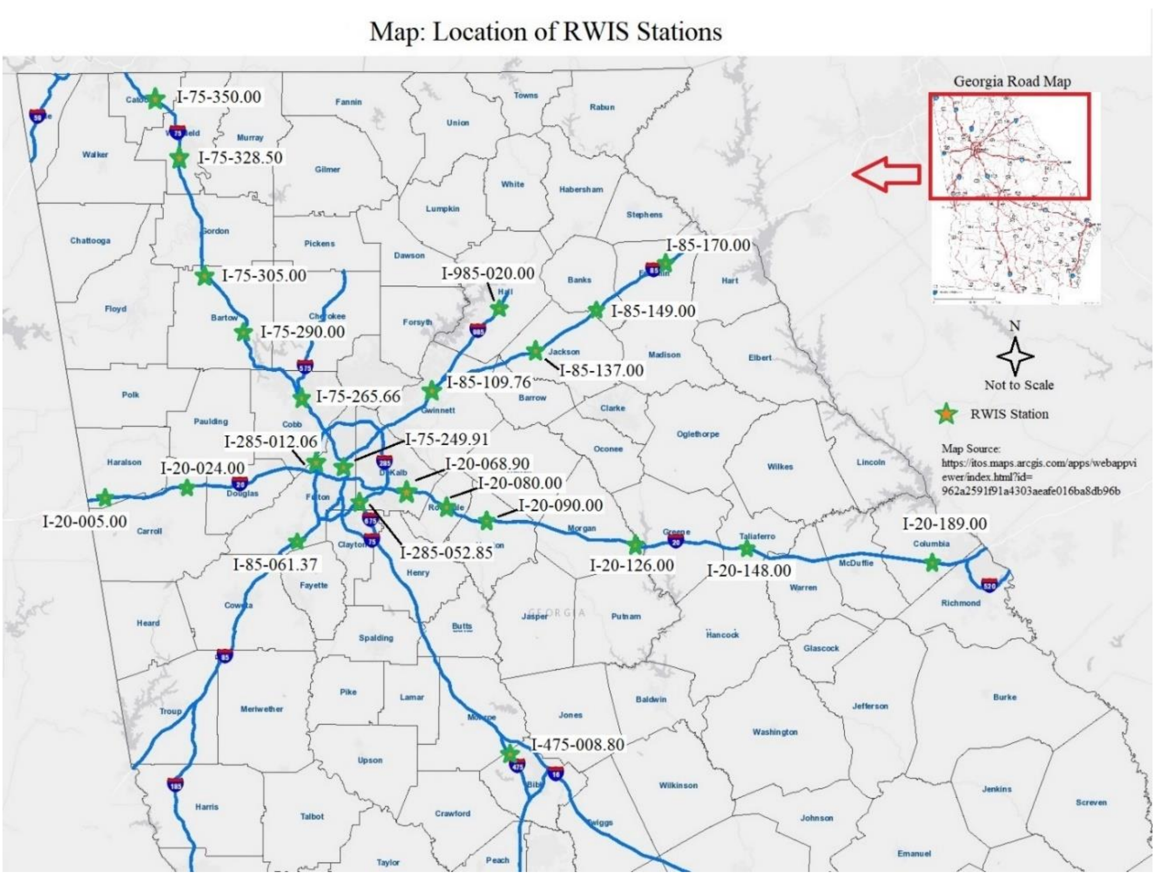

Figure 3.1: Location map of the RWIS stations along the interstates.

Table 3.1: List of weather stations and serving interstates and counties.

No	RWIS Station	Route	Interstate	County
1	GDOT-RWIS-I-75-328.50	401	I-75	Whitfield
2	GDOT-RWIS-I-75-350.00	401	I-75	Catoosa
3	GDOT-RWIS-I-75-290.00	401	I-75	Bartow
4	GDOT-RWIS-I-75-305.00	401	I-75	Gordon
5	GDOT-RWIS-I-75-265.66	401	I-75	Cobb
6	GDOT-RWIS-I-75-249.91	401	I-75	Fulton
7	GDOT-RWIS-I-20-005.00	402	I-20	Haralson
8	GDOT-RWIS-I-20-024.00	402	I-20	Carroll
9	GDOT-RWIS-I-20-068.90	402	I-20	Dekalb
10	GDOT-RWIS-I-20-080.00	402	I-20	Rockdale
11	GDOT-RWIS-I-20-090.00	402	I-20	Newton
12	GDOT-RWIS-I-20-126.00	402	I-20	Morgan
13	GDOT-RWIS-I-20-148.00	402	I-20	Greene
14	GDOT-RWIS-I-20-189.00	402	I-20	Columbia
15	GDOT-RWIS-I-85-061.37	403	I-85	Fulton
16	GDOT-RWIS-I-85-109.76	403	I-85	Gwinnett
17	GDOT-RWIS-I-85-137.00	403	I-85	Jackson
18	GDOT-RWIS-I-85-149.00	403	I-85	Banks
19	GDOT-RWIS-I-85-170.00	403	I-85	Franklin, Hart
20	GDOT-RWIS-I-285-012.06	407	I-285	Fulton
21	GDOT-RWIS-I-285-052.85	407	I-285	Dekalb, Clayton
22	GDOT-RWIS-I-475-008.00	408	I-985	Bibb
23	GDOT-RWIS-I-985-020.00	419	I-985	Hall, Gwinnett

3.2 Collection of Data

All data were collected from secondary sources, and they can be divided into two types. Winter maintenance data from GDOT maintenance office, and weather data from MeteoGroup's transport product suite called RoadMaster.

3.2.1 Maintenance Data

Georgia DOT initiates a winter weather preparation plan 48-72 hours before the predicted snow event. The brining operation usually starts 24 to 36 hours (sometimes compressed to 12 hours) before the event. Each maintenance job is associated with a work order number and a Project ID. Maintenance data recorded includes county, route, beginning and ending mileposts, direction (both sides of the road or increasing-decreasing side), person hour accomplished, material used, etc.

3.2.2 Weather Data

Weather data available from the roadmaster.mg website include surface temperature, presence of black ice, snowfall, precipitation, air temperature, relative humidity, average wind speed, wind gust, and station height above mean sea level. The locations of the stations were determined along with the counties they serve. Both location and date were used to match with maintenance data.

3.3 Selection of Weather Events

From the weather data collected, three major snow events were found in the last three years, two in 2018 and one in 2020.

3.3.1 January 16, 2018 Event

The January 16 event was the biggest among the three selected events. Almost all the stations received 0.5 to 1.5 inches of snow. The event started at around 4 PM or late afternoon in some stations and lasted until midnight. Stations situated on the far northern part of Georgia started receiving snow at midnight, and the snowstorm lasted until 5 AM the next day. The lowest temperature during the event was below 30°F throughout all weather stations. The lowest temperature was 19°F at station GDOT-RWIS-I-75-350.00 during the snowstorm (Figure 3.2).

