JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Reducing the Dependency on Chlorides and Impacts

Ajuna P. John, Hoon C. Shin, Isaiah C. Mwamba,
David J. Yu, Amisha Shah, and Samuel Labi

SPR-4808 • Report Number: FHWA/IN/JTRP-2025/15 • DOI: 10.5703/1288284317879

RECOMMENDED CITATION

John, A. P., Shin, H. C., Mwamba, I. C., Yu, D. J., Shah, A., & Labi, S. (2025). *Reducing the dependency on chlorides and impacts* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2025/15). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317879

AUTHORS

Ajuna P. John
Graduate Research Assistant
Purdue University

Hoon C. Shin
Postdoctoral Research Associate
Purdue University

Isaiah C. Mwamba
Graduate Research Assistant
Purdue University

David J. Yu
Associate Professor
Purdue University
davidyu@purdue.edu
Corresponding Author

Amisha Shah
Associate Professor
Purdue University

Samuel Labi
Professor
Purdue University

ACKNOWLEDGMENTS

The authors acknowledge the assistance of the study advisory committee: Messrs. Justin Berger, Nick Evans, Michael Nichols, and Zechariah DeLoach of Indiana Department of Transportation (INDOT), and Dr. Timothy Wells of INDOT Research Division.

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP.

Published reports of the Joint Transportation Research Program are available at https://docs.lib.purdue.edu/jtrp/.

NOTICE

COVER IMAGE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2025/15		

4. Title and Subtitle	**5. Report Date**
Reducing the dependency on chlorides and impacts	May 20, 2025
	6. Performing Organization Code
7. Author(s) Ajuna P. John, Hoon C. Shin, Isaiah C. Mwamba, David H. Yu, Amisha Shah, Samuel Labi	**8. Performing Organization Report No.** FHWA/IN/JTRP-2025/15
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	**10. Work Unit No.** **11. Contract or Grant No.** SPR-4808
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This study examined the performance and environmental impacts of various deicing materials, assessed their short- and long-term effects on infrastructure, soil, and water quality, and identified opportunities for operational improvement within INDOT's winter maintenance practices. The study used a comprehensive methodology that included an extensive literature review, a detailed survey of INDOT personnel (both field crews and supervisory staff), in-depth interviews, and rigorous statistical analysis. Additionally, a multi-criteria decision analysis framework was developed and used to evaluate alternative deicing materials based on performance, cost, environmental impact, and ease of application. The results and findings suggest that sodium chloride remains the predominant deicing agent because of its cost efficiency and wide availability, despite its significant drawbacks such as corrosion and environmental degradation. Alternatives like calcium chloride, magnesium chloride, and environmentally benign deicers offer superior performance under extreme conditions, but face challenges related to higher cost and supply limitations. The survey provided indications of the benefits of specific practices including pre-plowing and reduced driving speeds, and highlighted issues with material overuse and inconsistent application rates. The study recommends greater integration of advanced technologies, more rigorous equipment calibration, enhanced route planning, and comprehensive training of staff, and the development and adoption of standardized guidelines for leftover-salt management, to optimize winter deicing operations.

17. Key Words	**18. Distribution Statement**
winter operations, winter maintenance, deicing; snow, ice control, workforce development	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	111, including appendices	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

The increasing reliance on chloride-based deicing methods has raised significant concerns regarding environmental pollution, infrastructure corrosion, and operational inefficiencies on Indiana's roadways. This study was undertaken to address these challenges and develop a strategic approach to optimize deicing operations while ensuring road safety during winter conditions. The project set out with clear objectives: to compare the performance and environmental impacts of various deicing materials; to assess both the short and long-term effects of chloride applications on infrastructure, soil, and water quality; and to identify areas for operational improvement in Indiana Department of Transportation's (INDOT's) deicing practices.

To achieve these goals, the study employed a comprehensive methodology that integrated multiple research approaches. A detailed literature review was conducted to synthesize findings from a wide array of documents regarding deicing materials, tools, and operational practices. In addition, a detailed survey was administered to INDOT personnel, encompassing both field crew members and supervisory staff. The survey collected data on current practices, material usage, and perceived challenges in winter operations, and its results were subjected to rigorous statistical analysis. This analysis aimed to uncover significant differences in practices between different geographic regions (Northern, Central, and Southern Indiana) and between roles (crew and supervisors) within INDOT. Furthermore, in-depth interviews were conducted with INDOT staff to gather qualitative insights into the operational challenges and decision-making processes encountered during winter maintenance. Finally, a multicriteria decision analysis (MCDA) was used to systematically compare deicing materials based on performance, cost, environmental impact, and ease of application, leading to actionable recommendations on material choice and operational improvements.

Findings

The synthesis of literature and the MCDA revealed that sodium chloride (NaCl) remains the most widely used deicing agent in Indiana due to its low cost, high availability, and sufficient performance under moderate winter conditions. However, despite its popularity, sodium chloride is not without its drawbacks. It is highly corrosive, leading to accelerated degradation of road surfaces, bridges, and other critical infrastructure components. Moreover, excessive chloride runoff poses significant risks to soil and water quality, adversely affecting local ecosystems. In contrast, alternative materials such as calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) offer improved performance in extremely cold conditions, maintaining effectiveness at lower temperatures where sodium chloride begins to lose its efficacy. Nevertheless, these alternatives are associated with higher costs and less favorable supply logistics which limits their use to specific situations. Environmentally benign deicers, such as acetates, were also evaluated. Although they are less corrosive and offer a reduced environmental footprint, their higher costs and limited availability restrict their widespread application. Abrasives, another category of deicing strategy, improve road traction without directly melting ice; however, they necessitate additional cleanup operations and are best used in targeted applications where chemical deicers may not be suitable.

The survey data provided a concise yet informative snapshot of current operational practices. Respondents reported several good practices, such as reduced driving speeds during deicing and preplowing before material application, practices that help improve material adherence and overall effectiveness. However, the survey also revealed notable challenges: most respondents indicated issues with material overuse and inconsistent adjustments in application rates during multiple passes or on long routes. In addition, while most respondents switch to alternative materials when pavement temperatures drop below 15 °F, there remains a gap in the consistent application of these best practices. Environmental awareness was high regarding issues like soil salinity and water quality impacts, yet awareness was comparatively lower for risks associated with harmful trace metals and the ecological effects of sand. Furthermore, although leftover salt management practices were generally effective, variability in practices among field crews regarding return of unused salt to stockpiles suggests room for improvement. The survey results also revealed notable differences in deicing practices across Indiana's regions. For example, practices in Northern Indiana, where winter severity tends to be higher, showed a higher incidence of proactive measures such as prewetting of deicing agents and more precise calibration of application equipment. Conversely, in Central and Southern Indiana, where weather conditions are relatively milder, there were instances of overapplication and inconsistent adjustment of material rates, leading to inefficient use of deicing agents and higher environmental risks. Overall, the survey results, supported by statistical tests, highlight a mixed landscape of strengths and weaknesses in current deicing operations.

In-depth interviews with INDOT staff provided rich qualitative insights that complemented the quantitative survey findings. Interviewees highlighted several challenges, including equipment failures related to salt-induced corrosion, difficulties in coordinating multi-pass operations, and the lack of uniform guidelines for material application. These interviews underscored the need for more flexible, data-driven decision-making processes that can adapt to varying weather conditions and operational contexts.

Implementation

The integrated findings from the literature review, survey, interviews, and data analyses form the basis for a series of strategic recommendations designed to strengthen INDOT's winter deicing operations. It is recommended that sodium chloride remains the primary deicing agent under normal winter conditions due to its proven cost efficiency and extensive availability. However, when faced with extremely low temperatures, the strategic use of calcium chloride and magnesium chloride should be considered to take advantage of their superior melting properties. In regions or specific road segments where environmental concerns are paramount, the targeted application of environmentally friendly alternatives such as acetates should be explored, despite their higher costs. Similarly, abrasives should be employed judiciously to improve road traction in high-traffic zones or areas where chemical deicers may be less effective.

Operational improvements are equally critical to enhancing overall deicing effectiveness. The study strongly supports the integration of advanced technologies to improve the precision and efficiency of material application. For example, the adoption of GPS-enabled spreaders and real-time monitoring systems would allow for more accurate distribution of deicing agents, thereby minimizing overuse and reducing collateral environmental damage. Additionally, the findings advocate improvements to prewinter planning processes. This includes rigorous equipment calibration, enhanced route planning, and comprehensive training programs that ensure both field crews and supervisory staff are aligned in their approach to deicing operations.

Training programs are a critical component of the recommended operational enhancements. Special attention should be given to correcting the practices identified as problematic in the survey—particularly the tendency to overuse deicing materials and the inconsistencies in material application on long routes. Additionally, training should address gaps in environmental awareness, especially concerning the risks associated with harmful trace metals and the ecological impacts of sand. Improved guidelines for leftover salt management are also imperative. Although most supervisors strive for the practice of returning residual salt to centralized stockpiles, variability among field crews indicates a need for standardized procedures. Clear, detailed guidelines should be developed and disseminated, outlining how leftover salt should be handled, stored, and ultimately reused. This will not only reduce material waste but also prevent potential environmental contamination resulting from improper salt disposal.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Problem Statement

The widespread use of chloride-based deicing and anti-icing materials, such as road salts and brines, is crucial in ensuring traffic safety and mobility during winter storms. However, this reliance on chloride presents significant challenges, including corrosion of infrastructure, environmental pollution, and potential health risks for workers handling these materials. The Indiana Department of Transportation (INDOT) faces the dual challenge of maintaining road safety while mitigating the negative long-term effects of chloride usage.

Beyond material choice, inefficiencies in the operational practices of workers during snow and ice removal may contribute to excessive salt use. Current INDOT practices involve a large-scale task force managing more than 1,000 snowplows and a workforce of up to 2,000 personnel, with operational complexities spanning procurement, storage, transportation, and application of deicing agents. Anecdotal accounts by INDOT staff suggest that certain operational inefficiencies, such as the unnecessary dumping of unused salt at the end of storm events, may exist and further exacerbate the negative impacts of chlorides.

Given these concerns, INDOT requires a comprehensive strategy to optimize chloride usage without compromising winter road safety. This study addresses key questions related to:

- The effectiveness of various deicing and anti-icing materials in reducing chloride dependency while maintaining performance.
- The short- and long-term impacts of chloride applications on infrastructure and the environment.
- Opportunities for operational improvements in INDOT's deicing practices, including material application methods, salt management, and workers' perceptions.

By investigating these factors, this study offers recommendations to INDOT for an agency-level deicing operations program that balances road safety, environmental sustainability, and cost efficiency.

This report represents the latest in a longstanding series of studies carried out by Purdue University to support INDOT's winter operations mission. These studies have addressed various aspects of the issue, primarily, salting and snow-removal management and operations; measurement and mitigation of environmental damage posed by salt applications; and infrastructure damage caused by deicing salts.

Regarding salting and snow removal operations, Wright (1988) developed a prototype system for snow route design and management, and McClellan et al. (2009) discussed the implementation of a winter maintenance decision support system in Indiana. McCullouch et al. (2013) established performance standards for snow and ice control. Desai et al. (2023) developed dashboards for real-time monitoring of winter operations activities, and Mahlberg et al. (2021) developed an intelligent snowplow truck that integrates telematics technology, roadway sensors, and connected vehicles. Iyer et al. (2021) proposed initiatives to improve and gain efficiency in winter operations. Iyer et al. (2022) developed methods to optimize the manpower allocation and routing of deicing trucks on state road networks. Mahlberg et al. (2023) focused on salt stockpile inventory reporting, studying salt use monitoring and reporting technology. Zhang et al. (2024) investigated automated record keeping for statewide winter road maintenance using telematics.

Regarding the measurement and mitigation of environmental damage posed by salt applications, Wilcox (1982) studied the effects of deicing salts on water chemistry and vegetation in Pinhook Bog, Indiana. Alleman et al. (2004) proposed innovative ways to manage the environmental effects of winter salt runoff at INDOT yards. Hashad et al. (2006) studied salt wash water toxicity on wastewater treatment. Corson (2004) addressed the management of storm water quality for INDOT. Ji et al. (2020) evaluated anti-icing/deicing products under controlled environmental conditions. Other studies in Indiana include Gardner and Royer (2010) who assessed the effect of road salt application on seasonal chloride concentrations and toxicity in south-central Indiana streams.

Regarding the infrastructure damage caused by deicing salts, Olek et al. (2013) investigated anti-icing chemicals and their interactions with pavement concretes. Frosch et al. (2014) and Labi et al. (2014) carried out laboratory experiments to study the corrosion rates of alternative rebar materials intended to extend deck life. Suraneni et al. (2016) assessed the performance of concrete pavement in the presence of deicing salts, and Tokpatayeva et al. (2025) investigated the interaction of cementitious systems containing nontraditional and natural pozzolans with chloride-based deicers. Other studies include Cope et al. (2011) who compared the cost-effectiveness of stainless steel and traditional steel for Indiana highway deck rebar based on their resistance to deicing salt, and Moomen et al. (2016) who investigated INDOT's bridge deck deterioration as a function of factors including salting-related climate attributes.

1.2 Objectives

In response to the challenges associated with chloride-based deicing materials, this study developed a comprehensive strategy for streamlining chloride dependency while maintaining road safety and operational efficiency. The key objectives of the study are as follows:

1. Comparison of different materials to streamline chloride dependency
    a. Assess the effectiveness of various chloride-containing deicing materials to determine if alternative formulations can provide similar performance with reduced environmental and infrastructure impact.
2. Chloride impact assessment
    a. Analyze the environmental consequences of chloride application, including its short and long-term effects on soil, water quality, and ecosystems.
    b. Investigate the structural and durability impacts of chlorides on road pavements, bridges, and other transportation infrastructure.
3. Identify opportunities to enhance operational practices and tools
    a. Identify discrepancies in INDOT workers' understanding and practices in current deicing/anti-icing operations that may lead to excessive chloride usage.

b. Explore different tools and technologies to determine areas for improvement in salt application efficiency.

3. Synthesize findings from material analysis, impact assessment, and operational evaluation to develop recommendations for enhancing INDOT's deicing operations program.

To achieve these objectives, this project adopted a methodological approach that integrates (1) a comprehensive literature review of various publicly available data on materials, tools and operational practices, (2) a survey and interviews with INDOT staff, and (3) statistical analyses of the survey responses data and a multicriteria decision analysis (MCDA) for synthesis and final recommendations.

2. DEICING MATERIALS, THEIR IMPACTS, AND EQUIPMENT

2.1 Deicing Materials Used in the United States

2.1.1 Material 1: Sodium Chloride (NaCl)

This section reviews the use of sodium chloride (NaCl) as both a deicer and anti-icing material for snow management. The application methods of sodium chloride—including its dry form, wet form, and brine solutions—along with the concentration mixes, the inclusion of corrosion inhibitors, and the quantity applied per lane mile, vary across different states. This review summarizes the effectiveness and application rates of sodium chloride, its harmful impacts, and findings on how to use it more effectively to minimize these impacts. The temperature of the pavement is a crucial factor when selecting a deicer, as the melting temperature of these materials needs to be analyzed before application. The eutectic temperature, which represents the lowest temperature at which a solution stays in liquid form, is a key factor in this context. At this temperature, the solution requires a prolonged period to melt the ice. The Michigan Department of Transportation (MDOT) notes that sodium chloride (in its dry form) works effectively at pavement temperatures above 15 °F (MDOT, 2013). Since its efficiency decreases at lower temperatures, sodium chloride is often applied in excess to compensate for this reduction in effectiveness. Table 2.1 illustrates sodium chloride's melting capacity at different temperatures.

Sodium chloride is also utilized in its brine form. By mixing liquid with granular salt, the melting process can be accelerated, reducing the overall amount of salt required. Brine, a liquid deicer, is created by combining rock salt and water, with an ideal concentration of 23% rock salt (Minnesota Department of Transportation [MnDOT], 2010). Additionally, brine mixtures with other additives, such as freezing point depressants like alcohols, are used to lower the water's freezing point, with sodium chloride brine being the main ingredient.