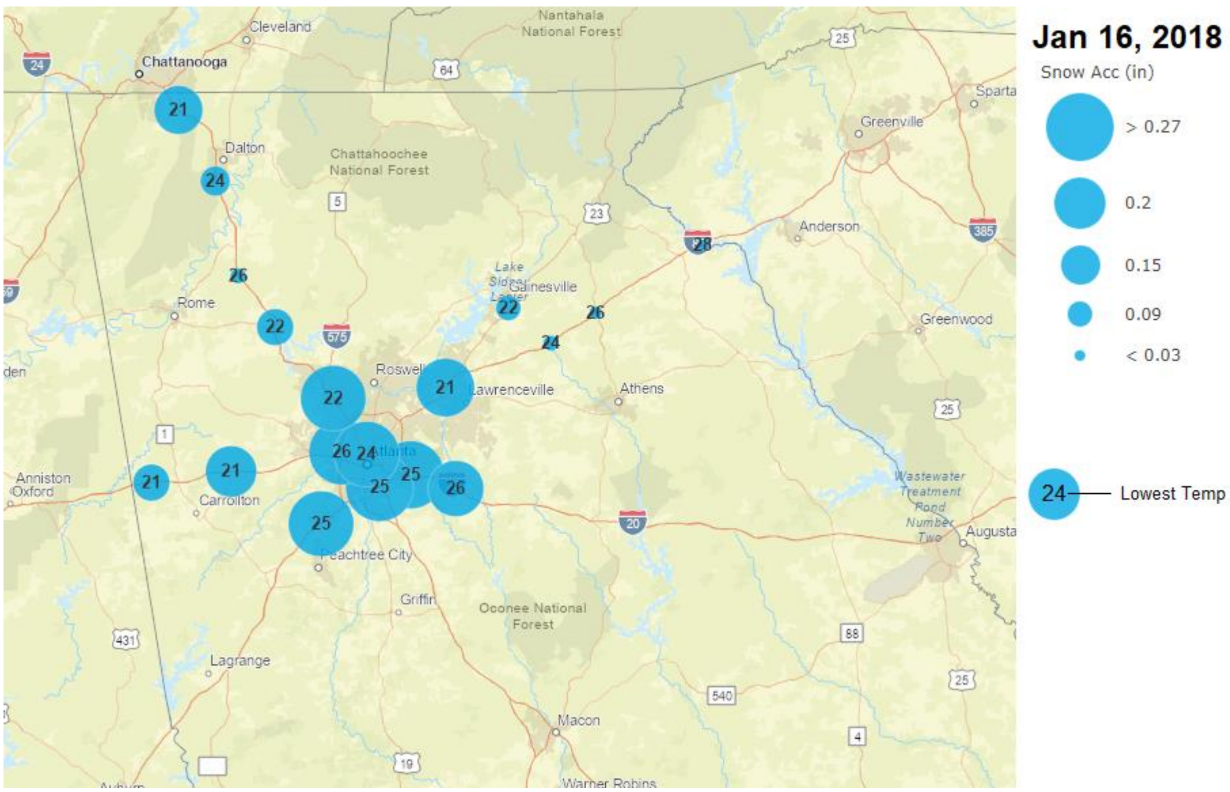

Figure 3.2: Total accumulated snow and lowest temperature on January 16, 2018 event.

3.3.2 December 9, 2018 Event

The snowstorm started after midnight and lasted until 10 AM in some stations. The northern stations received snow later than the southern stations. Although it snowed in several stations, the snow did not accumulate in most of them because the temperature started rising as the sun rose. The only station with a temperature less than 32°F was GDOT-RWIS-I-85-149.00, which received 3.39 inches of snow (Figure 3.3). The amount of snow recorded at this station looks like an outlier compared to other stations' data. However, it snowed for 10 hours there, and the temperature dropped from 33°F to 30°F during the event. The station height was also 705 ft, which is why the amount of snow received did not melt.

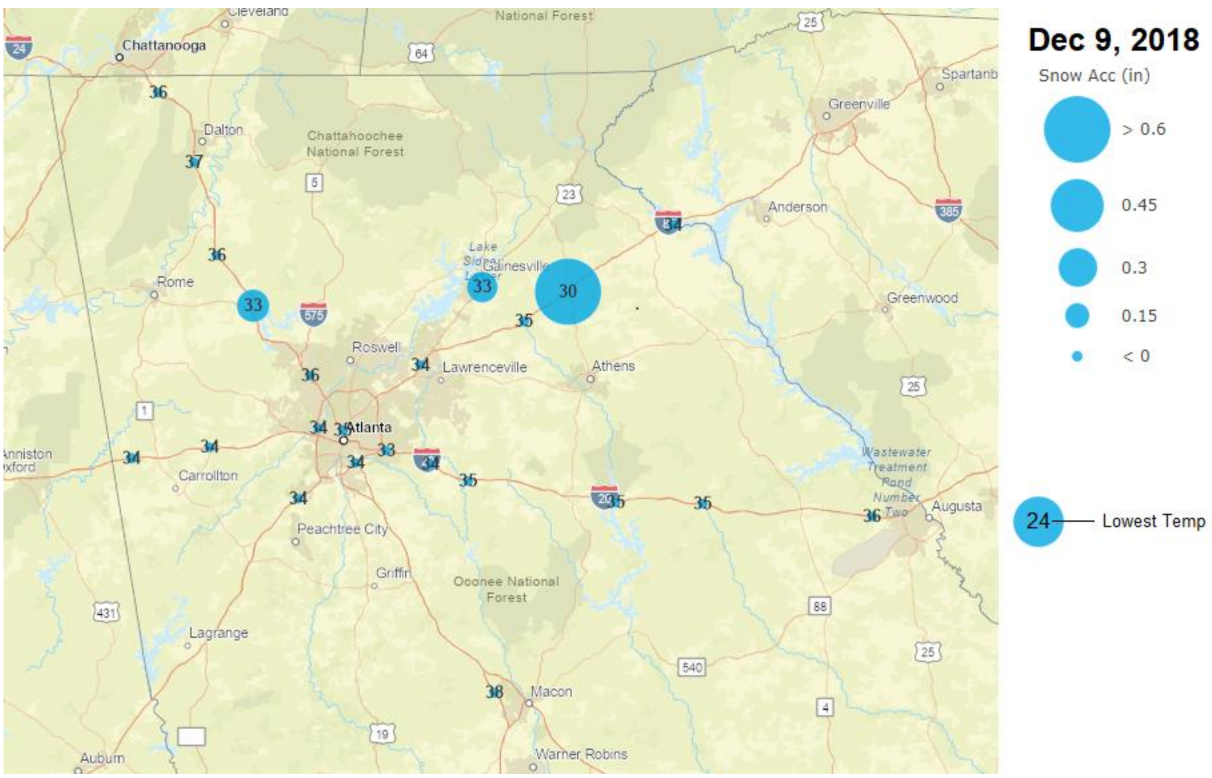

Figure 3.3: Total accumulated snow and lowest temperature on December 9, 2018 event.

3.3.3 February 8, 2020 Event

The February 8, 2020 event was the smallest among the three selected events. Snowfall started at 8 AM and lasted until 9 to 10 AM. None of the stations accumulated more than 0.1 inches of snow. The temperature did not drop below 29°F, and in some stations, the lowest temperature was found to be above the freezing point (32°F) (Figure 3.4).

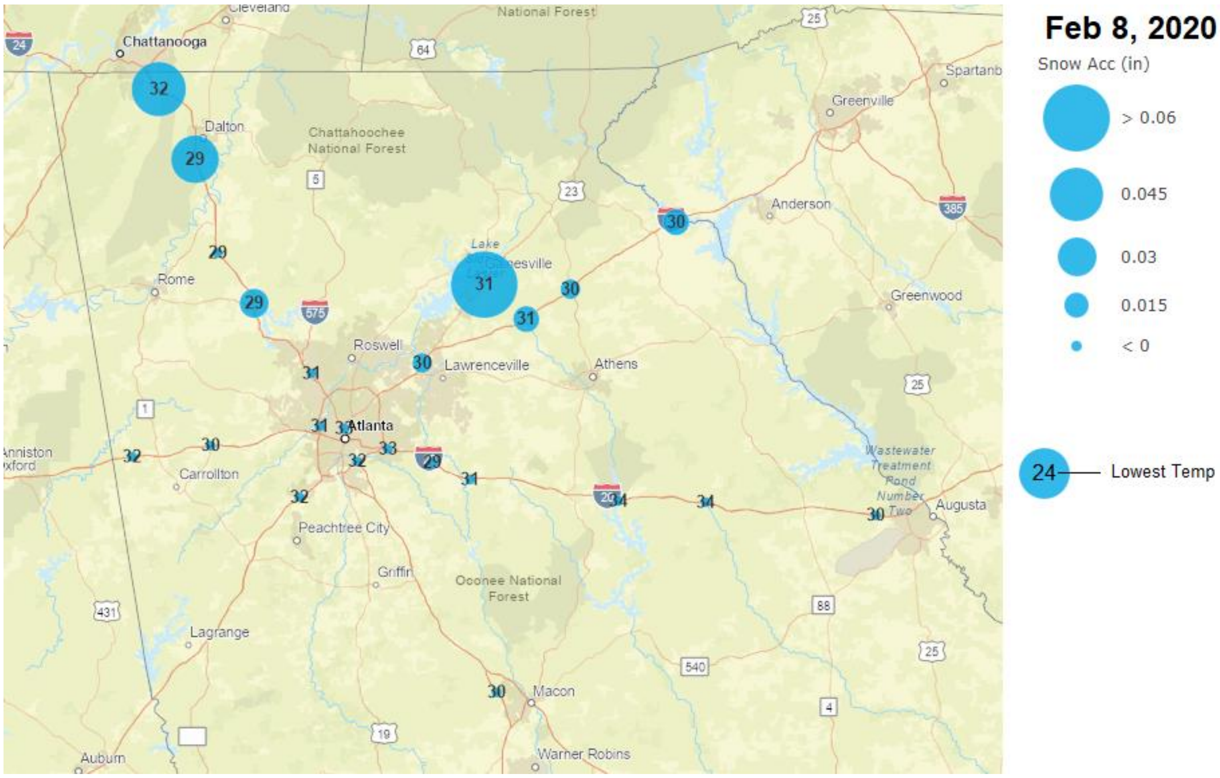

Figure 3.4: Total accumulated snow and lowest temperature on February 8, 2020 event.