Understanding how deicing chemicals interact with the roadway is crucial. Therefore, testing the materials is necessary to confirm that they are delivered as ordered and perform as needed. As part of their standard procurement practices, MDOT specifies a 1.5% moisture content limit for road salt (MDOT, 2013). Adhering to this standard helps avoid the additional transport cost associated with the weight of water and reduces the risk of salt leaching during pretreatment. Moreover, when salt contains excessive moisture, it is more susceptible to freezing in storage, creating significant handling and operational challenges.

TABLE 2.1
Effectiveness of Sodium Chloride (NaCl) Based on Pavement Temperature (MDOT, 2013).

Pavement Temp (°F)	One Pound of Salt (NaCl) Melts	Melt Time
30	46.3 lb of ice	5 min
25	14.4 lb of ice	10 min
20	8.6 lb of ice	20 min
15	6.3 lb of ice	1 hr
10	4.9 lb of ice	
5	4.1 lb of ice	Dry salt is ineffective and will blow away before it melts any significant amount of ice
0	3.7 lb of ice	
−6	3.2 lb of ice	

2.1.2 Material 2: Calcium Chloride ($CaCl_2$)

This section reviews the use of calcium chloride ($CaCl_2$) as both a deicer and anti-icing material for snow and ice management. Calcium chloride is widely used due to its ability to effectively melt ice at lower temperatures compared to sodium chloride. The material is applied in both liquid (brine) and solid forms, with varying concentration mixes and quantities per lane mile depending on the state. According to studies by MnDOT (2015), calcium chloride can remain effective at pavement temperatures as low as −20 °F, significantly outperforming sodium chloride in similar conditions. The eutectic temperature of calcium chloride is much lower (−60 °F), allowing it to remain in liquid form under freezing conditions. Unlike sodium chloride, calcium chloride absorbs moisture from the atmosphere, which speeds up the melting process, making it a good choice for both prewetted applications and solid forms.

It is recommended that before application, the purity and concentration of calcium chloride must be verified through materials testing. According to the Illinois Department of Transportation (IDOT), material quality is assured by testing the concentration of calcium chloride in brine solutions (IDOT, 2017). An organizational guideline on the use of calcium chloride should indicate these critical parameters, including moisture content, to ensure consistent performance.

2.1.3 Material 3: Magnesium Chloride ($MgCl_2$)

Magnesium chloride ($MgCl_2$) is used for both anti-icing and deicing purposes. Like calcium chloride, magnesium chloride is effective at lower temperatures, though slightly less than calcium chloride. Magnesium chloride is typically effective down to approximately −10 °F, with similar properties to calcium chloride but with a slightly higher freezing point. The South Dakota Department of Transportation (SDDOT) reports on the use of magnesium chloride for deicing to prewet dry products, such as rock salt and sand, to enhance performance (SDDOT, 2024). Magnesium chloride is also used in slurry applications where it helps reduce the overall salt use by enhancing its melting capability. According to MnDOT (2022), magnesium chloride remains efficient at temperatures as low as 5 °F, making it a superior option compared to sodium chloride for colder weather deicing. It is commonly used in liquid form for prewetting solid materials like sodium chloride or as a standalone brine. A typical brine solution contains 27–30% magnesium chloride and is often preapplied to roads to stop snow and ice from bonding to surfaces. This approach has proven more effective than applying dry magnesium chloride, particularly when used as part of prewetting applications or liquid anti-icing strategies. The Idaho Transportation Department (ITD) also uses magnesium chloride extensively for colder regions where temperatures regularly drop below the effective range of sodium chloride (Casey et al., 2014). Its low freezing point allows for reduced application quantities while maintaining effectiveness in extreme conditions. Several states, such as Minnesota and Vermont, conduct detailed tests on magnesium chloride for moisture content, purity, and optimal concentration levels.

2.1.4 Material 4: Acetates

Acetates, particularly calcium magnesium acetate (CMA) and potassium acetate (KAc), are widely recognized as effective nonchloride deicing materials. They are preferred in environmentally sensitive and corrosion-prone areas due to their reduced impact on infrastructure, ecosystems, and health compared to traditional chloride-based salts. Acetates are primarily used in liquid or granular forms depending on the application and environmental conditions.

CMA is effective for deicing and anti-icing in moderate winter conditions and performs well at temperatures above 20 °F with a 32% concentration. CMA is commonly used in Minnesota, Michigan, Idaho, and Wisconsin where environmental sensitivity is a concern. It is available in both granular and liquid forms, with granular CMA used for deicing and liquid CMA for anti-icing or pretreatment. CMA has been tested and found to exhibit effectiveness in melting snow and ice under moderate cold conditions.

Potassium acetate is a nonchloride-based deicer widely used for anti-icing and deicing, particularly at airports, due to its noncorrosive nature. It is known for being environmentally friendly and effective at lower temperatures, performing well at temperatures reaching as low as −15 °F (−26 °C) when applied at a 50% concentration, but its cost often limits widespread highway use outside of high-priority areas.

Montana utilizes 11,603 gal of liquid potassium acetate annually for deicing, focusing on protecting wildlife and sensitive environments. North Dakota employs 7,050 gal annually, leveraging its superior low-temperature performance in regions with frequent subzero conditions. Washington applies 8,600 gal annually, emphasizing its noncorrosive properties and ability to mitigate chloride contamination in urban areas. Nebraska and New York use potassium acetate in smaller quantities (6,400 gal and 2,516 gal, respectively), typically for high-priority areas like bridges and critical roadways (Clear Roads, 2024). It is biodegradable and less likely to accumulate in the environment, hence ideal for use near aquatic ecosystems. Similarly, in areas with harsh winter conditions, such as Alaska, Montana, and North Dakota, potassium acetate has gained attention due to its performance in colder temperatures and noncorrosive properties. The Alaska Department of Transportation (ADOT) prefers potassium acetate in regions with extensive steel infrastructure, and protecting wildlife from chloride contamination is critical.

2.1.5 Material 5: Abrasives and Blends

Abrasives and blends are critical materials used for snow and ice control, particularly in areas where extreme cold limits the effectiveness of traditional deicing chemicals. Abrasives see extensive use across multiple regions: Northern and Snowbelt states rely heavily on them for additional traction during severe winter conditions, while Northeastern states use them to mitigate frequent freezing rain and snowstorms. Midwestern, Western, and Southern states also use abrasives to address icy conditions in their respective climates. Sand is primarily employed as an abrasive to enhance traction on icy or snowy surfaces, particularly in environments where temperatures drop below the effective range of chemical deicers. Sand significantly improves vehicle and pedestrian safety by providing friction but does not melt ice or snow, making it unsuitable as a standalone solution for ice removal.

Minnesota advises against excessive sand usage due to its ineffectiveness in extreme cold but acknowledges its utility in specific situations, such as freezing rain events, when combined with salt in a 75:25 or 50:50 ratio. Vermont uses winter sand for anti-icing due to its better-melting properties at lower temperatures, making it a practical choice for the region (Vermont Agency of Transportation [VTrans], 2020). Blends such as sand and salt mixtures (e.g., 90% sand and 10% salt) supplemented with urea are used in regions like Alaska (where 62,840 tons are used annually) to provide a balance between traction and limited melting capacity. These blends are particularly effective during transitional temperatures, freezing rain events, or when temperatures hover around the melting threshold of salt. States such as Minnesota recommend the use of sand-salt mixes to reduce ice slipperiness while maintaining some melting capability. Abrasives, including anti-skid materials, are also widely used in colder regions like Idaho and Alaska. These materials are particularly effective at extremely low temperatures and are often combined with small amounts of salt for improved performance. In Michigan, blends of anti-icing chemicals are commonly used to prevent ice formation, while abrasives are preferred in Idaho for their non-corrosive properties and effectiveness in traction improvement.

Materials testing has confirmed the effectiveness of sand and abrasives in providing traction during extreme cold conditions. Abrasives, such as antiskid materials, undergo testing to ensure durability and consistency, particularly under heavy traffic conditions. Testing of sand-salt blends evaluates the balance between melting efficiency and traction improvement, with results showing their effectiveness during moderate winter conditions. However, these blends lose effectiveness in extreme cold, where salt's melting capabilities diminish significantly. Idaho's testing focuses on particulate abrasives, which are noncorrosive and suitable for deicing. MDOT's (2013) *Winter*

Maintenance Manual provides detailed guidelines on using blends and abrasives based on road and weather conditions, ensuring optimal application and performance. These results highlight the importance of customizing material use to regional requirements and road safety standards.

2.1.6 Material 6: Enhanced Brines

SDDOT (2024) describes enhanced sodium chloride as salt that has been prewetted with a liquid to enhance its performance. Prewetting increases the temperature range at which sodium chloride remains effective and helps the salt adhere better to the pavement, reducing the typical roll and bounce seen with dry materials. Prewetting liquids include magnesium chloride, agricultural products, and salt brine.

Salt is effective down to 15 °F, but below that temperature, its ability to melt snow and ice becomes less efficient as the ice forms faster than it can melt. In these colder conditions, sand is applied to enhance traction, although it does not offer as much grip as salt making it necessary for the agency to warn drivers to drive with caution.

The most common method of prewetting involves spraying a liquid to the sand/salt mixture as it enters the truck's spinner. This requires specialized equipment, including a prewetting spray system and controls, ensuring consistent and even distribution.

2.1.7 Material 7: Agricultural By-Products

Agricultural by-products are innovative materials increasingly used for anti-icing and deicing applications due to their ecofriendly properties and lower corrosivity (MDOT, 2013). These by-products, such as beet juice and other agricultural derivatives, enhance the performance of traditional brine solutions by lowering the freezing point and improving adhesion to road surfaces (MDOT, 2013). For example, South Dakota uses 27,134 gal of agricultural by-products for anti-icing to ensure effective performance in winter conditions. Similarly, Wisconsin applies 332,503 gal of these materials, combining their use with traditional chlorides for enhanced efficiency. Ohio used 187,054 gal and Illinois used 183,120 gal of agricultural products for snow and ice control (Clear Roads, 2023).

Materials testing for agricultural by-products focuses on ensuring their performance under various environmental conditions and their compatibility with existing road maintenance practices. These materials are particularly valued for their ability to reduce road salt usage while maintaining effectiveness at lower temperatures. In Wisconsin, for example, testing has validated their enhanced adhesion to road surfaces, which minimizes material loss due to traffic or weather. Additionally, the integration of these by-products with traditional chlorides has been shown to improve melting capacity and extend operational temperature ranges.

2.1.8 Summary of Deicing Material Properties

Table 2.2 summarizes the pros and cons of various deicing materials used for winter highway management. Traditional options like sodium chloride and calcium chloride are cost effective and widely available but pose environmental and corrosion concerns. Magnesium chloride offers lower corrosivity but is still costly and moisture sensitive. Acetates provide an ecofriendly alternative but come with high costs and limited availability. Abrasives enhance traction but require extensive

TABLE 2.2
Pros and Cons of Deicing Materials.

Material	Pros	Cons
Sodium Chloride (NaCl)	Cheap and readily available	Ineffective below 15 °F
	Effective above 15 °F (−9 °C)	Highly corrosive
	Versatile in various forms	Significant environmental impacts
Calcium Chloride ($CaCl_2$)	Works at lower temperatures (−20 °F [−29 °C])	Expensive compared to NaCl
	Fast-acting	Extremely corrosive
	Requires less material than NaCl	Significant environmental impacts
Magnesium Chloride ($MgCl_2$)	Effective to −10 °F (−23 °C)	Expensive compared to NaCl
	Less corrosive than NaCl	Corrosive
	Attracts moisture for better melting	Limited life due to moisture absorption
Acetates (e.g., CMA, KAc)	Noncorrosive	Very expensive
	Biodegradable and environmentally friendly. Used in areas where chloride use must be limited	Can increase chemical oxygen demand (COD) in water bodies
	Effective at low temperatures	Limited widespread availability
Abrasives	Immediate traction improvement	Requires significant cleanup
& Blends	Effective in extreme cold	Does not melt ice
	Noncorrosive materials available	Sediment can harm aquatic habitats
	Enhanced performance at lower temperatures	Requires precise application
Enhanced Brines	Reduces salt usage	Chlorides still pose environmental risks
	Reduces material scatter	Higher costs
	Ecofriendly and biodegradable	Expensive
Agricultural By-products	Reduces material scatter	Increases biological oxygen demand (BOD) in water bodies
	Lowers freezing point in brines	Limited regional availability

TABLE 2.3
Practical and Eutectic Temperatures of Deicers (MDOT, 2013).

Material	Lowest Practical Melting Temp.	Eutectic Temp.	Optimal Concentration
Sodium Chloride (NaCl)	15 °F	−6 °F	23%
Magnesium Chloride ($MgCl_2$)	−10 °F	−28 °F	27 to 30%
Calcium Chloride ($CaCl_2$)	−20 °F	−60 °F	30%
CMA (Calcium Magnesium Acetate)	20 °F	−18 °F	32%
KAc (Potassium Acetate)	−15 °F	−76 °F	50%
Blends	Varies	Varies	Varies
Winter Sand/Abrasives	Never melts—provides traction only	N/A	N/A

cleanup, while enhanced brine and agricultural by-products improve efficiency and environmental impact but remain expensive and regionally constrained. Selecting the right deicing material involves balancing effectiveness, cost, and environmental considerations.

Table 2.3 presents the practical and eutectic temperatures of various deicing chemicals, highlighting their effectiveness under different conditions. Sodium chloride is effective at temperatures as low 15 °F, while magnesium chloride and calcium chloride work at much lower temperatures of −10 °F and −20 °F, respectively. Potassium acetate has the lowest eutectic temperature at −76 °F making it highly effective in extreme cold. CMA is limited to above 20 °F but offers environmental benefits. Blended deicers provide variable performance based on composition, while winter sand and abrasives do not melt ice but improve traction. Selecting the right deicer depends on temperature conditions and environmental considerations.

2.2 Impact Assessment of Deicing Materials

2.2.1 Impacts of Using Sodium Chloride

For almost a century, road agencies across the United States have relied on sodium chloride to manage snow and ice on roadways. Salt is an efficient deicer, readily available, and more affordable than other deicing materials. However, there are downsides to its use. Overapplication can harm bodies of water and vegetation, and salt is corrosive to vehicles, bridges, and other infrastructure on or near the road. Salt is not biodegradable, and its environmental impact can be significant. MDOT (2013) reports that a single tandem load of salt can contaminate up to 8 million gal of water. To put this into perspective, MDOT used 7–40 tons of salt (14,000 to 80,000 lb) per mile during a typical winter season. Chloride-based deicing chemicals are typically the most corrosive. sodium chloride is reported as the most corrosive material among the chlorides used for deicing (Casey et al., 2014). Deicing chemicals, particularly salt-based deicers, significantly contribute to motor vehicle corrosion because their chloride ions form solutions that are highly electrochemically active when dissolved in water or melted snow.

Several states have implemented corrosion inhibitor use in dry salt to minimize the corrosive effect on public vehicles and agencies. Montana prewets between 75% and 100% of the dry salt or salt-sand mix with inhibited liquid, while nonprewetted salt is not inhibited (Casey et al., 2014). The New York State Department of Transportation (NYSDOT) requires all of the state's salt to be in inhibited form (NYSDOT, 2012). Wisconsin uses between 10% to 50% of dry corrosion inhibiting salt, and nearly all of the state's 72 counties prewet their salt and many pretreat with corrosion inhibitors in the salt brine. The state of Washington previously used inhibited dry salt and found the mix to not be consistent in quality and to be significantly more costly (Casey et al., 2014).

The major environmental problem with chloride salts is that they harm vegetation by chloride uptake and soil degradation because of sodium accumulation and have detrimental effects on water and aquatic life (Casey et al., 2014). Plants are harmed by salts by contact with leaves and by permitting chloride and other ions to be taken up by the soil. Contact directly, particularly in the first 10 m off the road, will induce dehydration of tissues, destruction of stems and buds of young shoots, gradual growth, and early shedding of leaves in conifers. Leaf scorch, tissue necrosis, decline in the plant, and decreased growth are caused by the uptake of chloride ions. Sodium uptake, while less injurious, will cause inhibition of uptake of water and nutrients and thus stunted growth. Plants are highly susceptible by species. Conifers and younger plants are highly susceptible, while woody trees are less susceptible to salts. Grasses are highly tolerant of high concentrations of most salts. For the rest of the components of salts, high contents of calcium, magnesium, and potassium are tolerant by plants (Casey et al., 2014).