3.4 Calculation of Snowmelt Due to Application of Salt

Before calculating the salt-induced snowmelt, snow accumulated on the surface was calculated using Anderson's rain-on-snow melt and non-rain melt equations. Both equations are part of Anderson's SNOW-17 model (Anderson, 2006). The model accounts for precipitation during the snow events and considers non-rain melt during very little or no rain. Salt-induced melt was calculated by Bunce's equation (Trenouth, Gharabaghi and Perera, 2015).

3.4.1 Rain-on-Snow Melt Equation

Anderson's rain-on-snow-melt equation computes surface melt based on energy balance. This equation is applicable when the amount of precipitation is more than .01 inches per hour. The model makes the following assumptions:

- There is a negligible amount of solar radiation due to overcast conditions.
- The relative humidity is assumed to be high (90%).
- Snow surface temperature is 32°F.

For this study, it was assumed that there was no accumulated snow on the surface before the event started. So, if there was no snowfall at a station, but there was still a positive amount of melt, accumulated snow was zero. Also, a negative melt was considered as zero.

The Anderson's equation is:

$$M_r = \sigma \times \Delta t_p \left[(T_a + 273)^4 - 273^4\right] + 0.0125\, P \times f_r \times T_r + 8.5\, \boldsymbol{UADJ} \times \frac{\Delta t_p}{6} \left[(0.9 \times E_{sat} - 6.11) + 0.00057\, P_a \times T_a\right] \quad (1)$$

where:

M_r = melt on snow time intervals (mm),

σ = Stefan-Boltzmann constant –6.12×10^{-10} mm/°K/hr,

Δt_p = time interval of precipitation data (hours),

T_a = air temperature °C,

273 = 0°C in Kelvin scale**,**

P **=** Total precipitation and snowfall (mm/hour)

f_r = fraction of precipitation in the form of rain,

T_r = temperature of rain (°C), (T_a or 0°C, whichever is greater),

UADJ = average wind function = $0.002 \times U_1$

where: U_1 = 6 hr. wind travel in km at 1-meter height above snow surface.

E_{sat} = saturated vapor pressure at T_a (mb), computed from:

$$E_{sat} = 2.7489 \times 10^8 \times e^{(\frac{-4278.63}{T_a+242.792})}$$

P_a = atmospheric pressure (mb), computed using the altitude versus pressure relationship:

$$P_a = 33.86\ (29.9 - 0.335\ H_e + 0.00022\ {H_e}^{2.4})$$

where: H_e = elevation (meters).

If the result is negative, the accumulated snow is zero, as there was no snow on the road to melt before the event started.

3.4.2 Non-Rain Melt Equation

If there is very little or no rainfall, the amount of surface snowmelt was calculated using the non-rain melt equation. In this study, the non-rain melt equation was used when rainfall was less than 0.01 inches per hour. A negative melt was considered as zero.

$$M_{nr} = M_f \times (T_a - \boldsymbol{MBASE}) \times \frac{\Delta t_p}{\Delta t_t} + 0.0125\ P \times f_r \times T_r \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where:

M_{nr} = melt during the non-melt period,

M_f = Melt factor (mm/°C/Δt_t). Melt factor depends on incoming solar radiation that varies with the time of the year. Melt factor for the three snow events was calculated from Anderson's SNOW-17 model graph. Melt factor for December 09, January 16, and February 08 events was considered as 0.4, 0.5, and 0.6 respectively.

Δt_t = Time interval for temperature data (hours),

$\boldsymbol{MBASE}$ = Base temperature (°C). Base temperature was considered 0°C, due to the physiographic condition of the location melt starts at a different temperature.

The amount of melt was converted to inches and then subtracted from hourly snowfall to find the accumulated snow in that specific time interval, Δt_p .

3.4.3 Calculation of Salt-induced Melt

The freezing point of a liquid is lowered or depressed when another compound is added to it. This phenomenon is known as freezing point depression. The freezing point of the solution is lower than that of the solvent (Helmenstine, 2019). That is why historically, salt has been used in winter road treatment to melt snow on the road. As stated in Section 3.3, the lowest temperature during the three snow events in Georgia was recorded at 19°F. The eutectic temperature of NaCl solution is -6°F (see Section 2.6.1.1), which is way below 19°F. There are other chemicals with even lower eutectic temperature, NaCl is the most available, least expensive, and easy to handle (See chapter 2.6). For this study, NaCl was used in the analysis as the snow melting salt.

The following assumptions were made before calculating salt-induced melt:

- The salt used is pure salt with no impurities that can alter the properties of the salt.
- The temperature of snow is air temperature or -1°C (30.2°F), whichever is smaller.
- Traffic action has little or no effect on the amount of salt applied on the road. Traffic does not carry away salt from the road.

- There are no other impurities on the road that can affect the snowmelt capacity of salt.
- Snow density is 0.15 g/cm^3. The new snowpack has a density of 0.15 g/cm^3, according to (Dingman, 2002).
- Standard lane width is 12 feet.

The change in melting point was calculated using the following equation (Trenouth et al., 2015):

$$\Delta T_m = K_m \times m \times i \qquad (3)$$

where:

ΔT_m = Change in the melting point of snow (°C),

K_m = Cryoscopic Constant or molal freezing point depression constant (1.853 °C/g/mol),

m = molarity (mol/g),

i = van't hoff factor or number of particles a solute split into when dissolved (i = 2 for NaCl).

If snow melts at the current temperature, ΔT_m will be the difference between 0°C and temperature of snow (which in this case is considered air temperature or -1°C (30.2°F), whichever is smaller). From here, the required molarity of salt to melt snow can be calculated.

$$m = \frac{\Delta T_m}{K_m \times i} \qquad (4)$$

One molar NaCl (molarity = 1) = $\frac{58.44}{1000\ ml}$ = 0.05844 gm/ml NaCl

[1 mol NaCl = 58.44 gm]

Since the density of water is 1 g/ml, the amount of salt R_s required to maintain the molarity m in order to melt 1 g of water can be calculated using Equation (4).

$$R_s = \frac{\Delta T_m}{K_m \times i} \times 0.05844 \quad \text{………………..……….………..………………..(5)}$$

Multiply R_s with the weight of snow (in g) accumulated to find the amount of salt required to melt that amount of snow. This study used the weight of snow accumulated per lane-mile.

$$S_s = R_s \times Weight\ of\ snow \quad \text{…………………………………………(6)}$$

where:

S_s = Required amount of salt in g to melt snow per lane-mile

R_s = g salt required to melt 1 g of snow

Weight of snow = $V_i \times \rho$ ……………………………………………………………………(7)

where:

V_i = Volume of snow per lane-mile

= 2.54 × A_i × 1 mile (cm) × width of a standard lane (cm)

= 2.54 × A_i × 160934.4 × 365.76 cm^3

= 149512950 × A_i cm^3

where, A_i = Accumulated snow (in)

ρ = Density of snow = 0.15 g/cm^3

So, weight of snow (g) = 22426942.5 × A_i ……………………………………………………(8)

If we put the results from the Equations (5) and (8) into Equation (6), the required amount of salt in g to melt snow per lane-mile (S_s) can be found.

$$S_s = \frac{\Delta T_m}{K_m \times i} \times 0.05844 \times 22426942.5 \times A_i$$

Or

$$S_s = \frac{\Delta T_m}{K_m \times i} \times 1310630.52 \times A_i \text{ ....(9)}$$