Use of chloride salts in deicing raises chloride, sodium, calcium, and magnesium concentrations in both groundwater and surface water, with the potential to harm aquatic life to some extent and human health to a less significant extent. Per Casey et al. (2014), citing various studies, chloride levels as low as 400 mg/L will cause harm to fish, though most species will tolerate significantly greater amounts. For instance, minor bluegills will tolerate between 8,100 and 10,500 mg/L, while rainbow trout will tolerate between 19,000 and 52,000 mg/L. The research also cites the range of acute chloride toxicity in fish to be between 8,500 and 12,000 mg/L and between 1,300 and 2,300 mg/L in small organisms. Larval fish are more susceptible to chloride than adults, and fish eggs will harden if salinity is above 3,000 mg/L.

Deicing activities have also been linked in research to increased chloride contents in the groundwater which accumulate and sometimes are above the EPA's secondary drinking standard of 250 mg/L. Groundwater-sourced sodium has been the source of public concerns, and the Massachusetts Department of Transportation has received on average 12 complaints every year about drinking water contamination with sodium. Even though the EPA does not regulate sodium, there are health concerns regarding its impacts on those suffering from heart diseases or high blood pressures (Casey et al., 2014). Sodium contents from deicing salts are not likely to account for a major part of one's daily intake though. Sodium chloride is toxic to 25% of microbial soil species in dosages of 4,700 mg/kg and exerts nonlethal impacts in dosages of 1,200 mg/kg (Bright & Addison, 2002). It was established in research conducted in 2008 that soils in cities in eastern New York were "in enough salt to be toxic to soil protozoa and terrestrial flora" due to the application of deicing salts (Casey et al., 2014, p. 37).

Studies in Indiana that have identified or measured the effects of sodium chloride include:

- Wilcox (1982), who studied the effects of deicing salts on water chemistry and vegetation in Pinhook Bog, Indiana;
- Hashad et al. (2006), who evaluated the toxicity of the saline waste water generated from washing of INDOT deicing trucks and to study the feasibility of discharging it into wastewater treatment plants;
- Nees (2025), who discussed the impact of specific deicing materials on specific trees and shrubs, plants;
- Spragg et al. (2011), Olek et al. (2013), Farnam et al. (2015), and Suraneni et al. (2016), who evaluated the behavior and performance of concrete pavement in the presence of deicing salts and deicing salt cocktails;
- Frosch et al. (2014) and Cope et al. (2011), who assessed alternative bridge deck reinforcement materials to address corrosion caused by deicing salt; and
- Alleman et al. (2004), who developed innovative environmental management of winter salt runoff problems at INDOT yards.

2.2.2 *Impacts of Using Calcium Chloride*

Calcium chloride is generally effective at low temperatures but has environmental drawbacks. Prolonged use could cause soil degradation, damage to vegetation, and contamination of groundwater. Calcium chloride can accumulate in roadside soil and plants, leading to similar issues as sodium chloride but at different thresholds. Studies by the Minnesota Pollution Control Agency indicate that calcium ions can disrupt soil structure leading to poor drainage and reduced soil fertility (Bouchard, 2016). It has corrosive impacts on infrastructure and vehicles but is less severe compared to sodium chloride. The corrosivity of calcium chloride can be mitigated using corrosion inhibitors which are commonly added to liquid brine solutions. However, calcium chloride tends to cause scaling on concrete surfaces which could result in long-term deterioration of roads and bridges.

Calcium ions are less toxic to aquatic life than sodium ions. However, the increased salinity from calcium chloride runoff still poses risks to water bodies and groundwater supplies. ADOT advises that calcium chloride should never be used in open drains due to its extreme toxicity to aquatic systems. Studies in Illinois have shown that prolonged use of calcium chloride could lead to increased chloride concentrations in nearby water sources, which may harm fish and invertebrates.

2.2.3 *Impacts of Using Magnesium Chloride*

Magnesium chloride is often seen as a more environmentally friendly option compared to sodium chloride. However, its use is also not without drawbacks. Like other chloride-based deicers, magnesium chloride can cause environmental and infrastructure damage if overapplied or used carelessly.

- In Alaska, magnesium chloride is used due to its low temperature performance, but ADOT (2014) has raised concerns about its impact on metal infrastructure, as it can accelerate corrosion when it comes into prolonged contact with steel.
- In Michigan, similar concerns have been raised, with MDOT (2013) citing an increased rate of corrosion in vehicles and bridges when magnesium chloride is overapplied. Corrosion inhibitors are often added to reduce these effects.
- In Wisconsin, magnesium chloride use has been linked to vegetation damage and soil degradation, particularly when applied in large quantities. Wisconsin DOT mitigates this by blending magnesium chloride with other, less harmful materials or by using it in combination with sand for traction purposes.
- In Vermont, the state has reported minimal but notable effects on nearby water bodies, with elevated magnesium levels found in groundwater. Vermont has taken steps to control application rates and to use corrosion inhibitors wherever possible to minimize environmental damage (VTrans, 2015).

Both calcium chloride and magnesium chloride are considered permanent pollutants that do not break down over time. Excessive use could lead to high chloride concentrations in soil and water bodies causing compaction, erosion, and harm to aquatic life. Chloride levels above 70 parts per million (ppm) can damage vegetation and negatively impact sensitive fish species (MnDOT, 2022). Hence, minimizing overapplication and optimizing usage rates through technological improvements is crucial for reducing environmental impact.

2.2.4 *Impacts of Using Acetates*

CMA is less corrosive compared to chlorides. It is biodegradable but its excessive use could deplete oxygen levels in nearby water systems, potentially harming aquatic life. CMA is significantly more expensive than traditional deicers, limiting its widespread adoption. Also, it requires proper application rates to avoid waste and ensure efficiency.

In Minnesota, Michigan, and Idaho, potassium acetate is valued for its environmental and infrastructure benefits. Potassium acetate is biodegradable, reducing its long-term ecological footprint. It is less harmful to aquatic ecosystems and wildlife than chloride-based deicers. Potassium acetate is noncorrosive, making it ideal for use on bridges, steel structures, and other critical infrastructure. It is often added to sodium chloride as a corrosion inhibitor (MnDOT, 2022). Its biodegradability ensures that it does not accumulate in surrounding environments, further protecting infrastructure from potential chemical damage caused by deicer residues. In Vermont, potassium acetate is favored for deicing in regions near protected water resources due to its biodegradability and minimal harm to aquatic life. However, in Idaho, the ITD cautions that excessive use of potassium acetate may increase the chemical oxygen demand (COD) in water bodies, though this is less severe than with chloride-based materials (Casey et al., 2014). Potassium acetate is among the most expensive deicers, making it practical only for high-priority areas. While less corrosive than chlorides, potassium acetate may still cause minor effects on exposed metals if overapplied.

2.2.5 Impacts of Using Sands and Abrasives

The environmental and infrastructure impacts of sand, blends, and abrasives are significant and require careful management. Excessive use can lead to sediment accumulation in stormwater systems, causing clogged drains and sedimentation in nearby water bodies. Minnesota reports that sand negatively impacts aquatic organisms in lakes and streams, posing a threat to local ecosystems. Sand-salt blends, while effective, can contribute to chloride contamination in water resources, posing risks to both flora and fauna. Residual sand and abrasives also require significant cleanup efforts during the spring, further adding to environmental concerns.

From an infrastructure perspective, sand and abrasives can cause abrasion and damage to road surfaces over time, increasing wear and tear and necessitating more frequent maintenance. Fine particulates from these materials can clog pipes and drainage systems, leading to higher maintenance costs. Sand-salt blends, although beneficial, can accelerate corrosion on metal structures such as bridges and guardrails due to their chloride content. Vermont and Idaho mitigate these risks by using noncorrosive alternatives like particulate abrasives. Additionally, residual sand on roads can cause wear on surfaces, necessitating frequent cleaning and repair. These impacts highlight the importance of adopting environmentally conscious practices and using materials that minimize long-term damage to both infrastructure and ecosystems.

2.2.6 Impacts of Using Agricultural By-Products

The use of agricultural by-products offers significant environmental benefits compared to traditional deicing methods. These materials are biodegradable and reduce the reliance on corrosive chlorides, minimizing the risk of soil and water contamination. For example, South Dakota highlights the use of agricultural by-products as a nonchloride alternative, helping to protect aquatic ecosystems and roadside vegetation. However, in states like Wisconsin, where agricultural by-products are combined with chlorides, some environmental risks remain, particularly in terms of infrastructure corrosion. Despite this, the reduced overall chloride usage contributes to longer-lasting roads and bridges while lowering maintenance costs over time.

Agricultural by-products are particularly effective in creating a sticky layer on road surfaces, reducing material runoff and increasing longevity during snow and ice events (Casey et al., 2014). Additionally, agricultural by-products are often used as prewetting agents to treat solid salts before application. This practice enhances the salt's efficiency by activating the brine formation process more quickly and reducing material loss to road shoulders (MDOT, 2013).

Studies have shown that agricultural by-products inhibit the corrosive effects of chloride-based salts, which can prolong the lifespan of vehicles and infrastructure. The inclusion of organic compounds derived from agricultural sources minimizes the oxidation process that leads to metal degradation (Casey et al., 2014). Environmentally, agricultural by-products present advantages over traditional salts, which contribute to elevated chloride levels in soil and water. However, concerns about biochemical oxygen demand (BOD) have been raised, as some agricultural by-products cause oxygen depletion in aquatic ecosystems if not properly managed (MDOT, 2013).

Storage and handling requirements also differ from traditional salts, as some agricultural by-products require specialized storage solutions to prevent degradation and maintain their effectiveness over time (MDOT, 2013).

2.2.7 Summary of the Impacts of Deicers

There are many potential environmental impacts of common snow and ice control chemicals, as outlined in Appendix B (Casey et al., 2014). Road salt (sodium chloride), calcium chloride, and magnesium chloride contribute to moderate water quality concerns due to excessive chloride loading and heavy metal contamination, while acetates and organic biomass products significantly impact aquatic life by increasing oxygen demand. Abrasives pose high risks to air quality and water turbidity due to sedimentation. Soil degradation is most pronounced with sodium chloride, whereas other chemicals have minimal or mixed effects. Vegetation damage is highest with chloride-based deicers, while acetates and organic products have lower risks. Impacts on animals are generally low, with sodium chloride posing some risk of salt toxicosis. Balancing effectiveness with environmental impact is crucial in selecting deicing materials.

Appendix C includes a summary of various impacts specific to using chloride-containing materials for deicing, including those mixed with abrasives. These impacts span across public health, infrastructure, and air quality. Chloride persists in the environment, contaminating water bodies, reducing biodiversity, and harming vegetation. Long-term accumulation increases soil and water salinity, affecting sensitive species. Public health concerns arise from elevated chloride levels in drinking water, particularly for individuals with hypertension. Chlorides accelerate corrosion of vehicles, bridges, and infrastructure, with corrosion inhibitors offering mitigation at higher costs. Additionally, sedimentation from deicing chemicals clogs stormwater systems, requiring extensive cleanup. Air quality is also affected by fine particulates from abrasives, which contribute to respiratory issues. Lastly, road and pavement wear from abrasives increases maintenance demands. Managing chloride use effectively is essential for minimizing these environmental and infrastructural challenges.

2.3 Tools and Equipment for Winter Operations

Winter road maintenance across the US heavily relies on specialized tools and equipment to ensure safe and efficient operations during severe weather conditions. Common tools include snowplows, road graders, sanders, blowers, and various attachments designed for clearing roads and applying deicing materials. States adapt their equipment usage based on local weather conditions, road priorities, and budget considerations.

2.3.1 State-Specific Equipment Highlights

Minnesota uses a comprehensive and advanced system for winter road maintenance, combining traditional snow removal equipment with cutting-edge technology to manage its extremely cold and heavy snowfall. The state relies heavily on its fleet of 886 plow trucks, which serve as the primary tools for clearing snow, along with 166 snow blowers for areas where plowing alone is insufficient. To enhance efficiency, Minnesota deploys 932 wing plows and 786 belly plows that expand the clearing width and 868 prewetting systems that improve the effectiveness of salt by reducing scatter and ensuring better adherence to road surfaces (Clear Roads, 2023).

As per MnDOT (2022), innovative technologies are at the heart of Minnesota's winter operations. Truck-mounted temperature sensors provide real-time data on pavement temperatures, enabling precise application of deicing materials and reducing waste. Road and weather information systems (RWIS) are installed near roadways to monitor air and pavement temperatures, precipitation, and wind conditions, which are crucial for tailoring winter maintenance strategies (MnDOT, 2024). Additionally, structure-mounted and handheld infrared sensors allow for accurate measurement of pavement conditions, supporting timely and efficient decision-making.

The Maintenance decision support system (MDSS) integrates weather forecasts, RWIS data, and pavement conditions to recommend optimal treatment strategies, ensuring cost-effective use of materials while maintaining road safety. Automated Vehicle Location (AVL) systems complement these efforts by tracking plow trucks in real time, monitoring material spread rates, and enabling dynamic responses to evolving storm conditions. Minnesota emphasizes equipment calibration to minimize waste and reduce environmental impact. Prewetting, a process that enhances the effectiveness of salt, is widely employed, with application rates between 8–14 gal per ton of material. The state also utilizes slurry applications, where supersaturated salt slurries activate rapidly, reducing overall material use. Anti-icing measures, such as applying salt brine before a storm, prevent snow and ice from bonding to pavement, further optimizing operations. Environmental protection is a priority in Minnesota's winter maintenance strategy. By using prewetting systems and precise calibration, the state reduces chloride runoff into water systems. Snow storage and stockpile management practices are carefully designed to prevent contamination of sensitive areas.

Michigan's winter operations heavily incorporate prewetting systems, where liquid is added to granular salt before application. This method reduces salt scatter, ensures better adhesion to road surfaces, and increases melting efficiency. Anti-icing strategies, involving the application of liquid deicers before snowfall, are also widely used, particularly on high-traffic routes. These measures prevent snow and ice from bonding to the pavement, simplifying subsequent plowing and reducing the need for reactive deicing (MDOT, 2013). The state utilizes underbody blades, belly plows and wing plows extensively for mechanical snow removal, which is cost-effective and reduces the reliance on chemical deicers. In recent years, Michigan has tested tow plows which allow operators to clear an entire lane in a single pass, thereby enhancing operational efficiency. Additionally, segmented blades are commonly used to provide flexibility on uneven road surfaces, reducing vibration for the operator and ensuring effective snow removal (MDOT, 2013).

According to MDOT (2013), the state integrates advanced technologies such as RWIS and MDSS into its operations. RWIS stations monitor pavement temperatures, weather conditions, and road surface data, which are critical for planning material application and treatment strategies. MDSS combines weather forecasts, real-time road conditions, and maintenance practices to recommend optimal treatments, thereby ensuring the efficient use of resources. Environmental sustainability is a key focus in Michigan's winter maintenance. The state employs precise calibration of equipment to prevent over-application of salt, reducing runoff into water systems. Prewetting and anti-icing practices also minimize the overall use of deicers, contributing to environmental protection.

Idaho employs a comprehensive and advanced approach to winter road maintenance, utilizing a combination of state-of-the-art technologies and traditional equipment to ensure safe and efficient travel during severe weather conditions. As per Clear Roads (2023), Idaho's fleet includes 436 plow trucks and 345 wing plows which are critical for effective snow removal, particularly in the mountainous and rural regions of the state. Wing plows extend the clearing width, allowing for more efficient operations on multi-lane roads and highways.

According to Casey et al. (2014), Idaho is successful in integrating advanced technologies into its winter operations. AVL systems are used extensively to monitor the real-time locations of plow trucks, enabling better coordination and response during snow events. MDSS combine weather forecasts, road sensor data, and operational inputs to recommend optimal treatment strategies, which reduce resource waste and enhance road safety. RWIS play a critical role in monitoring pavement and atmospheric conditions, providing real-time data that informs decisions on when and where to deploy resources.

In addition to these systems, Idaho uses sensors to assess conditions like air temperature, pavement moisture, and ice formation. This data-driven approach allows for the precise application of deicing materials, minimizing environmental impact and optimizing resource use. The state's emphasis on improved forecasting ensures that preemptive measures, such as anti-icing, are implemented before severe conditions arise, preventing snow and ice from bonding to the road surface. Idaho's focus on sustainability and efficiency is reflected in its material application strategies. Prewetting systems are widely used to enhance the adherence of salt and brine to road surfaces, reducing scatter and improving melting efficiency. These systems, combined with the use of corrosion inhibitors in deicing chemicals, help mitigate environmental and infrastructural impacts.