3.4.4 Calculation of Application Amount

According to Chapter 2 literature review, the optimum NaCl solution is 23.3% or 23.3 g NaCl dissolved in 100 ml of water. Considering the density of brine 1.18 g/cm^3 (Pollard Highway Products, 2020), 1g of salt is dissolved in 4.53 ml of water to produce a gallon of 23.3% brine (Researcher's Calculation). 4.53 ml converts into 0.001196699 gallons. The required amount of salt in g to melt snow per lane-mile, S_s was multiplied by 0.001196699 to obtain the application rate in gallon/lane-mile.

$$Application\ rate = \frac{\Delta T_m}{K_m \times i} \times 1310630.52 \times A_i \times 0.001196699 \text{ gallon/lane-mile}$$

Or

$$Application\ rate = \frac{\Delta T_m}{K_m \times i} \times 1568.43 \times A_i \quad \text{gallon/lane-mile ....(10)}$$

3.5 Data Analysis

Based on current practices around the world, the appropriate pre-treatment material was selected. The salt requirement model that includes the three equations was then analyzed for different scenarios. The change in snow accumulation was analyzed based on the change in temperature, precipitation, wind speed, and different salt application rate. Then the applicability of the pre-treatment practice was determined based on the weather data of the three snow events. The input weather data and the result of the salt requirement model were used to prepare a decision flowchart. Finally, the result of the salt requirement was compared with the current material application practice in Georgia.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Analysis of Pre-treatment Requirement During the Snowstorm Events

The salt requirement model was programmed in an Excel worksheet (see Appendix A). The input file contains the following weather parameters of the snow event:

1. Name of the weather station (location)
2. Date: Date of the event.
3. Time interval: hour of the day in 24-hour format.
4. Presence of black ice: Yes or No, 1 for Yes and 0 or empty cell for No.
5. Snowfall: in inch.
6. Precipitation: in inch.
7. Surface temperature: in Fahrenheit.
8. Air temperature: in Fahrenheit.
9. Wind Speed: in mile per hour.
10. Station Elevation: in meter.

The program generates the following output:

1. Total accumulated snow: daily and hourly in inch
2. Total black ice hours: number of hours black ice present on the road.
3. Application rate: required salt in gallon/lane-mile to melt total accumulated snow.
4. Change in snow accumulation at different brine application rates.

4.1.1 January 16, 2018 Event

Among the three events, the January 16, 2018 event received the most amount of snow across the state. Table 4.1 illustrates the lowest temperature, snow accumulation, and brine requirement at different RWIS stations. The results clearly show that the salt requirement is below 40 gallon/lane-mile at only two stations. It confirms that pre-treatment was not sufficient at most of the stations. At only two stations, only 60 gallon/lane-mile should have melted all accumulated snow.

Table 4.1: Salt application requirement to melt snow on January 16, 2018 event.

Station	Black Ice (hours)	Lowest Air Temperature (F)	Accumulated Snow (in)	Brine Requirement Rate (gallon/lane-mile)
I-20-005.00	0	21	0.14	233.0
I-20-024.00	0	21	0.20	309.9
I-20-068.90	0	25	0.27	268.2
I-20-080.00	0	26	0.22	170.8
I-285-012.06	0	26	0.26	263.5
I-285-052.85	0	25	0.27	273.0
I-75-249.91	0	24	0.26	284.7
I-75-265.66	0	22	0.26	388.3
I-75-290.00	0	22	0.14	193.0
I-75-305.00	0	26	0.05	45.6
I-75-328.50	0	24	0.11	88.0
I-75-350.00	0	21	0.19	193.0
I-85-061.37	0	25	0.26	267.3
I-85-109.76	0	21	0.23	220.7
I-85-137.00	0	24	0.05	50.6
I-85-149.00	0	26	0.04	30.6
I-85-170.00	0	28	0.03	10.6
I-985-020.00	0	22	0.09	102.9

At this event, 40 gallon/lane-mile across all the interstates around the state could be applied as a pre-treatment amount. However, all stations except two required snow-plowing or other post-treatments.

4.1.2 December 9, 2018 Event

Table 4.2: Salt application requirement to melt snow on December 9, 2018 event.

Station	Black Ice (hours)	Lowest Air Temperature (F)	Accumulated Snow (in)	Brine Requirement Rate (gallon/lane-mile)
I-20-005.00	0	34	0.009	3.8
I-20-024.00	0	34	0	0
I-20-068.90	0	33	0	0
I-20-080.00	0	34	0	0
I-20-090.00	0	35	0	0
I-20-126.00	0	35	0	0
I-20-148.00	0	35	0	0
I-20-189.00	0	36	0	0
I-285-012.06	0	34	0	0
I-285-052.85	0	34	0	0
I-475-008.00	0	38	0	0
I-75-249.91	0	35	0	0
I-75-265.66	0	36	0	0
I-75-290.00	1	33	0.24	101.2
I-75-305.00	0	36	0	0
I-75-328.50	0	37	0	0
I-75-350.00	0	36	0	0
I-85-061.37	0	34	0	0
I-85-109.76	0	34	0	0
I-85-137.00	0	35	0	0
I-85-149.00	0	30	3.26	1155.2
I-85-170.00	0	34	0.01	4.2
I-985-020.00	0	33	0.22	91.9

The December 9 event was a smaller snow event compared to January 18. Only one station at I-85, one at I-985, and one at I-75 required both pre-treatment and post-treatment. Two of the brine requirements were between 0 and 40 gallon/lane-mile. Moreover, there was no black ice warning at any of the stations where the snow accumulation was zero. So, these two stations required a pre-treatment of 40 gallon/lane-mile and three others required both pre- and post-treatment. At the station I-85-149.00, the brine requirement was 1,155 gallon/lane-mile to remove 3.26 inches of snow. Although on table 4.1, at the station I-75-265.66, the brine requirement was 388 gallon/lane-mile to remove just 0.26 inches of snow. The reason was, at the station I-75-265.66, the lowest temperature was 21°F. Whereas, at the station I-85-149.00, the lowest temperature was 30°F. At lower temperatures, salts are less effective in snow-melting.

4.1.3 February 8, 2020 Event

Table 4.3: Salt application requirement to melt snow on February 8, 2020 event.

Station	Black Ice (hours)	Lowest Air Temperature (F)	Accumulated Snow (in)	Brine Requirement Rate (gallon/lane-mile)
I-20-005.00	0	32	0	0
I-20-024.00	1	30	0	0
I-20-068.90	4	33	0	0
I-20-080.00	4	29	0	0
I-20-090.00	5	31	0	0
I-20-126.00	0	34	0	0
I-20-148.00	0	34	0	0
I-20-189.00	3	30	0	0
I-285-012.06	0	31	0	0
I-285-052.85	0	32	0	0
I-475-008.00	0	30	0	0
I-75-249.91	0	33	0	0
I-75-265.66	0	31	0	0
I-75-290.00	0	29	0.02	8.5
I-75-305.00	2	29	0	0
I-75-328.50	0	29	0.04	16.9
I-75-350.00	0	32	0.046	19.8
I-85-061.37	0	32	0	0
I-85-109.76	0	30	0.01	2.4
I-85-137.00	0	31	0.016	5.2
I-85-149.00	0	30	0.01	4.2
I-85-170.00	0	30	0.017	5.2
I-985-020.00	0	31	0.06	21.6

The February 8 event was a smaller snow event. Most of the stations received little or no snowfall, and the output of the salt requirement model shows that none of the stations required more than 40-gallon brine per lane-mile to melt all the accumulated snows. There were three stations where snow did not accumulate, but there were black ice warnings. So, only pre-treatment was sufficient for anti-icing in this event.

4.2 Sensitivity Analysis of the Model

The salt requirement model was analyzed for different salt application rates and weather scenarios. For the analysis, different weather stations and weather events were used to show the impact meaningfully. Since different stations received different amounts of snow and precipitation, the temperature varied depending on the location.

4.2.1 Impact of Different Salt Application Rate

Figure 4.1 shows the snow accumulation at the station GDOT-RWIS-I-75-328.50 on January 16 event under different salt application rates.

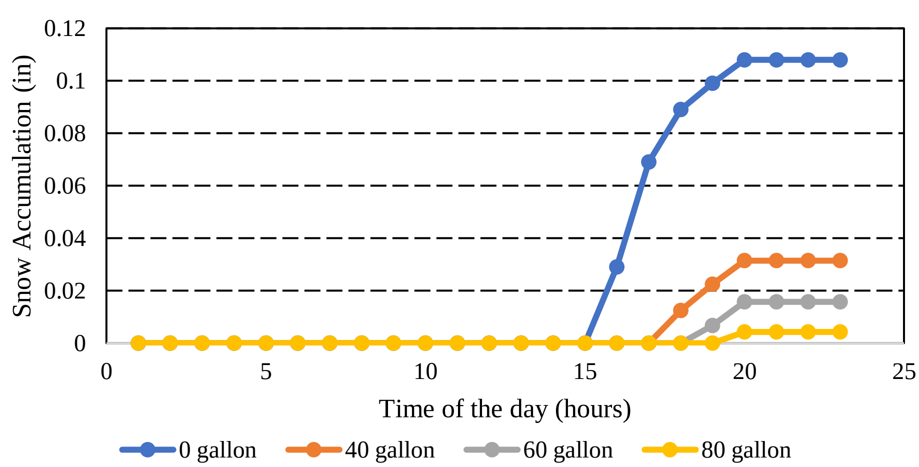

Figure 4.1: Snow accumulation at different brine application rates.

At this station, the snow accumulation was not much, which clearly shows the impact of different salt application rates. The snow accumulation started on the 16th hour of the day, and the total accumulation was 0.11 inches. At a brine application rate of 40-gallon per lane-mile, there is a significant drop in snow accumulation (0.03 inches). If the application rate is increased to 60-gallon per lane-mile, the snow accumulation further drops. At the application rate of 80-gallon per lane-mile, there is a negligible amount of snow on the ground after the 20th hour. The graph also shows that, if 40-gallon is applied, the snow accumulation gets delayed by two hours. At 60-gallon, the snow accumulation gets delayed by three hours and at 80-gallon by four hours. This information can be used to determine a time for re-applying anti-icers.

4.2.2 Impact of Different Temperature

Figure 4.2 illustrates the change in snow accumulation at the weather station GDOT-RWIS-I-75-328.50 on the January 16, 2018 event, due to temperature change. The lowest temperature during the event was 24°F. If the temperature at every hour of that day was 5°F less (marked by the lowest temperature of 19°F on the figure), the total snow accumulation would increase by a small margin. However, at a 5°F increase in hourly temperature, the snow accumulation would drop significantly.

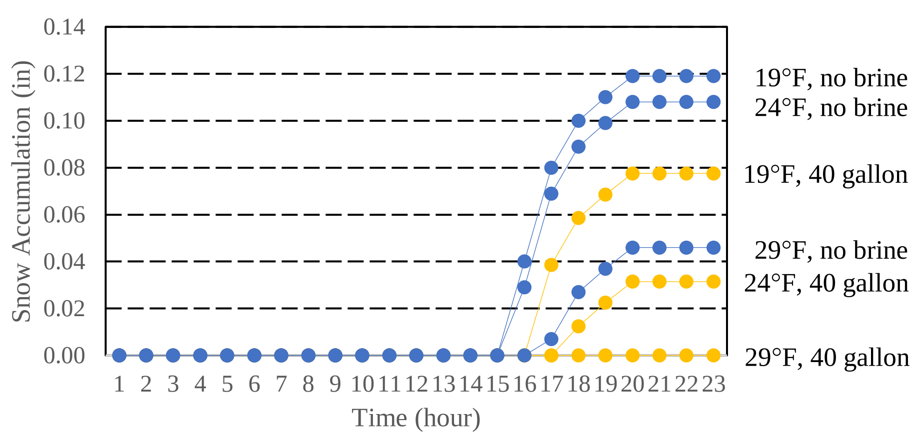

Figure 4.2: Impact of temperature change on snow accumulation.

An application of 40-gallon per lane-mile of brine makes a considerable difference when the temperature is increased or decreased. When the temperature drops by 5°F, even after the salt application, the snow accumulation stays close to the original accumulation amount. However, at 5°F increase in temperature, 40-gallon brine per lane-mile melts all the snow. This implies that brine works better at higher temperatures.

4.2.3 Impact of Wind Speed

As mentioned in Chapter 2: Section 2.6, blowing snow occurs at a wind speed of 15 mph or more. Snow does not accumulate at higher wind speed, but it has little impact on snow accumulation at lower wind speeds. The relation is explained in Figure 4.3, which shows wind speed and snow accumulation at the weather station GDOT-RWIS-I-985-020.00 on the December 09, 2018 event.

Figure 4.3 illustrates that at the original wind speed (the lowest windspeed was 15 mph during the event), the snow accumulation was very low. If the wind speed is reduced by 5 mph at every hour, more snow is accumulated. At zero wind speed, the snow accumulation is very high compared to the original snow accumulation. Another noticeable aspect of the graph is that the snow accumulation drops due to the application of 40-gallon brine per lane-mile are similar at different wind speeds. As we are concerned about pre-treatment here, brine stays between the surface and the snow layer during the event; that is why the wind has little or no impact on the effectiveness of the snow melting capacity of brine.

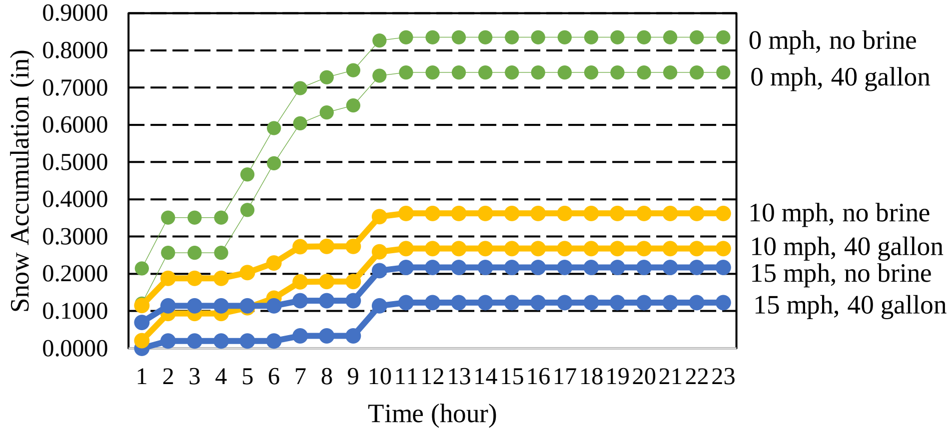

Figure 4.3: Snow accumulation at different wind speeds.

At this station during the event, the wind speed was between 15 and 16 mph at different hours. Due to high wind speed, the total snow accumulation was only 0.21 inches, while the total snowfall was 0.86 inches that day.

4.2.4 Impact of Precipitation

Figure 4.5 shows snow accumulation in the presence and absence of precipitation at the station GDOT-RWIS-I-75-328.50 on the January 16, 2018 event. Precipitation lasted only the first few hours of the snowfall event. The lowest temperature during the event was 34°F, which is one of the reasons why snow did not accumulate much. However, the graph clearly demonstrates that if there was no rain, more snow would accumulate. The snow gets heat from the rain, which accelerates the process of snow melting. There was a substantial amount of snow accumulation when the amount of rain was lowered by less than 15%. Above 15% of the original amount, the snow accumulation stayed close to the original condition.

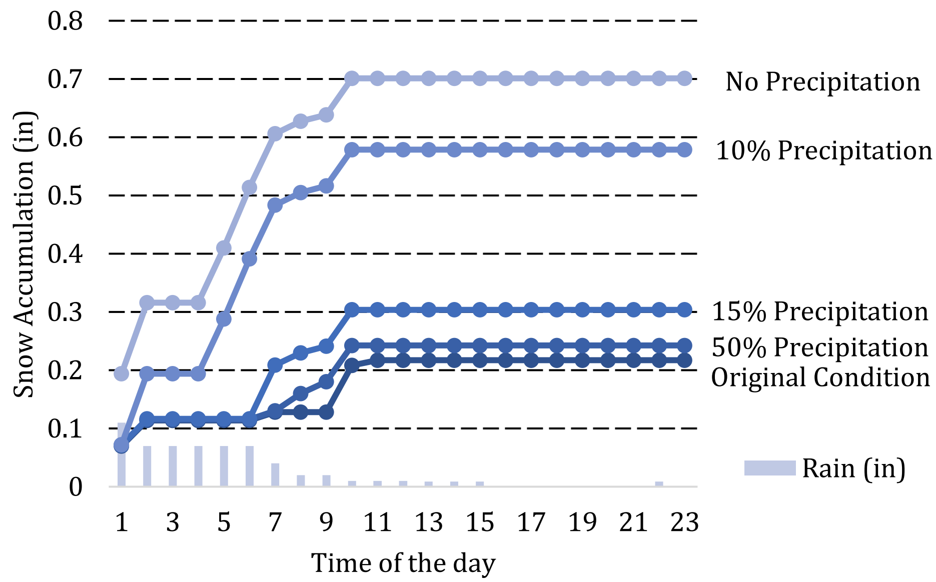

Figure 4.4: Impact of precipitation on snow accumulation.