According to Clear Roads (2023), Vermont operates a relatively small fleet, with 275 plow trucks and 275 wing plows, emphasizing efficiency. The state uses proactive strategies including prewetting systems to improve material adherence to roads. Vermont's equipment is adapted for operations in low temperature conditions which dominate its winter season (VTrans, 2015).

South Dakota uses a comprehensive and innovative approach to winter highway maintenance, ensuring road safety and accessibility during harsh winter conditions. The state's fleet consists of 485 plow trucks, 90 snow blowers, 296 belly plows and 555 wing plows, which are strategically deployed across its regions to clear snow and maintain roadways efficiently. These tools are complemented by specialized equipment such as tow plows which expand snow-clearing capacity and are particularly effective on interstates and major routes (Clear Roads, 2023).

According to the SDDOT *Winter Highway Maintenance Plan*, the state has embraced advanced technologies like the MDSS which integrates real-time weather data, road conditions, and maintenance activities to optimize resource allocation and improve operational decisions. Snowplows are equipped with Mobile Data Collectors (MDCs) that gather detailed information on pavement temperatures, plow positions, and deicer applications, further enhancing the precision and effectiveness of winter operations. Environmental Sensor Stations (ESS) located along highways provide continuous updates on atmospheric and pavement conditions, enabling proactive responses to changing weather patterns.

South Dakota also focuses on safety innovations, including the use of blue lights on snowplows to improve visibility during low-visibility conditions such as blizzards and fog. High Friction Surface Treatments (HFST) are applied to high-risk areas like curves and intersections, reducing crash rates by up to 80%. These treatments enhance traction and durability, ensuring safer travel even in challenging conditions. South Dakota also tests environmentally friendly deicers, including agricultural by-products, to minimize ecological impact while maintaining performance in subfreezing temperatures.

Alaska uses a robust and adaptive approach to winter road maintenance, leveraging advanced tools and strategies to manage its unique and severe winter conditions. The state's fleet consists of 306 plow trucks, 291 road graders, and 107 blowers, designed to clear snow effectively across Alaska's diverse and challenging terrains (Clear Roads, 2023). Road graders are particularly essential for maintaining unpaved or partially paved roads in remote areas, while blowers handle large accumulations of snow in high-altitude or heavily drifted regions. According to ADOT's (2014) *Standard Operating Procedures for Winter Road Maintenance*, Alaska prioritizes proactive anti-icing strategies as the first line of defense against winter road hazards. By applying chemical freezing-point depressants before storms, the state prevents snow and ice from bonding to pavement surfaces. Anti-icing is cost effective (requiring a fraction of the material used in deicing) and reduces environmental impacts and enhances traffic safety. Prewetting systems further improve the adhesion of salt to road surfaces (20–30% less material is used), and enhance its melting efficiency, particularly in temperatures above 15 °F. For areas where temperatures are too low for chemical deicers to function effectively, Alaska relies on sand and other abrasives to provide temporary traction. Sand is applied in critical areas such as intersections, curves, and steep grades. The state ensures the strategic placement of stockpiles and the use of environmentally sensitive practices to minimize the impact of sand runoff on waterways.

Alaska also integrates advanced technology into its operations. RWIS and truck-mounted temperature sensors provide real-time data on pavement and atmospheric conditions, allowing operators to make informed decisions regarding material application and timing. These tools are essential in a region where pavement temperatures can differ significantly from air temperatures, particularly on bridges and in shaded areas. The state's commitment to sustainability and safety is reflected in its focus on minimizing material usage while maintaining effectiveness. Regular calibration of equipment and adherence to strict application rate guidelines ensure efficiency and reduce waste. Additionally, Alaska emphasizes poststorm evaluations and documentation, enabling continuous improvement of its winter maintenance practices.

Wisconsin uses a comprehensive and innovative approach to winter road maintenance, combining a large fleet of equipment with advanced technologies and efficient strategies. The state has 3,200 plow trucks, 3,000 wing plows and 400 road graders, supported by various add-ons such as prewetting systems to improve material application efficiency (Clear Roads, 2023). These tools are essential for managing the state's diverse winter conditions, ranging from heavy snowfall to icy road surfaces.

In Greenville, Wisconsin, priority-based road maintenance is used to allocate resources efficiently (Town of Greenville Department of Public Works, 2015). Primary and secondary roads are treated and cleared first, with goals to achieve bare pavement on 75% of primary roads within 24 hours after a storm ends. Residential streets and cul-de-sacs are treated next, ensuring safe and passable conditions for all road users. The town integrates data-driven technologies such as RWIS to monitor pavement and atmospheric conditions, allowing for precise decision-making. Prewetting systems enhance the adherence of deicing agents to road surfaces and improve their effectiveness at lower temperatures. These practices not only improve road safety but also reduce the environmental impact by minimizing the use of abrasive and chemical materials. INDOT uses a combination of specialized vehicles, sensing technologies, and data systems to support winter operations. The primary equipment includes a fleet of nearly 1,100 snowplow trucks used for snow removal and the application of deicing materials such as salt and brine (Desai et al., 2020).

Appendix D presents the various tools and equipment used for winter operations in various states. It presents a comparison of winter road maintenance tools and equipment used across eight states: Minnesota, Michigan, Idaho, Wisconsin, South Dakota, Vermont, Alaska, and Indiana. All states use basic snow removal tools such as plow trucks, wing plows, tow plows, road graders, spreaders and prewetting system (Clear Roads, 2024). Advanced technologies like AVL and RWIS are also widely adopted (Clear Roads, 2018). However, there are variations in specialized equipment usage—underbody scrapers and slurry systems are not implemented universally. Notably, Minnesota and Michigan lead in deploying a comprehensive range of winter maintenance technologies.

2.4 Comparison of Indiana's Deicing Material Usage with Other States

This section analyzes data from the 2019–2023 winter season, gathered through the Clear Roads Winter Maintenance Survey, which covers a range of approaches and materials used across multiple states. Clear Roads is a national research consortium dedicated to enhancing winter maintenance practices through rigorous testing of materials, equipment, and methods used by highway maintenance crews. By systematically collecting and analyzing data from state departments of transportation, Clear Roads supports informed decision making to improve winter road safety and efficiency. Through ongoing research and collaboration, Clear Roads helps state agencies implement effective and environmentally responsible snow and ice control strategies. The analysis in this section is based on data from Clear Roads' 2024 survey.

Indiana has a high reliance on chloride-based materials (Appendix E, Table E.1). The state's use of sodium chloride is notable, with an average annual usage of 238,173 tons from 2019 to 2023. Compared to its neighboring states, Indiana's sodium chloride usage is moderate—higher than Kentucky (138,908 tons) and Missouri (106,928 tons) but lower than Illinois (408,800 tons), Ohio (507,635 tons), and Michigan (436,023 tons). It can be observed from the data that Indiana uses only sodium chloride as dry deicing material. Unlike some states, Indiana does not report the use of calcium chloride or magnesium chloride in dry form, focusing primarily on traditional dry sodium chloride. The state also reports minimal use of abrasives, suggesting a reliance on chemical deicing rather than traction-based solutions. In contrast, Missouri and Michigan have incorporated treated salt mixtures with magnesium chloride and calcium chloride to enhance performance in colder conditions.

Examining chloride-based deicer usage nationwide, it can be observed that Indiana falls into the mid to high range but it does not lead to overall salt consumption. States like New York (830,406 tons), Pennsylvania (597,611 tons), and Ohio (507,635 tons) have significantly higher sodium chloride usage due to their extensive winter maintenance needs. Indiana's reliance on sodium chloride salt aligns more with states like Iowa (122,250 tons) and Kansas (91,234 tons) rather than those adopting higher proportions of alternative treatments. Notably, Indiana does not report the same level of abrasives or blended materials as states like Montana (222,809 tons of abrasives) or Washington (57,532 tons of abrasives, 34,316-ton sand-salt mix), indicating a preference for chemical deicing over mechanical traction aids.

Indiana's heavy reliance on chloride-based deicing liquid materials places it among the higher-usage states for traditional salt brine (Appendix E, Table E.2). Over the past five years, Indiana has averaged 3.54 million gal of sodium chloride brine, along with 27,695 gal of calcium chloride brine and 14,136 gal of magnesium chloride brine. This places Indiana in line with other Midwest states like Illinois (1.35 million gal of sodium chloride brine, 124,720 gal of calcium chloride brine) and Ohio (12.2 million gal of sodium chloride brine, 208,096 gal of calcium chloride brine) but far behind states like Iowa (27.3 million gal of sodium chloride brine) and Nebraska (9.4 million gal of sodium chloride brine). Indiana has limited adoption of alternative treatments, using only 32,315 gal of agricultural by-products and 26,583 gal of materials like Beet Heet. This volume is relatively modest when compared to similarly winter-impacted states. For instance, Ohio used 832,861 gal of brine mixed with beet juice, Wisconsin applied 269,211 gal, North Dakota applied 637,979, and Illinois applied 175,204 gal of agricultural by-products. Even states with less severe winters, such as Missouri (404,706 gal) and Nebraska (326,930 gal), reported significantly higher usage. In contrast, Indiana's application levels are closer to those of Kansas (40,217 gal), and considerably above Oregon (2,954 gal) and New Jersey (20,000 gal). The data suggest that while Indiana has begun to incorporate agricultural by-products into its deicing strategy, it lags behind many other states that more aggressively utilize these materials to enhance performance, reduce corrosion, and mitigate environmental impacts.

2.5 Summary and Key Takeaways

This chapter reviewed various deicing materials used in the US, focusing on their effectiveness, environmental impact, and application methods. Sodium chloride is seen to be widely used across the states but loses effectiveness below 15 °F and poses environmental risks. Calcium chloride works at lower temperatures but is more expensive and corrosive. Magnesium chloride is less corrosive and effective to −10 °F. Acetates are environmentally friendly but costly. Blends and abrasives improve traction, especially in extreme cold. Enhanced brines increase effectiveness at lower temperatures, while agricultural by-products offer an ecofriendly alternative. The chapter also discusses tools and equipment used in winter road maintenance, highlighting state-specific practices and innovations.

It can be seen that compared to other states, Indiana lags in the adoption of ecofriendly deicing options. While some states, such as Ohio and Illinois, have incorporated agricultural by-products like beet juice and enhanced brines to reduce chloride dependency, Indiana's use of Beet Heet and other alternatives remains minimal. It is recommended to diversify its winter maintenance strategy to contribute to long-term environmental degradation and rising infrastructure costs. With mounting concerns about chloride pollution and its lasting consequences, Indiana must explore more balanced and sustainable deicing practices to mitigate these risks.

3. BEST PRACTICES IN OPERATIONS ACROSS STATES

3.1 Summary of Winter Operations in Various States

This section presents a high-level overview of winter operations in several states based on an analysis of their state-level winter road maintenance manuals. The section emphasizes innovative techniques, effective material applications, and policy-driven improvements that enhance overall winter road efficiency. The states featured in this chapter—Michigan, Idaho, Wisconsin, Minnesota, Alaska, and South Dakota—represent a diverse range of winter climates and maintenance challenges, offering valuable insights into effective strategies tailored to regional needs.

3.1.1 Winter Operations in Michigan

The state's operations are guided by MDOT (2013), which provides detailed recommendations for snow and ice control. Michigan's overall operational strategy can be summarized as:

- *Planning and Preparation*: Michigan emphasizes prewinter preparation, including route inspections and snow trap removals. Operators are assigned specific routes, improving familiarity and performance during snow events.
- *Advanced Equipment and Calibration*: Equipment like underbody blades and segmented plows are used for efficient snow removal. Annual calibration ensures proper material application rates, reducing waste and cost.
- *Deicing and Anti-Icing Practices*: Michigan utilizes a mix of dry and liquid deicers, such as prewetting salt with brine or using hygroscopic chemicals like calcium chloride. Anti-icing is proactively applied to prevent ice formation, reducing the need for reactive deicing.
- *Environmental Conservation*: The state minimizes the impact of road salt on freshwater systems by following strict storage and application guidelines. Best practices include using covered salt storage and double-wall tanks for liquid deicers.
- *Postevent Procedures*: After snow events, Michigan evaluates performance, stores materials safely, and ensures that vehicles are cleaned to prevent salt corrosion.

In line with the strategy, Michigan implemented specific operational practices, organized by key operational areas, as outlined in Appendix F, Table F.1.

3.1.2 Winter Operations in Idaho

ITD uses a range of strategies and practices to ensure effective winter road maintenance (Casey et al., 2014). Idaho's overall operational strategy can be summarized as:

- *Material Application*: Idaho uses solid salts, salt brines, and magnesium chloride, each tailored to specific temperatures and road conditions. The addition of corrosion inhibitors reduces environmental and vehicle damage.
- *Anti-Icing and Deicing*: Anti-icing is a key strategy, applied before winter storms to prevent snow and ice from bonding to pavement. This reduces material usage and improves safety.
- *Environmental Stewardship*: The ITD stores materials in environmentally secure facilities and monitors runoff to protect soil and water quality. ITD limits the overapplication of materials to reduce ecological harm.
- *Wildlife Protection*: Recognizing that salt can attract wildlife to roadways, Idaho implements measures such as alternative materials or redirecting roadside water to reduce wildlife-vehicle collisions.
- *Advanced Technology*: ITD uses GPS-enabled systems to monitor material application in real-time, ensuring precision and minimizing waste.
- *Poststorm Reviews*: After major winter events, ITD conducts thorough evaluations to refine strategies, improve cost-efficiency, and maintain environmental compliance.

In accordance with this strategy, Idaho adopted specific operational practices, categorized by key operational areas, as outlined in Appendix F, Table F.2.

3.1.3 Winter Operations in Wisconsin

Wisconsin uses a multifaceted approach encompassing proactive strategies, advanced equipment utilization, and compliance with environmental regulations. The state's overall operational strategy can be summarized as:

- *Proactive Weather Monitoring*: Weather data from RWIS and other sources enable Wisconsin's teams to anticipate and prepare for winter storms effectively. This ensures timely responses for anti-icing and plowing operations.
- *Priority-Based Snow Removal*: Snow removal follows a defined hierarchy, starting with primary roads for essential transportation and concluding with residential areas. This systematic approach ensures roads remain navigable throughout a storm.
- *Efficient Use of Deicers*: Wisconsin relies on pretreated salt and liquid anti-icers to prevent ice bonding on road surfaces, reducing the amount of material needed for subsequent deicing operations.
- *Environmentally Conscious Practices*: To minimize environmental impact, the state regulates salt application rates and ensures that storage facilities prevent runoff into water sources.
- *Robust Equipment and Staffing*: A well-maintained fleet of snowplows, salt spreaders, and liquid dispensing equipment supports efficient operations. Shifts are managed to maintain 24-hour coverage during major events.
- *Public and Emergency Coordination*: Wisconsin communicates effectively with the public regarding snow emergencies and collaborates with emergency services to ensure access during storms.

In line with this strategy, Idaho implemented specific operational practices across key areas, as outlined in Appendix F, Table F.3.

3.1.4 Winter Operations in Minnesota

Minnesota's winter operations follow the local operations manual (MnDOT, 2015) which offers comprehensive recommendations for snow and ice management. The state's overall operational strategy can be summarized as:

- *Preparation and Planning*: Minnesota emphasizes thorough preparation, including equipment calibration and route planning, before the winter season. Operators are trained to address potential hazards and efficiently manage snow traps.
- *Advanced Deicing Techniques*: Anti-icing is prioritized using liquid deicers such as sodium chloride brine or magnesium chloride. This prevents ice from bonding to roads and reduces the need for reactive deicing.
- *Environmental Stewardship*: Strict material storage protocols and controlled application rates help minimize the environmental impact of deicers and abrasives. Minnesota actively works to reduce chloride contamination in nearby water sources. Slurry applications reduce the overall use of salt, which aligns with cost efficiency and environmental sustainability

- *Efficient Snow Removal*: Snowplows and underbody blades are used to remove snow before chemical applications, reducing material waste. Prewetting and pretreating techniques ensure optimal use of resources.
- *Continuous Improvement*: Postevent evaluations and training sessions refine strategies and enhance operational efficiency. Real-time data from RWIS guide adjustments during storms.