4.3 Decision Flowchart for Winter Treatment in Georgia

4.3.1 Decision-Making Flowchart for Pre-treatment

A decision-making flowchart was prepared by reviewing different pre-treatment guidelines and articles (Figure 4.6). The flowchart contains conditions mentioned in Chapter 2: Literature Review and uses the output from the decision model prepared in Microsoft Excel. The flowchart comprises the following steps:

1. The decision flowchart starts with the monitoring of weather forecast for the next 48 hours. Although the possible snowstorm will be monitored even before a week, the critical decision should be made 48 hours before the event.
2. If there is a predicted weather condition like snow, ice, sleet, freezing rain, or frost, the decision for pre-treatment should be considered.
3. There would be no need for another pre-treatment if there was a pre-treatment already applied within the last 48 hours. There could be salt residue still on the road. If the road is dry and no salt residue is visible on the road, the decision will be made based on the output

of the decision model. The decision model is shown in green color in the flowchart (See Figure 4.4).

4. If the surface temperature is 35°F and rising or below 20°F at the onset of the event, pre-treatment is not recommended. Higher temperatures will melt the snow, and lower temperatures will reduce the effectiveness of salt.
5. If there is a prediction of blowing snow (average wind speed more than 15 mph), pre-treatment may not be required.
6. If the decision model generates the required salt application rate of zero and no black ice warning, pre-treatment is not required.
7. If the model output shows the application rate of salt above zero or there is a black ice warning, then 40 gallons of brine should be applied per lane-mile.
8. If the required salt application rate is more than 40, then 60 gallons per lane-mile should be applied. More brine can make the road slippery, and excess liquid can flow away from the road.

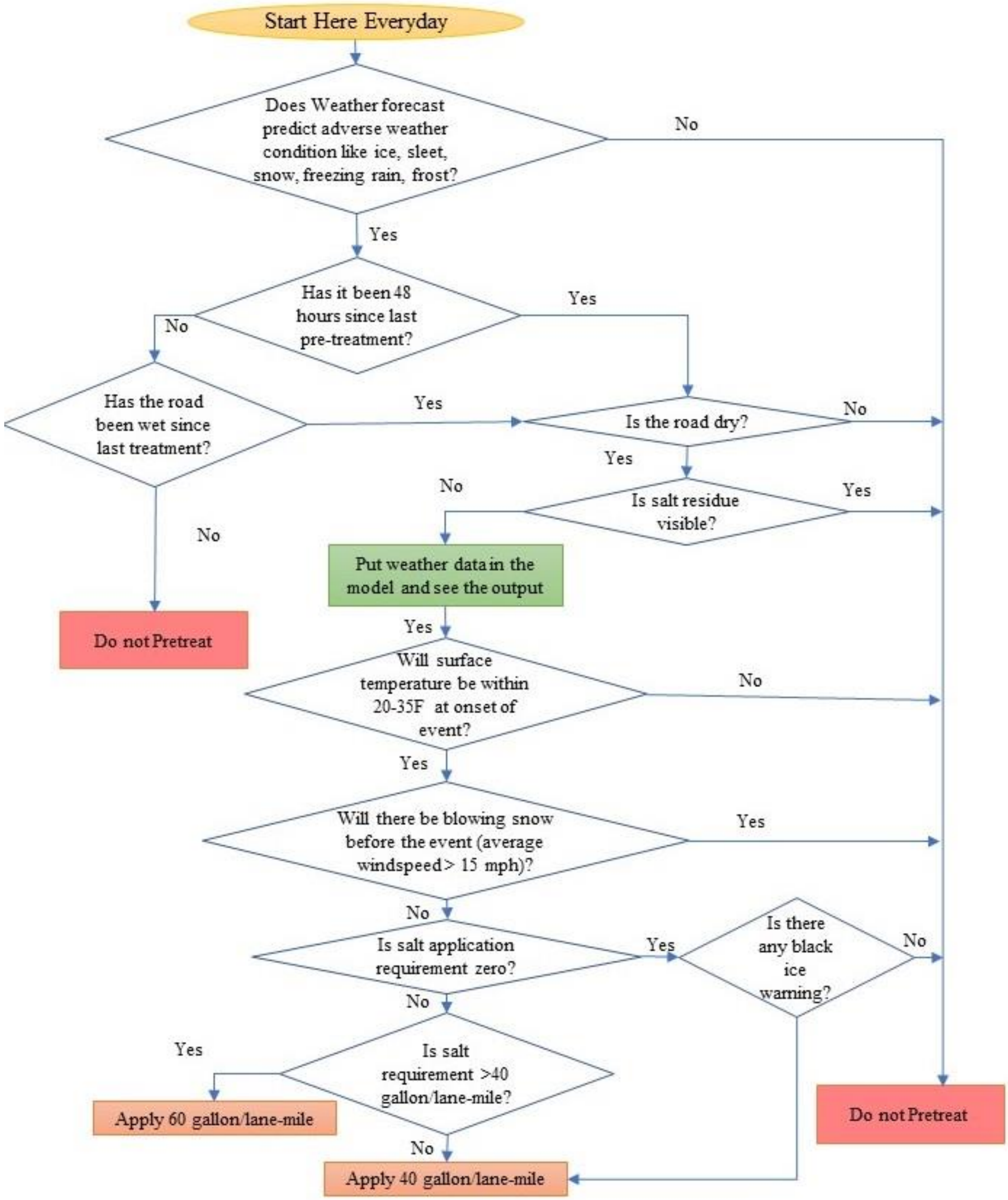

Figure 4.5: Decision flowchart for pre-treatment with brine.

4.4 Applicability of the Decision Flowchart in Georgia Weather

As stated in Section 3.4.2, NaCl solution or brine is the best-suited anti-icing material for Georgia weather. Air temperature, surface temperature, and wind speeds were analyzed across the stations to determine if they allow the application of anti-icing materials.

4.4.1 Lowest Hourly Air Temperature

Figure 4.7 suggests that among the three events, the January 16 event was the coldest. The average lowest average hourly temperature was 23.8°F, with 2.2 standard deviation, 21°F being the lowest among all the stations. Although there are some missing data, from the trend of all the events, we can reasonably assume temperature did not drop below 21°F. The eutectic temperature of NaCl solution is -6°F, which is way below 21°F. NaCl being the least expensive and easily available; other anti-icing chemicals with lower eutectic temperature are not necessary.

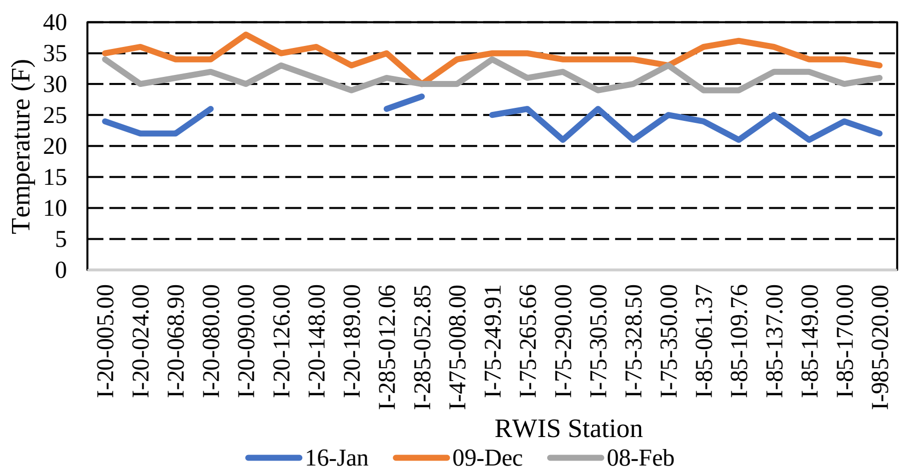

Figure 4.6: Lowest hourly temperature during three weather events.