In line with the overall directions outlined above, Minnesota implemented specific operational practices across key areas, as detailed in Appendix F, Table F.4.

3.1.5 Winter Operations in Alaska

The winter operations of ADOT emphasize adaptive and environmentally conscious practices while addressing the challenges posed by its diverse and extreme weather conditions (ADOT, 2014). Its overall strategy is guided by:

- *Preparation and Planning*: Alaska focuses on early preparation by clearing routes of obstructions and calibrating equipment for efficient material application. Staff are trained annually to ensure readiness.
- *Anti-Icing Techniques*: Anti-icing is a primary strategy, reducing the need for reactive deicing. Stream nozzles are used for targeted applications, ensuring materials are applied efficiently without overuse.
- *Plowing and Abrasive Use*: Snowplowing is prioritized to remove loose snow and reduce chemical dilution. Abrasives like sand are applied sparingly for traction in high-risk areas, balancing safety and environmental impact.
- *Environmental Stewardship*: Alaska employs rigorous environmental protection measures, including the use of covered storage facilities and limiting the use of harmful chemicals. These practices mitigate risks to local ecosystems.
- *Continuous Improvement*: Poststorm evaluations are integral to refining operations. The state records material usage and performance, using this data to optimize future responses.

Alaska implemented specific operational practices across key areas to meet its unique circumstances. For example, prewetting strategies help ensure salt sticks to roads, while abrasives are used for temporary traction during extremely cold conditions. A proactive anti-icing strategy based on accurate weather forecasting is also used to improve operational readiness. Appendix F, Table F.5 provides more detail.

3.1.6 Winter Operations in South Dakota

South Dakota's winter operations are designed to ensure safe and efficient travel during severe weather conditions. SDDOT (2024) employs a structured, data-driven approach to maintain nearly 7,800 mi of roadway during the winter months. The key elements of these operations are as follows.

3.1.6.1 Preparation Before Winter:

- *Snow Fence Installation*: Temporary snow fences are erected in October–November and dismantled in March–April. Living snow fences, such as rows of trees or standing corn, are used to reduce drifting snow and maintain clear roadways.
- *Equipment Inspection*: Before the season, all snow removal equipment is inspected using a standardized checklist (Form 825). Maintenance issues are addressed to ensure readiness.
- Material Storage: Anti-icing and deicing materials, including sodium chloride and magnesium chloride, are stockpiled and monitored to meet projected needs.

3.1.6.2 Proactive Practices During Winter:

- *Anti-Icing*: This proactive method involves applying chemicals like salt brine before storms to prevent snow and ice from bonding to road surfaces. Anti-icing reduces the need for extensive plowing and chemical applications later.
- *Deicing*: During and after storms, deicing agents are used to break existing snow/ice bonds. Materials like prewetted sodium chloride are favored for efficiency.
- *Equipment Deployment*: Snowplows, sanders, and specialized tow plows are deployed strategically to clear roads. Tow plows, which cover wider areas, are particularly effective on interstates.

3.1.6.3 Use of Advanced Technology:

- *MDSS*: The MDSS integrates weather data, road conditions, and traffic forecasts to recommend optimal treatment strategies. It helps prioritize routes, reduce material waste, and enhance safety.
- *MDCs*: Snowplows equipped with MDCs collect real-time data on road and equipment conditions, which informs MDSS decisions.
- *Road Condition Sensors*: ESSs are installed statewide to monitor air and pavement temperatures, precipitation, and visibility.

3.1.6.4 Communication and Public Engagement:

- *Traveler Information System (SD511)*: The SD511 platform provides real-time updates on road conditions, closures, and weather forecasts. Information is disseminated via a website, mobile app, and phone system.
- *Social Media and Dynamic Signs*: Updates are shared on platforms like Facebook and Twitter, and dynamic message signs provide real-time updates to motorists.

3.1.6.5 Environmental Considerations:

- *Sustainable Materials*: The state tests agricultural by-products like sugar beet and corn derivatives for anti-icing and deicing, which lower environmental impacts compared to traditional chemicals.
- *Precision Application*: Materials are applied at specific rates and intervals to minimize overuse and environmental damage.

3.1.6.6 Safety Enhancements:

- *HFST*: HFST is applied to critical areas like curves and intersections to improve traction and reduce crashes. This has led to an approximate 80% reduction in crashes.
- *Blue Lights on Equipment*: Blue lights on snowplows enhance visibility for both operators and other drivers during low-visibility conditions.
- *Variable Speed Limits*: Variable speed limits based on weather conditions enhance safety and allow flexibility in road usage.

3.1.6.7 Poststorm Operations:

- *Clean-Up and Maintenance*: After storms, equipment is thoroughly cleaned to remove corrosive residues, and materials are restocked. Inspections are conducted to ensure equipment readiness for the next event.
- *Data Recording*: Material usage and operational data are meticulously recorded to improve planning and efficiency in future seasons.

Appendix F, Table F.6 summarizes the best practices for winter operations as outlined in the SDDOT (2024) *Winter Maintenance Plan*.

3.2 Application Rates for Deicing Materials

In the following subsections, we explore the recommended application rates for several commonly used deicing materials, including sodium chloride, calcium chloride, magnesium chloride, and acetate-based products. Each section examines factors that influence these rates, such as pavement temperature, weather conditions, and equipment capabilities. By understanding the nuances of proper application, agencies can optimize their deicing strategies to ensure both safe travel and responsible resource management.

3.2.1 Application Rate of Sodium Chloride

The efficient use of materials for snow management depends on applying them at the optimal rate. To maximize salt efficiency, it should be applied at the lowest effective rate possible. One way to minimize salt usage is by ensuring as much salt as possible remains within the target area, which is about 4 ft on either side of the roadway centerline. This can be achieved by reducing salt bounce and scatter during application (MDOT, 2013). Several factors influence the amount of bounce and scatter, including road conditions, salt moisture content, type of distribution equipment, and truck speed. MDOT works to limit salt loss by using effective application equipment and enforcing a speed limit for trucks applying salt. According to MDOT's (2013) current winter operations policy, salt should be applied at speeds of 35 mph or less, when possible. MDOT also encourages pretreating (prewetting) salt before application. Casey et al. (2014) reports Idaho using 130 lb of salt per lane mile for snow management, which is much lower than in other states, especially in the Midwest, where application rates range from 600 to 1,500 lb of salt per lane mile per application. The salt application rate for a two-lane road as per MDOT is provided in Table 3.1.

TABLE 3.1
Application Rate of Salt for Deicing (MDOT, 2013).

Pavement Temperature and Trend	Weather Conditions	Maintenance Actions	Salt Prewetted/ Pretreated with Salt Brine (lb per 2-lane road)	Salt Prewetted/ Pretreated with Other Blends (lb per 2-Lane Road)	Dry Salt (lb per 2-Lane Road)	Winter Sand/Abrasives (lb per 2-Lane Road)
> 30 °F ↓ (Decreasing)	Snow	Plow, treat intersections only	80 (40/lane mi)	70	100*	Not recommended
	Freezing Rain	Apply product	80–160	70–140	100–200*	Not recommended
30 °F ↓ (Decreasing)	Snow	Plow & apply product	80–160	70–140	100–200*	Not recommended
	Freezing Rain	Apply product	150–200	130–180	180–240*	Not recommended
25–30 °F	Snow	Plow & apply product	120–160	100–140	150–200*	Not recommended
	Freezing Rain	Apply product	150–200	130–180	180–240*	Not recommended
25–30 °F ↓ (Decreasing)	Snow	Plow & apply product	120–160	100–140	150–200*	Not recommended
	Freezing Rain	Apply product	160–240	140–210	200–300*	Not recommended
20–25 °F	Snow or freezing rain	Plow & apply product	160–240	140–210	200–300*	Not recommended
20–25 °F ↓ (Decreasing)	Snow	Plow & apply product	200–280	175–250	250–350*	Not recommended
	Freezing Rain	Apply product	240–320	210–280	300–400*	400
15–20 °F	Snow	Plow & apply product	200–280	175–250	250–350*	Not recommended
	Freezing Rain	Apply product	240–320	210–280	300–400*	400
15–20 °F ↓ (Decreasing)	Snow or freezing rain	Plow & apply product	240–320	210–280	300–400*	500 for freezing rain
0–15 °F	Snow	Plow, treat with blends, sand	Not recommended	300–400	Not recommended	500–750 spot treat as needed
< 0 °F	Snow	Plow, treat with blends, sand	Not recommended	300–400	Not recommended	500–750 spot treat as needed

Notes:
To calculate for 1 lane, divide application rate numbers in half
Use lower end of application rate range when using supersaturated mixes
*Dry salt has reduced melting effectiveness compared to prewetted or blended materials, particularly at lower pavement temperatures.

3.2.2 Application Rate for Calcium Chloride

The application of calcium chloride varies based on its form (solid or liquid) and the road conditions. Generally, road agencies apply it in lower quantities compared to sodium chloride due to its higher efficacy. According to MnDOT (2022), prewetting dry products with calcium blends can help reduce application rates, emphasizing the importance of active chemical concentration. For example, the recommended concentration for calcium chloride is 29.8%. Overapplication of liquid chemicals can cause road surfaces to become slippery, reinforcing the principle that less is better. In its liquid form, calcium chloride is often mixed with other chemicals or inhibitors to minimize environmental impacts and maximize performance in extremely cold weather.

3.2.3 Application Rate for Magnesium Chloride

Magnesium chloride has a higher cost per gallon but can be more efficient in certain scenarios, such as preventing ice formation before a storm (anti-icing). The application rate in Minnesota was recorded at 5,282 gal for magnesium chloride (MnDOT, 2022). The application rates of magnesium chloride are similar to those of calcium chloride but generally lower than sodium chloride due to its higher melting efficiency. In states like Idaho, magnesium chloride is often applied during colder conditions, where its properties are optimized for winter maintenance. Adjustments to application rates are made based on factors like pavement temperature and road conditions monitored through RWIS and AVL systems. The application rates differ across states, often depending on temperature and expected snow conditions. Table 3.2 presents the anti-icing application rate guideline as per MDOT.

- In Michigan, magnesium chloride is applied at an average rate of 100 to 300 lb per mile per lane, significantly reducing the overall chloride load compared to sodium chloride (MDOT, 2013).
- In Minnesota, MnDOT suggests using around 200 lb per lane mile in liquid brine form, particularly in colder temperatures where sodium chloride is ineffective (MnDOT, 2022).
- In Idaho, ITD recommends a prewet rate of 15–18 gal per ton for salt brine and 7–10 gal per ton for magnesium chloride. ITD emphasizes the importance of using magnesium chloride in high-moisture environments, given its ability to draw moisture and enhance melting (Casey et al., 2014).
- In South Dakota, SDDOT (2023) uses magnesium chloride at a rate of approximately 150 lb per lane mile for prewetting purposes, ensuring better adhesion of deicing materials to the road surface.
- In Alaska, ADOT (2024) advises against applying magnesium chloride or calcium chloride on warm roads (above 28 °F pavement temperature) as it can become slippery and lead to accidents.

TABLE 3.2
Anti-Icing Application Rate Guideline (MDOT, 2013).

Condition	$CaCl_2$ or $MgCl_2$ (Gal per lane mile)	Brine (Gal per lane mile)
Regularly scheduled application	15–25	20–40
Prior to frost or black ice	15–25	20–40
Prior to light or moderate snow	15–25	20–50

3.2.4 Application Rates for Acetates

CMA is applied at 90–120 lb per lane mile for deicing, depending on ice thickness and weather conditions. Its usage has been reported in Michigan (90 tons annually) and other states for moderate snowfall regions. CMA is more expensive compared to chloride-based alternatives. Potassium acetate is applied in liquid solution form, with rates varying by region and environmental conditions. In Minnesota, Michigan, and Idaho, the material cost of potassium acetate is significantly higher compared to traditional chloride-based deicers. In Wisconsin, application rates are between 30–50 gal per lane mile for anti-icing purposes. Vermont reports similar application rates, noting its effectiveness in reducing the need for frequent reapplications during heavy snowfall. Potassium acetate is significantly more expensive than chloride-based alternatives, limiting its use to high-priority areas such as bridges and critical roadways.

4. COMPARISONS OF OPERATIONAL RESOURCES ACROSS STATES AND TRENDS IN INDIANA

This chapter provides a multistate comparison of operational resources drawn from the 2022–2023 Clear Roads Winter Maintenance Survey, including data from Indiana (Clear Roads, 2023). The analysis presents a range of methods and materials used across multiple states, including Indiana. By comparing the different strategies and materials in use, this chapter highlights where Indiana stands relative to other comparable states in terms of winter operations methods and materials. In addition, this chapter examines the trends or the changes over time in Indiana's operational resources.

4.1 Comparison of Winter Maintenance Expenditure

The Accumulated Winter Season Severity Index (AWSSI) measures the severity of winter based on factors such as snowfall, temperature, and storm frequency, with higher values indicating harsher winter conditions. The winter maintenance expenditure data from the Clear Roads Survey provides insight into the financial investments made by states to manage these winter conditions effectively. Table 4.1 shows the winter maintenance expenditure, AWSSI, and total lane miles of selected states for the 2022–2023 season.

Indiana's winter management expenditure and AWSSI for the 2022–2023 season provide a basis to examine its spending compared to other states. Indiana spent $35.7 million on winter maintenance, with an AWSSI of 290, suggesting moderately severe winter conditions relative to other states. States with high AWSSI values generally spend more on winter maintenance. For example, Minnesota, with the highest AWSSI (1,646), allocates $173.9 million to winter operations, the largest expenditure across all states. Similarly, Wisconsin and Michigan, with AWSSI values of 1,053 and 1,080, respectively, also report substantial spending at $118.7 million and $108.9 million. This trend suggests that states experiencing severe winters require significant investments to manage snow and ice on roadways effectively.

States with lower AWSSI values generally show comparatively lower expenditures. For example, Virginia, with an AWSSI

TABLE 4.1
State-Wise Comparison of Winter Maintenance Expenditure, AWSSI and Lane Miles (Clear Roads, 2023).

State	Expenditure (USD)	AWSSI	Lane Miles	Expenditure Per Lane Mile	Expenditure Per AWSSI-Lane Mile
Illinois	$78,651,767	327	44,939	$1,750	$5.35
Indiana	$35,651,767	290	29,824	$1,195	$4.12
Kansas	$14,582,000	388	23,500	$621	$1.60
Kentucky	$45,968,551	119	27,616	$1,665	$13.99
Michigan	$108,969,258	1,080	32,000	$3,405	$3.15
Minnesota	$173,953,000	1,646	30,027	$5,793	$3.52
Nebraska	$37,420,000	726	10,001	$3,742	$5.15
New Jersey	$11,500,000	90	13,341	$862	$9.58
Ohio	$75,313,811	238	42,667	$1,765	$7.42
Oklahoma	$8,650,117	121	30,473	$284	$2.35
South Dakota	$40,984,194	1,478	18,287	$2,241	$1.52
Tennessee	$18,659,636	64	38,329	$487	$7.61
Virginia	$108,099,306	76	125,000	$865	$11.38
Wisconsin	$118,759,205	1,053	34,723	$3,420	$3.25

of 76, spends approximately $108 million, which is on the higher end. However, New Jersey and Tennessee, both with low AWSSI values of 90 and 64, respectively, report lower expenditures of $11.5 million and $18.6 million. This pattern indicates that states with milder winters typically allocate less funding for winter maintenance operations. Indiana is considered to be under the category of a milder winter. Indiana's AWSSI (290) indicates moderately harsh or milder winter conditions, and its expenditure of $35.7 million aligns with this, placing Indiana in the mid-range in terms of both winter severity and spending. States with similar AWSSI values, such as Illinois (AWSSI of 327, spending $78.6 million) and Ohio (AWSSI of 238, spending $75.3 million), have notably higher expenditures, indicating that Indiana achieves moderate winter coverage at relatively lower costs.

Some states do not follow a clear correlation between AWSSI and winter maintenance spending. For example, Virginia, with an AWSSI of 76, has a high winter maintenance expenditure of $108 million which could be due to population density, road network complexity, or specific state policies. Pennsylvania and Iowa are missing expenditure data but show moderate to high AWSSI values (281 and 653, respectively) which would be useful for a fuller comparison.

Comparing expenditure to the AWSSI point, we see that some states demonstrated more efficient use of resources. For example, Illinois, with an AWSSI of 327 and an expenditure of $78.6 million, spends roughly $240,410 per AWSSI point, whereas Minnesota, at $173.9 million with an AWSSI of 1,646, spends approximately $105,668 per AWSSI point. Such disparities suggest that states with robust winter infrastructure or more advanced technologies may manage severe winters at lower per-unit costs. Indiana's spending per AWSSI point is approximately $123,200, a middle-range efficiency rate. Minnesota, with a high AWSSI and a large budget, achieves an impressive efficiency of $105,668 per AWSSI point. On the other hand, Kentucky, which has a low AWSSI (119) but a high expenditure ($45.9 million), spends about $386,000 per AWSSI point.

This suggests Indiana achieves comparable maintenance outcomes at a lower cost per severity index point. This efficiency may be due to Indiana's operational strategies, infrastructure, or other cost-saving measures. Indiana's allocation may reflect the state's tailored approach to its specific winter needs, such as selective use of deicers, efficient equipment deployment, and timely snow clearance. Neighboring states like Ohio and Illinois spend considerably more despite similar AWSSI values, which might indicate that Indiana is maximizing operational efficiency while keeping costs lower.

Regional differences also play a role, as states in the Midwest and Northern Plains (e.g., Minnesota, Wisconsin, Michigan) experience more severe winters and therefore have higher AWSSI values and winter management costs compared to Southern and Mid-Atlantic states (e.g., Indiana, Tennessee, Virginia, New Jersey). Overall, there is a general trend where states with harsher winter conditions, as indicated by AWSSI, incur higher winter maintenance costs. However, factors such as state-specific strategies, population density, road network size, and resource allocation efficiency also impact total expenditures. Future analyses could benefit from additional data on regional cost-efficiency measures, maintenance methods, and specific weather events to better understand the nuances of winter management practices among states.

4.2 Comparison of Chlorides Usage

4.2.1 Comparison of Solid Chlorides Usage

To gain a clearer understanding of different states' chloride usage relative to winter severity, the chloride usage data have been normalized by considering chloride application per lane mile in relation to the AWSSI. These normalized data are represented in Figure 4.1.

When examining Indiana's chloride usage in relation to its AWSSI, the state presents a moderate to low chloride application rate relative to regional and national counterparts. With an AWSSI of 290 and a chloride usage of 2.64 tons per lane mile, Indiana applies less salt than Pennsylvania (5.26 tons, AWSSI 281) and Illinois (4.93 tons, AWSSI 327), but more than neighboring Kentucky (2.86 tons, AWSSI 119). However, states with significantly harsher winters, such as Michigan (AWSSI 1080,

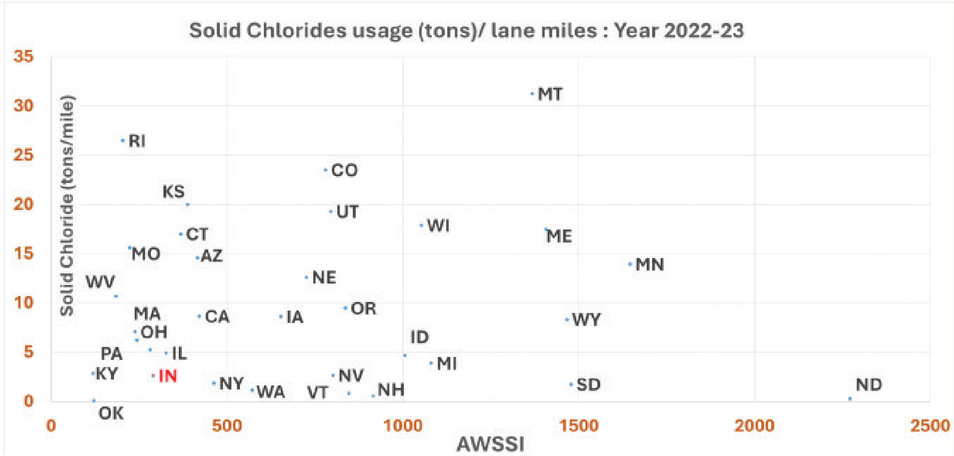

Figure 4.1 Solid Chloride Usage Per Lane Mile (ton/mi). Dataset Included in Appendix G, Table G.1.

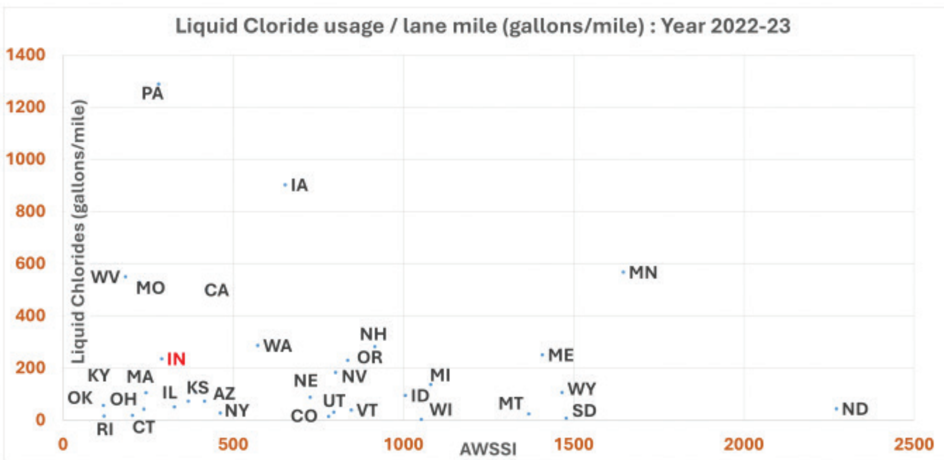

Figure 4.2 Liquid Chloride Per Lane Mile (gal/mi). Dataset Included in Appendix G, Table G.2.

3.89 tons) and Wisconsin (AWSSI 1053, 17.90 tons), show a wide variation in usage, with Wisconsin notably applying much more chloride. Meanwhile, states with higher AWSSI values but lower application rates, like South Dakota (AWSSI 1478, 1.75 tons) and North Dakota (AWSSI 2272, 0.29 tons), indicate a more conservative salt management strategy. This suggests that while Indiana's chloride usage is not excessive, it may still be higher than what is practiced in similarly or more severely affected states, highlighting potential for optimization in deicing practices.

4.2.2 Comparison of Liquid Chloride Usage

Figure 4.2 show the amounts of chloride brine used per lane mile relative to winter severity. Indiana's use of sodium chloride brine per lane mile (235.57 gal/mi) reflects a moderate application rate compared to other Midwestern and cold-climate states, given its AWSSI of 290. However, it surpasses neighboring Illinois (50.88 gal/mi, AWSSI 327) and Ohio (42.43 gal/mi, AWSSI 238), as well as colder states like Michigan (136.96 gal/mi, AWSSI 1,080) and Nebraska (87.80 gal/mi, AWSSI 726). However, Indiana's usage remains substantially lower than that of Pennsylvania (1,289.18 gal/mi, AWSSI 281) and Iowa (902.81 gal/mi, AWSSI 653), which exhibit notably high application rates despite comparable or moderately higher winter severity. Additionally, Missouri (527.96 gal/mi, AWSSI 224) and West Virginia (550.47 gal/mi, AWSSI 184) also report significantly higher usage levels.

Table 4.2 shows a heat map to visually assess the usage of solid and liquid chlorides across US states relative to their AWSSI. The solid and liquid chloride and AWSSI columns were color-coded using a green-to-red gradient—green indicating

TABLE 4.2
Heat Map Showing State-Wise Comparison of Solid and Liquid Chloride Usage Per Lane Mile With AWSSI.

STATE DOT	Solid Chlorides (tons/lane mi)	Liquid Chlorides (gal/lane mi)	AWSSI
Arizona	2.858	57.071	416
California	0.112	15.939	421
Colorado	10.697	550.467	780
Connecticut	26.492	18.721	368
Idaho	15.604	527.956	1,006
Illinois	7.090	42.430	327
Indiana	6.211	105.677	290
Iowa	5.256	1289.175	653
Kansas	2.638	235.574	388
Kentucky	4.925	50.876	119
Maine	17.017	72.685	1,408
Massachusetts	19.991	108.973	244
Michigan	14.600	72.590	1,080
Minnesota	8.672	503.050	1,646
Missouri	1.867	28.309	224
Montana	1.161	286.631	1,368
Nebraska	8.624	902.810	726
Nevada	12.622	87.801	801
New Hampshire	23.517	15.281	916
New York	19.302	31.731	462
North Dakota	2.664	183.866	2,272
Ohio	9.493	230.322	238
Oklahoma	0.838	39.379	121
Oregon	0.569	282.230	836
Pennsylvania	4.682	95.312	281
Rhode Island	17.896	2.904	204
South Dakota	3.894	136.962	1,478
Utah	31.238	24.883	795
Vermont	17.486	250.853	847
Washington	8.339	106.635	572
West Virginia	1.751	8.444	184
Wisconsin	13.935	567.439	1,053
Wyoming	0.292	44.390	1,466

lower usage/lower AWSSI and red indicating higher application rates/higher AWSSI values. This visual representation facilitates immediate identification of patterns and anomalies. For instance, states like Pennsylvania and Iowa, with moderate AWSSI scores, show very high liquid chloride usage, while some states with higher AWSSI, like North Dakota and South Dakota, exhibit relatively lower chloride usage.

4.2.3 Indiana in Comparison

Indiana's winter maintenance strategy demonstrates a moderate approach to both solid and liquid chloride usage, but comparison with peer states reveals clear opportunities for optimization. With an AWSSI of 290, Indiana applies 6.21 tons/mi of solid chlorides and 105.68 gal/mi of liquid chlorides. While this places it above warmer or similarly severe states like Kentucky (4.93 tons/50.88 gal, AWSSI 119) and Illinois (7.09 tons/42.43 gal, AWSSI 327), it also exceeds Pennsylvania in solid use (4.68 tons, AWSSI 281) and is nearly equal in liquid chlorides (95.31 gal), despite Pennsylvania's similar winter index. More notably, states with far harsher winter conditions, such as Michigan (AWSSI 1080) who uses 14.60 tons solid and only 72.59 gal liquid, Wisconsin (AWSSI 1053) who applies 13.94 tons solid and 567.44 gal liquid, and Minnesota (AWSSI 1646) who applies 8.67 tons solid and 503.05 gal liquid, suggest more targeted application strategies tailored to higher winter severity.

Conversely, Indiana's brine usage (105.68 gal/mi) is higher than many warmer states and comparable to some colder ones, yet its solid salt usage remains relatively high for its modest winter severity.

4.3 Comparison of Alternative Materials Usage

Figure 4.3 illustrates the deployment of alternative materials (beyond standard salts) across multiple states. As can be seen, Indiana's winter maintenance approach does not incorporate potassium acetate, enhanced brine, agricultural products, or blended materials, during the 2022–2023 season setting it apart from some other states that use additional materials for winter road treatment. For example, Illinois uses 625,259 gal of enhanced brine and 183,120 gal of agricultural products to improve deicing effectiveness, while Wisconsin employs 117,867 gal of enhanced brine and 332,503 gal of agricultural

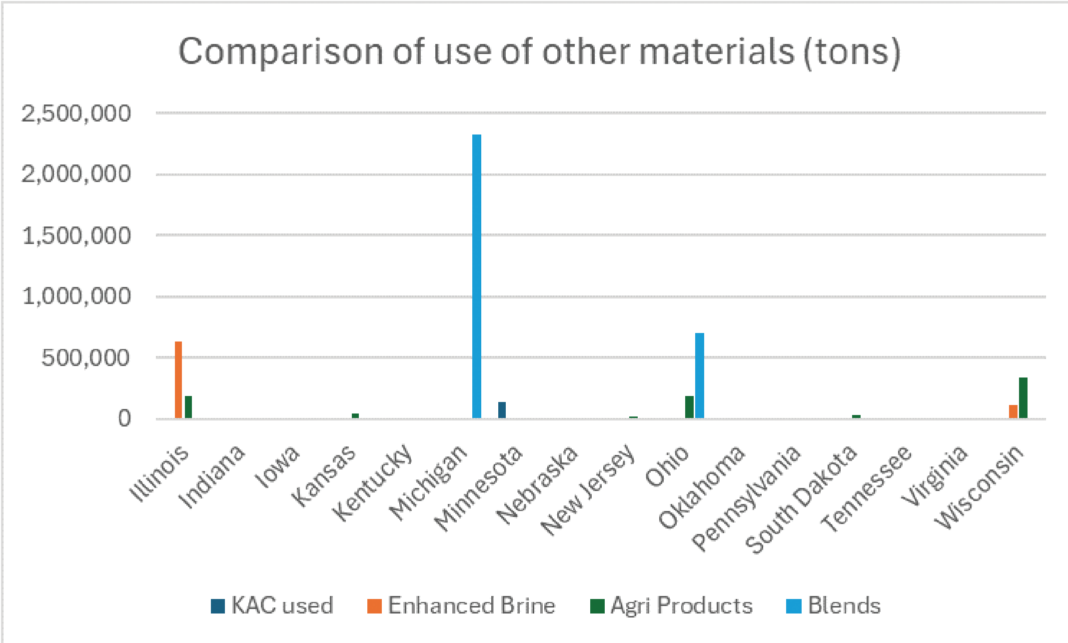

Figure 4.3 Comparison of Other Materials Usage by State.

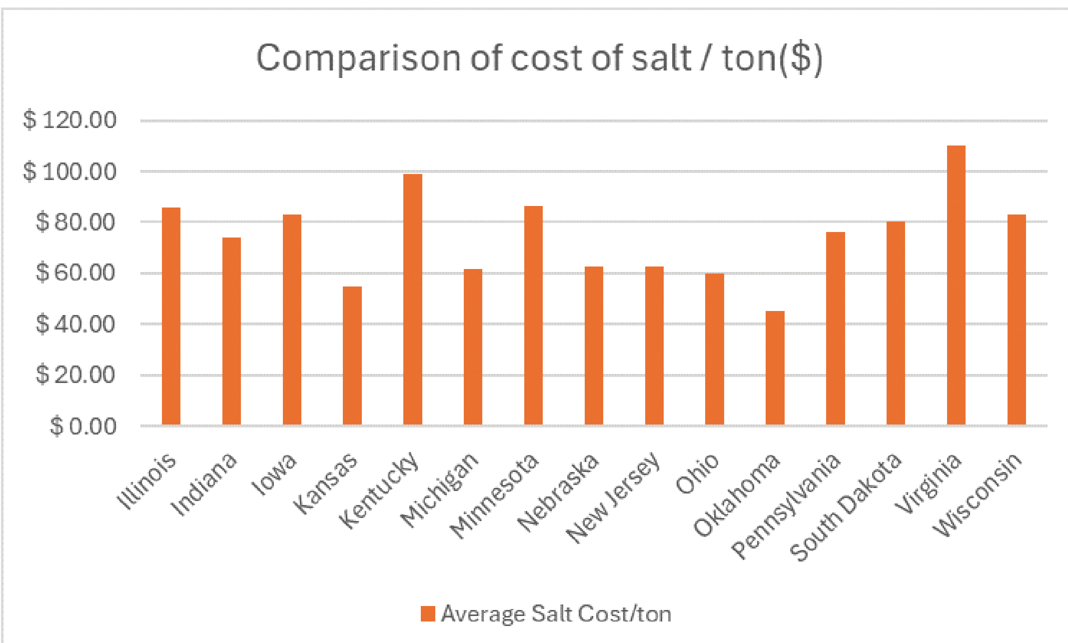

Figure 4.4 Comparison of Salt Cost Per Ton by State.

products. States like Ohio use a diverse mix, including 187,054 gal of agricultural products and 701,358 gal of blends. Indiana's primary use of conventional deicers, without supplementary materials, indicates a streamlined strategy appropriate for its typical winter conditions. In contrast, other states employ additional materials to handle more severe weather and enhance the environmental impact and efficiency of winter road treatments.