4.4.2 Lowest Hourly Surface Temperature

As mentioned in Section 2.6.2, anti-icing is not recommended when the surface temperature is below 15 to 20°F. Figure 4.2 depicts that the surface temperature did not drop below 20°F during any of the snow events.

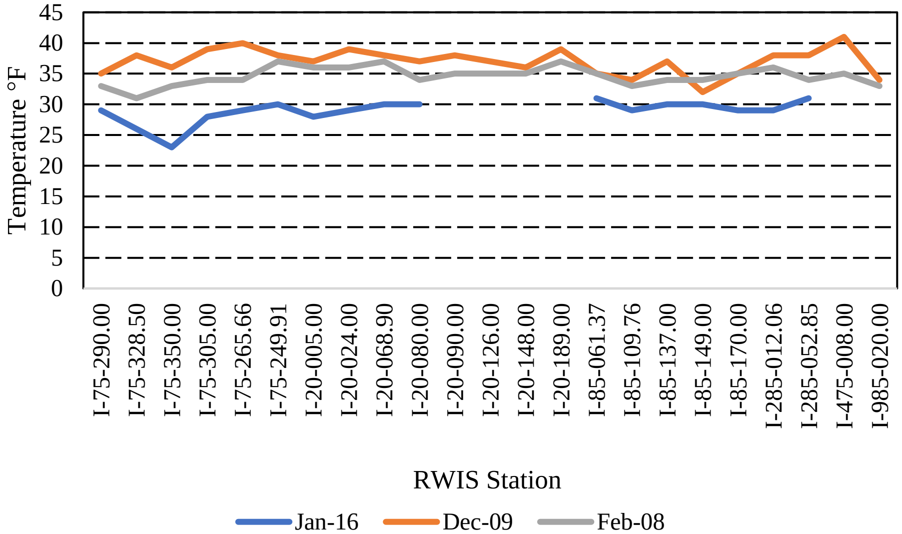

Figure 4.7: Lowest hourly surface temperature during three weather events.

4.4.3 Highest Average Hourly Wind Speed

Anti-icing may not be required if the wind speed is more than 15 mph since a higher wind speed can drift away snow. Figure 4.9 clearly shows that among the snow events, the wind speed reaches 16 mph only in three stations. As 16 mph is not substantially larger than 15 mph, anti-icing is recommended in all the stations during all the snow events.

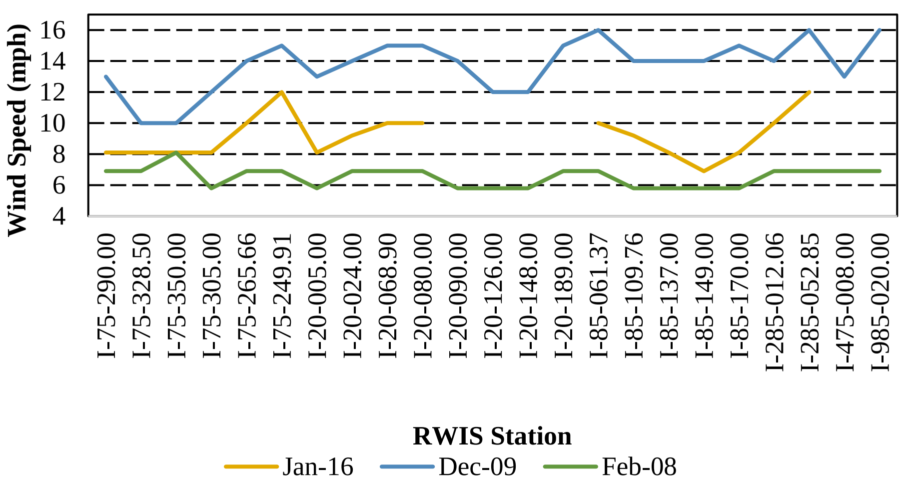

Figure 4.8: Highest average hourly wind speed during three weather events.

4.5 Comparing Treatment Practice in Georgia and Requirement

Table 4.4 depicts the comparison between materials applied during the three snow events and how they compare with the results of the brine requirement model. On the December 9 event, a few stations received significant snow, and they required both pre- and post-treatment. In practice, however, all the interstates were both pre-treated and post-treated. The model suggests that no post-treatment was required during the February 8 event, yet 40-gallon of brine was applied per lane-mile two times. The reason might be an inaccurate prediction of snowfall. The table also shows a uniform amount of pre-treatment throughout the routes. According to the salt requirement model, the application rate can be varied, which will decrease the amount of brine application.

Table 4.4: Comparing required and applied material during the snow events.

Station	Date	Snow Accumulation (in)	Brine requirement (gplm)	Brine Applied (gplm)	Post Treatment
I-20-126.00	Dec-09-2018	0	0	40	Yes
I-75-249.91	Dec-09-2018	0	0	40	Yes
I-85-137.00	Dec-09-2018	0	0	40	Yes
I-85-149.00	Dec-09-2018	3.26	1532.7	40	Yes
I-985-020.00	Dec-09-2018	0.22	91.93	40	Yes
I-285-012.06	Feb-08-2020	0	0	80	Yes
I-75-249.91	Feb-08-2020	0	0	80	Yes
I-75-265.66	Feb-08-2020	0	0	80	Yes
I-75-290.00	Feb-08-2020	0.02	14.1	80	Yes
I-75-305.00	Feb-08-2020	0	0	80	Yes
I-75-328.50	Feb-08-2020	0.04	28.2	80	Yes
I-75-350.00	Feb-08-2020	0.05	19.8	80	Yes

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Winter weather conditions make it difficult for people to travel on highways, but the demand of the ever-growing economy is to keep the communication facilities uninterrupted no matter what. That is why most states have implemented different winter road maintenance strategies. The Georgia Department of Transportation is working relentlessly to manage road treatment during winter weather and provide a safer road. Because winter in Georgia is not as extreme as other northern states in the US, optimizing the winter road maintenance practices for specifically this region is important. Increasing emphasis on pre-treating the road rather than relying heavily on snow plowing and other post-treatments is the current trend in winter road maintenance. Pre-treatment reduces chemical use and has several other benefits. In this research, a pre-treatment requirement model was prepared to calculate the amount of brine required to melt different amounts of snow and ice.

In the last three years, Georgia faced several winter events. Three major snow events were selected to calculate the amount of brine required to melt the total daily accumulated snow. The following conclusions can be drawn from the study:

- According to the output of the model, only pre-treatment is sufficient for certain events. The recommended tool can save the amount of brine used by identifying locations where treatment is required and where not.
- The sensitivity analysis of the model revealed that the most important factor for snow accumulation is temperature. The melting capacity of salt increases with the increase in temperature at the events.

- The model found that at higher wind speeds, the snow accumulation decreases. Higher wind speeds decrease the amount of brine required.
- Adjusting the brine application rate can eliminate the need for post-treatment completely at a smaller snow event.

The model shows how to choose the appropriate amount of pre-treatment during small snow events. In big weather events, the decision regarding choosing a time to re-apply pre-treatment can be taken based on the snow accumulation amount generated by the model. The model also showed that brine requirement is most sensitive to changes in temperature. At lower temperatures, salt is less effective in snow-melting, and hence more salt is required. The output of the model can be used in better decision making on winter road pre-treatment.

5.2 Recommendations and Further Research

The applicability of the model depends on how accurately the weather is predicted. Accurate weather prediction will reduce the margin of error, and the model will produce more precise output that will help make specific decisions. The model should be further validated using prediction weather data and observed data. The following areas are suggested for further research:

<u>Treatment practice:</u> The model is applicable for pre-treatment decisions. However, the study has shown pre-treatment is not enough in bigger snow events. The model can be used as a starting point to study post-treatment requirements.

<u>Material application:</u> The model does not produce a viable result when the temperature drops significantly. The use of calcium chloride and a mixture of sodium chloride and calcium chloride can be considered as a treatment material at a lower temperature. The equations used for calculation could be adjusted for the use of other chemicals.

Field testing the model: The model can be field-tested based on prediction data at different intervals before a snow event. Then, it can be compared to the observed weather data during the event. This will help calibrate the model.

Equipment adjustment: The output of the model can be used to adjust spreaders based on real-time sensor data. The spreader might be adjusted for application amount and even material type.