4.4 Salt Cost Comparison

During 2022–2023, Indiana's average salt cost of $74.14 per ton is on the lower end compared to other states (Figure 4.4), suggesting relatively cost-effective procurement for its winter maintenance needs. This is below nearby states like Illinois ($85.91) and Kentucky ($98.72) but slightly higher than

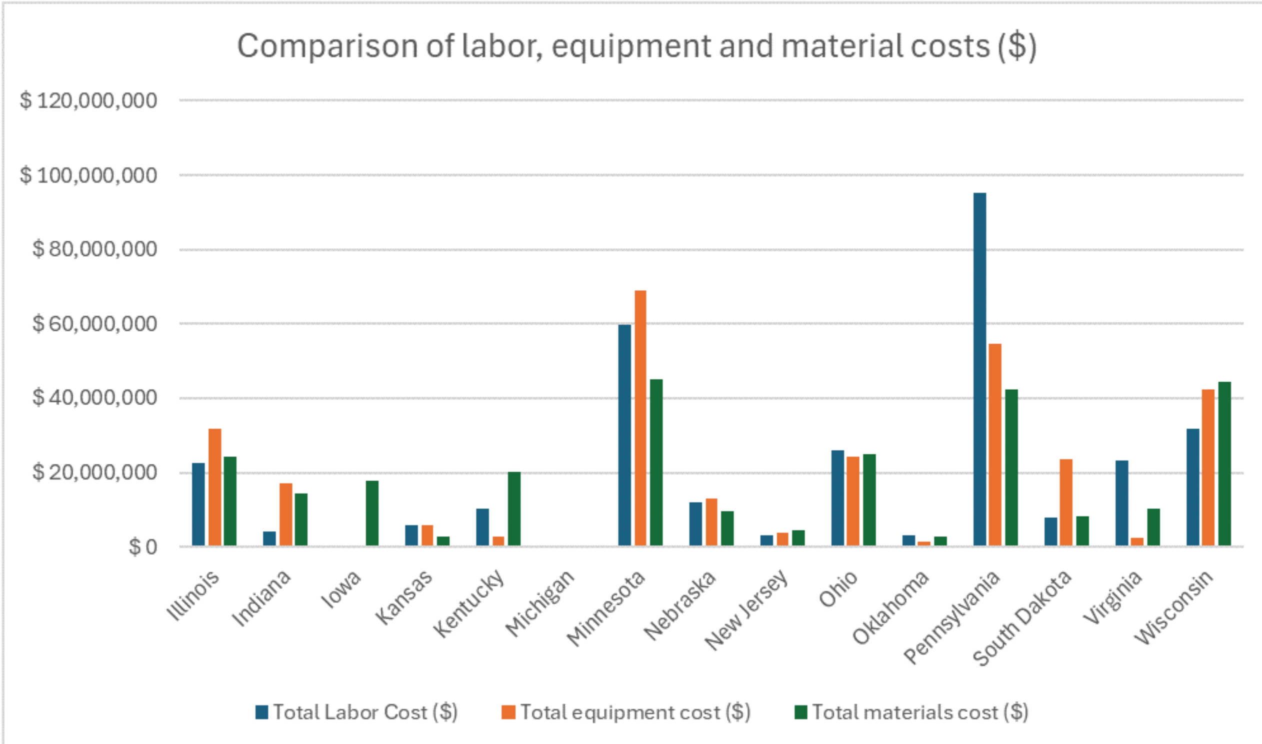

Figure 4.5 Comparison of Labor, Equipment, and Material Costs by State.

Ohio ($60.20) and Michigan ($61.41). States such as Kansas ($55.00), Oklahoma ($45.00), and New Jersey ($62.50) achieve even lower salt costs, while Virginia has the highest rate at $110.00 per ton. Indiana's moderate salt cost indicates an efficient balance between affordability and access, allowing it to maintain adequate winter resources without incurring the higher expenses seen in other states.

4.5 Comparison of Labor, Equipment, and Material Costs

During 2022–2023, Indiana's total labor cost for winter maintenance is $4,125,549, with equipment costs at $17,087,999 and material costs totaling $14,512,680. Figure 4.5 illustrates that Illinois incurs higher costs across all categories compared to Indiana, with total labor costs reaching $22,502,567, equipment costs at $31,839,781, and material costs totaling $24,309,419. In the case of Iowa, its total material cost alone is $17,824,812 (its labor and equipment costs data are not available). Kentucky shows a contrasting trend, with a labor cost of $10,252,827 but much lower equipment costs ($2,873,685) and higher material costs ($20,277,490). Pennsylvania stands out with the highest total labor cost at $95,300,000, combined with significant equipment and material costs, reflecting its extensive winter maintenance operations. In contrast, Oklahoma's total costs are much lower across the board, demonstrating a potentially less intensive winter maintenance strategy. Indiana's total expenditure suggests a balanced approach that effectively manages resources while maintaining reasonable costs, particularly when compared to the more extensive budgets seen in states with harsher winter conditions or larger populations.

4.6 Comparison of Winter Maintenance Cost per Lane Mile (USD/mi)

Figure 4.6 shows how different states compare in terms of total maintenance cost/expenditure per lane mile. In 2022–2023, Indiana's annual expenditure of $35,726,079 for winter maintenance translates to a cost of $1,197.90 per lane mile, which positions it as a cost-effective state in terms of managing winter road conditions. With a total of 29,824 lane miles, Indiana's approach demonstrates an efficient allocation of resources, especially when compared to Michigan and Minnesota, which incur significantly higher costs per lane mile due to their harsher winter climates. Michigan's expenditure stands at $3,405.29 per lane mile, while Minnesota's is even higher at $5,793.22, reflecting the increased investment required for more extensive snow and ice management operations. In comparison to neighboring states, Indiana's costs are lower than those of Illinois ($1,750.19 per lane mile) and Ohio ($1,765.15 per lane mile). This indicates that Indiana may be leveraging its resources more effectively, perhaps

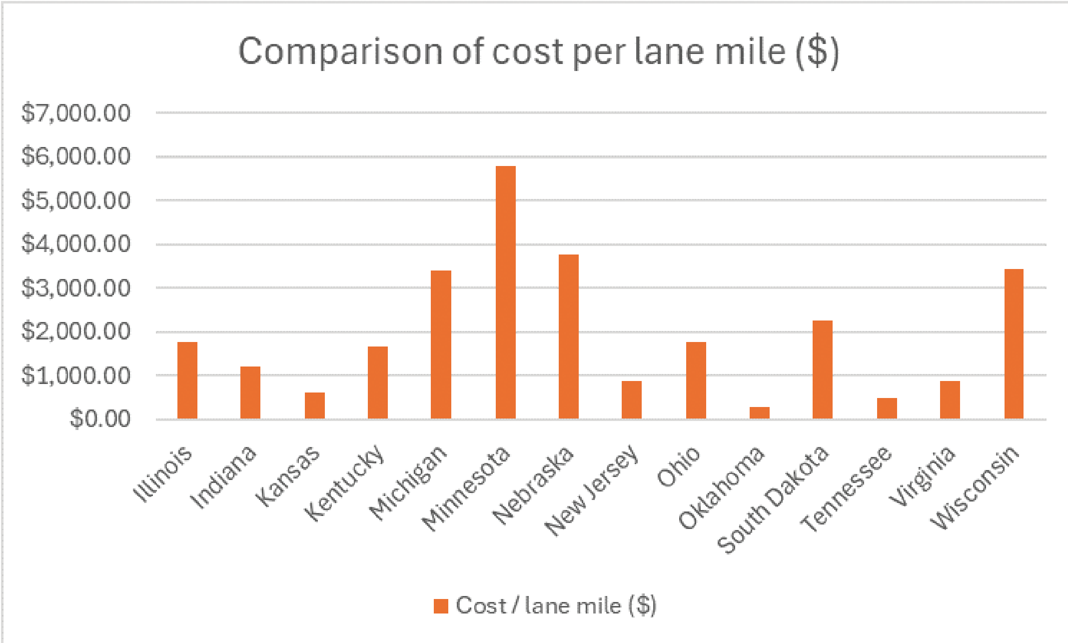

Figure 4.6 Comparison of Winter Maintenance Cost Per Lane-Mile (USD/mi) by State in 2022.

through a greater focus on in-house operations or optimized material use, as evidenced by its complete reliance on in-house maintenance.

Although Indiana's expenditure is higher than that of states like Kansas, which posts the lowest cost per lane mile at $620.51, and Oklahoma, at just $283.86 per lane mile, it is important to note that these lower expenditures may reflect a less comprehensive level of service. Kansas's and Oklahoma's lower costs could reflect differences in their winter maintenance strategies, potentially focusing on fewer lane miles or less intensive treatment methods. Furthermore, the variation in costs per lane mile across states underscores the diverse strategies employed in winter maintenance. For example, Kentucky, with a cost of $1,664.56 per lane mile, suggests a higher level of investment, possibly indicating more aggressive winter treatments or extensive use of materials. In contrast, New Jersey, which maintains 13,341 lane miles at a cost of $862.00 per lane mile, appears to effectively balance maintenance expenditures with a focus on vendor partnerships, which might contribute to its lower overall costs.

4.7 Comparison of Facility Numbers

Figure 4.7 presents a comparative analysis of the number of storage facilities operated across states during the 2022–2023 season. Indiana operates 120 salt facilities and 96 liquid facilities, which positions it as moderately equipped compared to other states. While Indiana's salt facilities align closely with states like Iowa (120 salt, 101 liquid) and Kentucky (131 salt, 124 liquid), it has fewer facilities than neighboring Ohio, which leads with 234 of each facility type. States with similar winter conditions, such as Illinois (170 salt, 160 liquid) and Minnesota (174 salt, 181 liquid), also have more extensive infrastructure than Indiana, likely contributing to their higher winter management expenditures. However, Indiana's facilities surpass those in smaller states like New Jersey (70 salt, 66 liquid) and Oklahoma (90 salt, 62 liquid). This suggests that Indiana's infrastructure is balanced and cost-efficient for moderate winters, remaining more compact than larger states with harsher climates and denser networks, such as Wisconsin (330 salt, 300 liquid) and Pennsylvania (445 salt, 65 liquid).

4.8 Comparison of Storage Capacity

Figure 4.8 compares the storage capacities of different states. As can be seen, in 2022–2023, Indiana's winter maintenance salt and liquid capacities, at 423,952 tons and 1,825,800 gal, respectively, are robust and position the state well in handling moderate to severe winter conditions. Compared to other states, Indiana's salt capacity ranks in the mid-range, below neighboring Ohio (845,803 tons) and Wisconsin (661,275 tons) but above states like Iowa (243,000 tons) and Oklahoma (175,900 tons). For liquid capacity, Indiana exceeds many states, including Illinois (1,688,800 gal) and South Dakota (1,752,000 gal), though it falls short of states with large capacities such as Ohio (7,881,950 gal) and Nebraska (7,800,000 gal). This capacity indicates that Indiana has prioritized substantial liquid reserves, aligning well with states that use liquid for efficient pretreatment and deicing, while maintaining a solid salt capacity for flexible winter response.

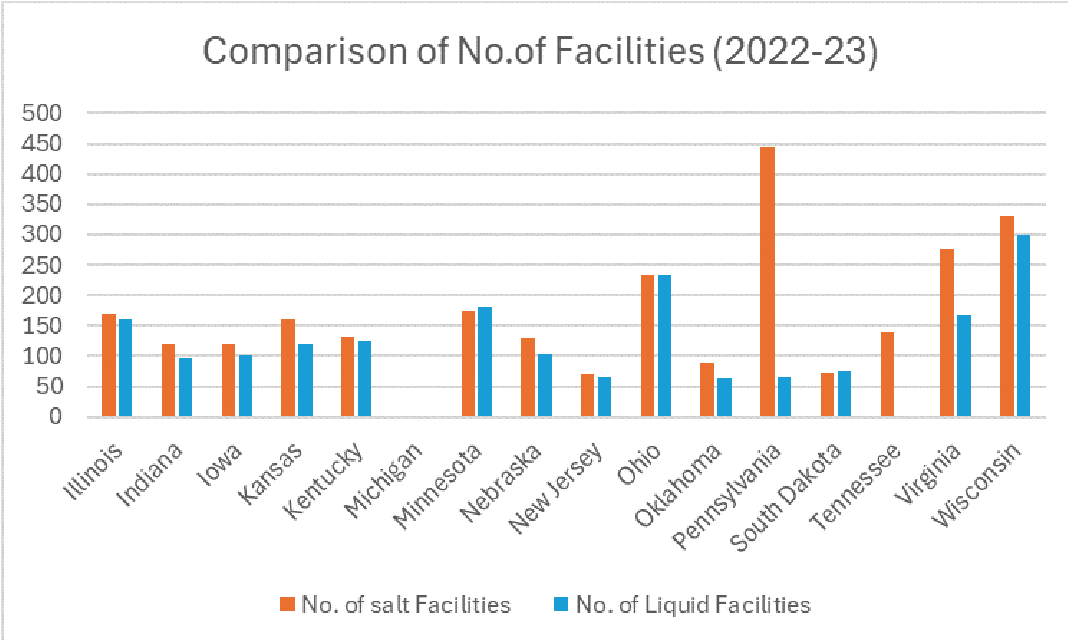

Figure 4.7 Comparison of Facility Numbers (2022).

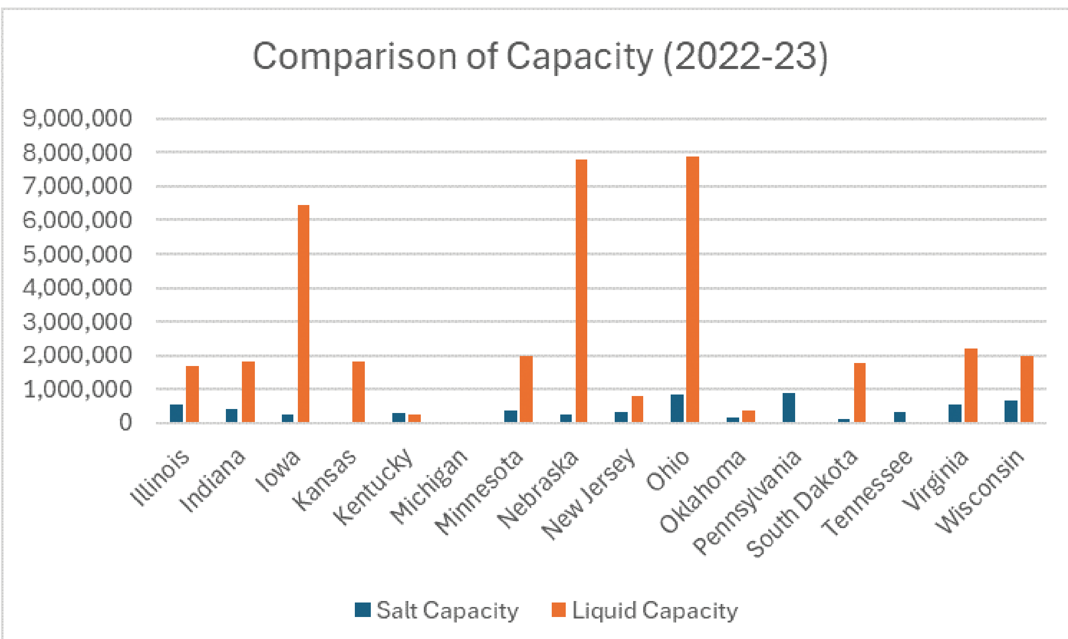

Figure 4.8 Comparison of Storage Capacity by State in 2022.

4.9 Comparison of Production Strategy

As shown in Figure 4.9, Indiana conducts 100% of its winter maintenance operations in-house, aligning with other states like Iowa, Kansas, Pennsylvania, Oklahoma, and Virginia, which also handle all operations internally without relying on external vendors. This contrasts with states like New Jersey and South Dakota, which contract out a significant portion of their winter maintenance (40% and 46% to vendors, respectively). States such as Illinois (80% in-house, 20% vendors) and Nebraska (78% in-house, 22% vendors) balance in-house operations with some outsourced support. Indiana's fully in-house approach allows for centralized control and potentially greater consistency in maintenance quality, especially compared to states that rely on vendor support for a portion of their winter management activities.