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APPENDICES

APPENDIX A: THE MODEL

The following example is only for one station for a single day. The same calculation was done for all 23 stations for all three event days.

Table 7.1: The model input

No	Station	Date	Time	lowest surface temp	Black Ice	Snowfall (in)	Precipitation (in)	Air temperature (F)	Relative Humidity (%)	Wind Speed (mph)	Station Height (m)
1	GDOT-RWIS-I-75-328.50	Jan-16-2018	1	29		0	0	26	98	1.2	231.19
2	GDOT-RWIS-I-75-328.50	Jan-16-2018	2	29		0	0	27	96	1.2	231.19
3	GDOT-RWIS-I-75-328.50	Jan-16-2018	3	29		0	0	27	94	1.2	231.19
4	GDOT-RWIS-I-75-328.50	Jan-16-2018	4	29		0	0	28	93	1.2	231.19
5	GDOT-RWIS-I-75-328.50	Jan-16-2018	5	29		0	0	27	94	1.2	231.19
6	GDOT-RWIS-I-75-328.50	Jan-16-2018	6	28		0	0	27	95	1.2	231.19
7	GDOT-RWIS-I-75-328.50	Jan-16-2018	7	28		0	0	27	96	1.2	231.19
8	GDOT-RWIS-I-75-328.50	Jan-16-2018	8	29		0	0	28	95	1.2	231.19
9	GDOT-RWIS-I-75-328.50	Jan-16-2018	9	33		0	0	29	92	1.2	231.19
10	GDOT-RWIS-I-75-328.50	Jan-16-2018	10	38		0	0	32	85	2.3	231.19
11	GDOT-RWIS-I-75-328.50	Jan-16-2018	11	41		0	0	35	76	3.5	231.19
12	GDOT-RWIS-I-75-328.50	Jan-16-2018	12	44		0	0	37	70	3.5	231.19
13	GDOT-RWIS-I-75-328.50	Jan-16-2018	13	45		0	0	38	66	4.6	231.19
14	GDOT-RWIS-I-75-328.50	Jan-16-2018	14	45		0	0.009	39	65	4.6	231.19
15	GDOT-RWIS-I-75-328.50	Jan-16-2018	15	42		0	0.009	36	71	5.8	231.19
16	GDOT-RWIS-I-75-328.50	Jan-16-2018	16	38		0.04	0.009	33	79	5.8	231.19
17	GDOT-RWIS-I-75-328.50	Jan-16-2018	17	35		0.04	0.009	30	82	6.9	231.19
18	GDOT-RWIS-I-75-328.50	Jan-16-2018	18	32		0.02	0.009	27	83	6.9	231.19
19	GDOT-RWIS-I-75-328.50	Jan-16-2018	19	30		0.01	0.009	25	81	6.9	231.19
20	GDOT-RWIS-I-75-328.50	Jan-16-2018	20	29		0.009	0	24	79	6.9	231.19
21	GDOT-RWIS-I-75-328.50	Jan-16-2018	21	28		0	0	24	75	6.9	231.19
22	GDOT-RWIS-I-75-328.50	Jan-16-2018	22	27		0	0	23	72	8.1	231.19
23	GDOT-RWIS-I-75-328.50	Jan-16-2018	23	26		0	0	21	72	8.1	231.19

Table 7.2: Calculation of snow accumulation applying the melt equations

No	Air temp C	Rain fraction	Rain Temp	UADJ	Sat Vap Pressure	Atm Pressure (mb)	Melt due to rain (mm)	Melt due to rain (in)	Melt Factor	Non Rain Melt (mm)	Non Rain Melt (in)	Total Melt (in)	Snow (in)
1	-3.3	0	0	0.02317	4.78	1902.66	0.00	0.00	0.50	-1.67	-0.07	0.00	0
2	-2.8	0	0	0.02317	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0
3	-2.8	0	0	0.02317	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0
4	-2.2	0	0	0.02317	5.19	1902.66	0.00	0.00	0.50	-1.11	-0.04	0.00	0
5	-2.8	0	0	0.02317	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0
6	-2.8	0	0	0.02317	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0
7	-2.8	0	0	0.02317	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0
8	-2.2	0	0	0.02317	5.19	1902.66	0.00	0.00	0.50	-1.11	-0.04	0.00	0
9	-1.7	0	0	0.02317	5.41	1902.66	0.00	0.00	0.50	-0.83	-0.03	0.00	0
10	0.0	0	0	0.044408	6.11	1902.66	0.00	0.00	0.50	0.00	0.00	0.00	0
11	1.7	0	1.668	0.067578	6.89	1902.66	0.00	0.00	0.50	0.83	0.03	0.03	0
12	2.8	0	2.78	0.067578	7.45	1902.66	0.00	0.00	0.50	1.39	0.05	0.05	0
13	3.3	0	3.336	0.088817	7.75	1902.66	0.00	0.00	0.50	1.67	0.07	0.07	0
14	3.9	1	3.892	0.088817	8.06	1902.66	0.00	0.00	0.50	1.96	0.08	0.08	0
15	2.2	1	2.224	0.111986	7.17	1902.66	0.00	0.00	0.50	1.12	0.04	0.04	0
16	0.6	0.183673	0.556	0.111986	6.36	1902.66	0.00	0.00	0.50	0.28	0.01	0.01	0.028993
17	-1.1	0.183673	0	0.133225	5.63	1902.66	0.00	0.00	0.50	-0.56	-0.02	0.00	0.04
18	-2.8	0.310345	0	0.133225	4.98	1902.66	0.00	0.00	0.50	-1.39	-0.05	0.00	0.02
19	-3.9	0.473684	0	0.133225	4.58	1902.66	0.00	0.00	0.50	-1.95	-0.08	0.00	0.01
20	-4.4	0	0	0.133225	4.39	1902.66	0.00	0.00	0.50	-2.22	-0.09	0.00	0.009
21	-4.4	0	0	0.133225	4.39	1902.66	0.00	0.00	0.50	-2.22	-0.09	0.00	0
22	-5.0	0	0	0.156395	4.21	1902.66	0.00	0.00	0.50	-2.50	-0.10	0.00	0
23	-6.1	0	0	0.156395	3.87	1902.66	0.00	0.00	0.50	-3.06	-0.12	0.00	0

Table 7.3: Salt requirement and snow accumulation at different brine application rate.

No	Snow Accumulation	Weight of snow/lane-mile (g)	Change in Melting point C	Required Molarity	g salt required to melt 1g snow	g salt required	Salt required (gallon/lane-m)	Salt required Running sum gplm	0 gallon	40 gallon	60 gallon	80 gallon
1	0	0	3.34	0.90	0.05	0	0	0	0	0	0	0
2	0	0	2.78	0.75	0.04	0	0	0	0	0	0	0
3	0	0	2.78	0.75	0.04	0	0	0	0	0	0	0
4	0	0	2.22	0.60	0.04	0	0	0	0	0	0	0
5	0	0	2.78	0.75	0.04	0	0	0	0	0	0	0
6	0	0	2.78	0.75	0.04	0	0	0	0	0	0	0
7	0	0	2.78	0.75	0.04	0	0	0	0	0	0	0
8	0	0	2.22	0.60	0.04	0	0	0	0	0	0	0
9	0	0	1.67	0.45	0.03	0	0	0	0	0	0	0
10	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
11	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
12	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
13	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
14	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
15	0	0	1.00	0.27	0.02	0	0	0	0	0	0	0
16	0.03	650214.52	1.00	0.27	0.02	10253.25	12.27	12.27	0.03	0	0	0
17	0.07	897077.70	1.11	0.30	0.02	15730.40	18.82	31.09	0.07	0	0	0
18	0.09	448538.85	2.78	0.75	0.04	19662.99	23.53	54.63	0.09	0.01	0	0
19	0.10	224269.43	3.89	1.05	0.06	13764.10	16.47	71.10	0.10	0.02	0.01	0
20	0.11	201842.48	4.45	1.20	0.07	14157.36	16.94	88.04	0.11	0.03	0.02	0.00
21	0.11	0	4.45	1.20	0.07	0	0	88.04	0.11	0.03	0.02	0.00
22	0.11	0	5.00	1.35	0.08	0	0	88.04	0.11	0.03	0.02	0.00
23	0.11	0	6.12	1.65	0.10	0	0	88.04	0.11	0.03	0.02	0.00