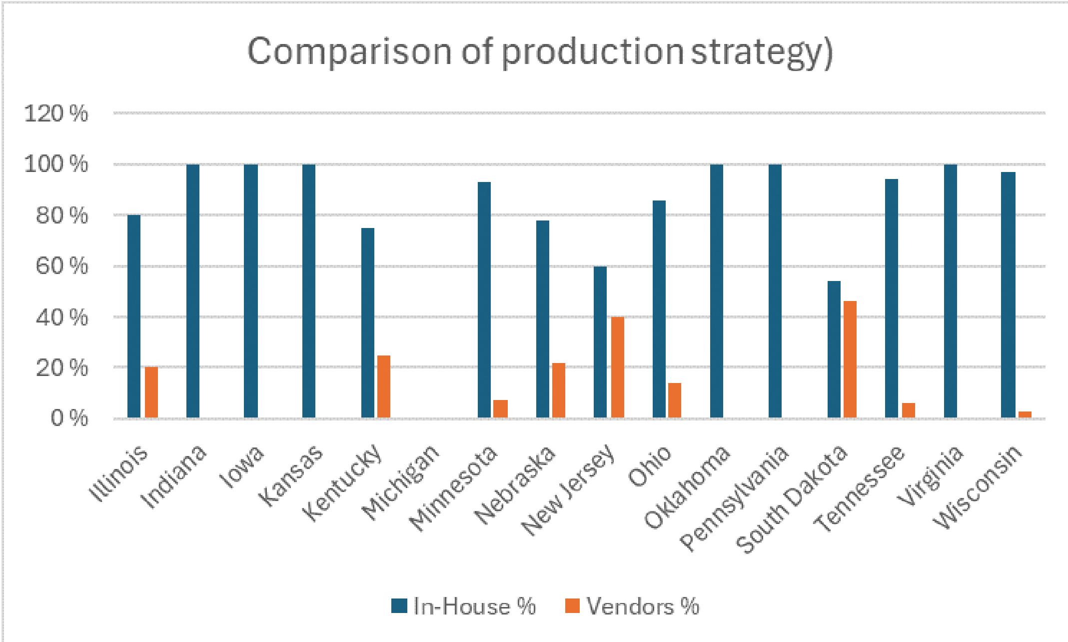

Figure 4.9 Comparison of Production Strategy by State in 2022.

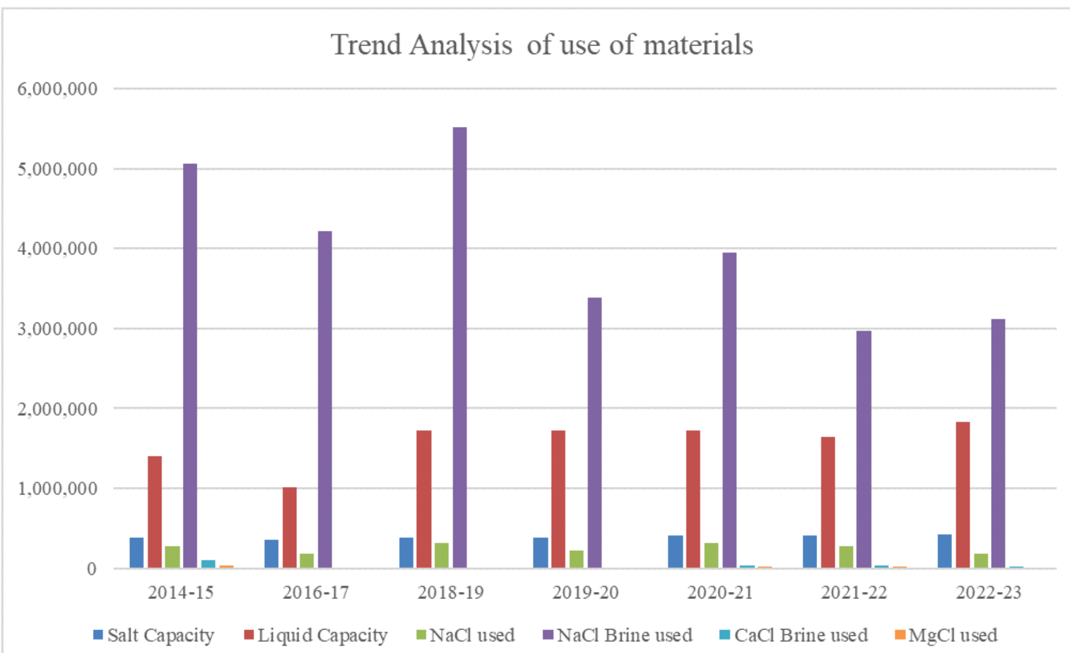

Figure 4.10 Trend Analysis of Deicing Material Usage in Indiana.

4.10 Trend Analysis of Deicing Material Usage in Indiana

Indiana's use of deicing materials, including sodium chloride (rock salt), sodium chloride brine, calcium chloride brine, and magnesium chloride, has varied widely from 2014–2015 to 2022–2023 in response to differing winter severities and evolving treatment strategies (Figure 4.10). Rock salt (sodium chloride) usage peaked in 2020–2021 at 321,834 tons, coinciding with a notably harsh winter (AWSSI 440), while milder seasons, like 2022–2023, saw a significantly lower usage of 185,242 tons. Similarly, sodium chloride brine usage fluctuated, with its highest recorded usage in 2018–2019 at 5,520,982 gal, potentially indicating a shift towards liquid treatments as a complementary or alternative approach to rock salt.

TABLE 4.3
Trends in Indiana's Annual Expenditure and AWSSI Changes.

Year	Annual Expenditure ($)	AWSSI
2014–15	$ 40,300,000	660
2016–17	$ 23,358,985	297
2018–19	$ 38,276,714	408
2019–20	$ 31,967,974	284
2020–21	$ 41,785,947	440
2021–22	$ 37,889,410	415
2022–23	$ 35,726,079	290

The use of calcium chloride and magnesium chloride brine was more sporadic. In particularly severe seasons, like 2014–2015, calcium chloride and magnesium chloride usage was substantial, with 96,071 gal and 28,547 gal, respectively, suggesting that these materials are employed strategically for extreme conditions. This trend, along with the general increase in liquid treatment capacities, reflects Indiana's adaptation towards optimizing material use in response to both economic and environmental demands, aiming to balance cost, effectiveness, and sustainability.

4.11 Trend Analysis of Indiana's Annual Expenditure and AWSSI Changes

Table 4.3 illustrates the changes over time in Indiana's annual winter management expenditure alongside the AWSSI, which reflects the severity of each winter season. From 2014–2015 to 2022–2023, expenditure and AWSSI figures illustrate notable variations, suggesting a correlation between winter severity and management costs. The highest expenditure, $41.8 million, occurred in 2020–2021, a season with an AWSSI of 440. However, the most severe winter season, as indicated by an AWSSI of 660 in 2014–2015, saw an expenditure of $40.3 million. Conversely, milder winters, such as 2019–2020 (AWSSI 284), had comparatively lower expenditures, with $31.9 million spent. These trends highlight how fluctuations in winter severity drive changes in operational costs and material usage, emphasizing the need for adaptive winter management strategies to optimize both resources and costs.

4.12 Trend Analysis of Winter Maintenance Cost in Indiana

The cost per lane mile in Indiana from 2014–2015 to 2022–2023 highlights how winter maintenance expenses fluctuate with winter conditions and the resources required (Figure 4.11). Notably, the 2020–2021 season saw the highest cost per lane mile at $1,401.08, likely due to its severe winter conditions (AWSSI of 440) and higher material requirements. Similarly, in 2014–2015, when the AWSSI peaked at 660, the cost per lane mile was also elevated, at $1,380. In contrast, milder winters, such as 2016–2017 with an AWSSI of 297, had significantly lower lane mile costs, at $881.24. These variations underscore the strong connection between winter severity and per-mile maintenance costs, emphasizing the need for efficient resource allocation to mitigate rising expenses during harsh winter seasons.

4.13 Trend Analysis of Salt Costs

As shown in Figure 4.12, the average cost per ton of salt used in Indiana's winter management operations show significant fluctuations from 2014–2015 to 2022–2023, reflecting economic and environmental factors. In 2014–2015, the average salt cost was at its highest, $85.00 per ton, likely influenced by high demand due to an exceptionally severe winter (AWSSI of 660). Over the following years, the cost per ton generally decreased, hitting a low of $69.60 in 2018–2019, before gradually rising again, with 2020–2021 recording a price of $79.70 per ton, paralleling the severity of that season (AWSSI 440). By 2022–2023, the cost decreased to $74.14 per ton, though it remained above the mid-decade lows. These price trends highlight how salt prices respond not only to seasonal demand but also to broader economic factors, impacting overall winter management budgets in Indiana.

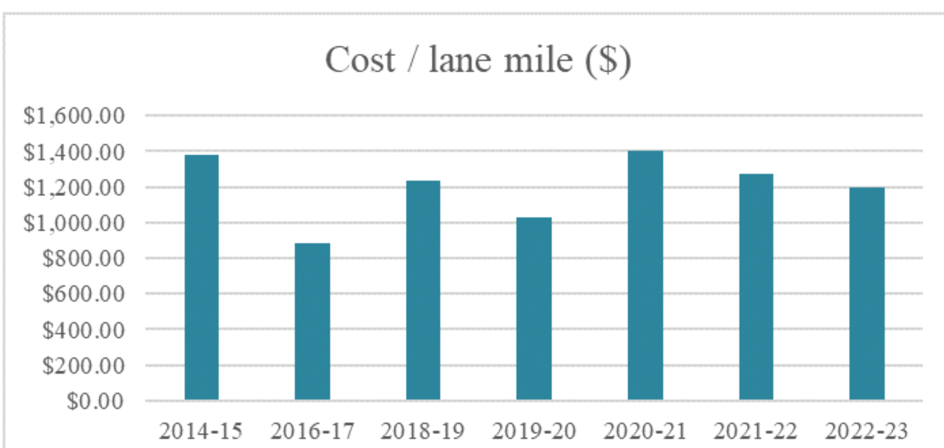

Figure 4.11 Trends in Indiana's Winter Maintenance Cost Per Lane-Mile.

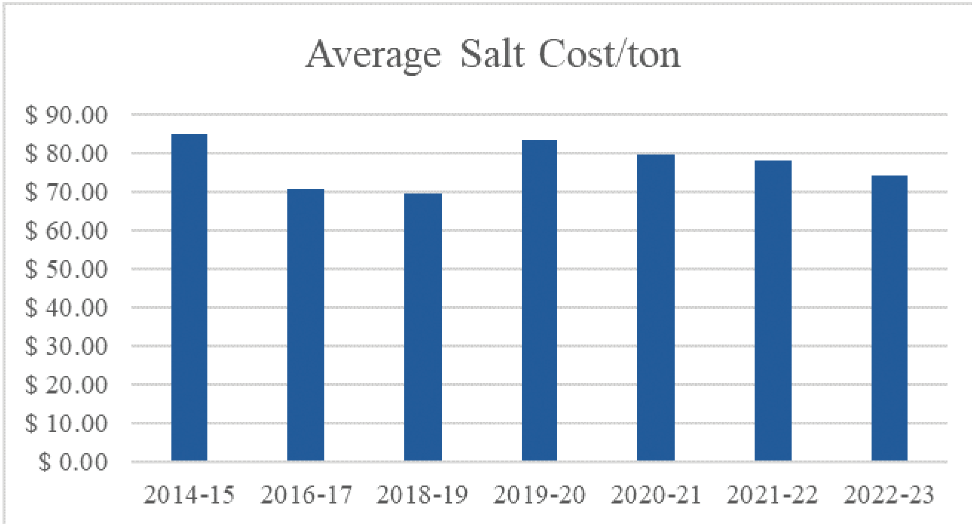

Figure 4.12 Trends in Indiana's Salt Costs.

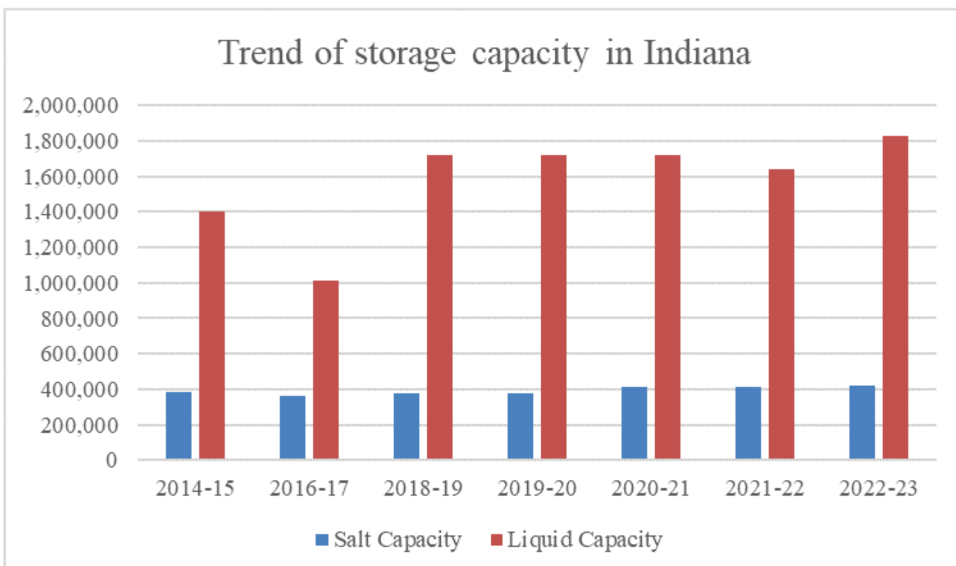

Figure 4.13 Trend in Indiana's Storage Capacity.

4.14 Trend Analysis of Indiana's Storage Capacity

Figure 4.13 shows that Indiana's salt and liquid storage capacities for winter operations have increased steadily from 2014–2015 to 2022–2023, reflecting a growing emphasis on preparedness and material availability for winter weather. In 2014–2015, salt capacity was 382,000 tons and liquid capacity was 1,400,000 gal. Both capacities have expanded significantly over the years, with 2022–2023 recording a salt capacity of 423,952 tons and a liquid capacity of 1,825,800 gal. This expansion suggests an evolving strategy to ensure adequate material reserves for severe winter seasons, which aligns with data showing costly winters like 2014–2015 and 2020–2021. Increasing liquid capacity, in particular, could also indicate a shift toward a greater reliance on liquid treatments, possibly to reduce overall salt usage and address environmental considerations. This growth in capacity supports the state's ability to respond more effectively to unpredictable winter severity, helping stabilize costs and optimize operations.

5. INDOT SURVEY: PERSPECTIVES ON OPERATIONAL PRACTICES AND IMPACTS

5.1 Survey Overview

A survey was conducted within INDOT to provide valuable behavioral insights that will assist the department in enhancing its operational procedures for deicing operations. The survey

TABLE 5.1
Survey Variable Categories and Distribution Overview.

Variable Category	Number of Variables (Total)	Number of Variables (Selected)
Backgrounds (regions, roles, years of work)	3	3
Deicing/Anti-Icing Materials	2	2
Practices for Deicing (overuse, driving speed, etc.)	16	14
Awareness of Chloride Impacts (soil, water, etc.)	10	10
Leftover Salt Management (leftover freq., return freq., etc.)	9	6
Tradeoff Between Traffic Safety and Corrosion/Natural Environment	2	2
Perceptions on Winter Maintenance Program (AASHTO)	10	10
Multicriteria Analysis (criteria for selecting the best materials)	1	1
Total	**53**	**48**

was conducted over a two-month period, beginning on July 25 and concluding on October 2, 2024. During this time, a total of 98 individuals accessed the online survey link. Out of these, 76 respondents provided their consent to participate. However, nine respondents did not provide answers to any major questions, which resulted in their exclusion from the analysis. Consequently, the final sample size used for analysis was 67 respondents.

The survey consisted of 53 questions, each designed as a variable to facilitate detailed analysis. These questions were aimed at exploring various aspects related to the use and management of deicing materials. To ensure data quality, 48 variables were ultimately selected for analysis. The questions that were excluded were primarily open-ended or had a high rate of nonresponse which limited their utility for statistical evaluation.

The 48 variables chosen for analysis were categorized into eight key areas that reflect the diverse focus of the survey. These categories include participants' backgrounds, the use of deicing/anti-icing materials by INDOT, practices for deicing, awareness of chloride impacts, leftover salt management, the tradeoff between public safety and corrosion or natural environments, perceptions related to deicing (following the American Association of State Highway and Transportation Officials [AASHTO] framework), and the evaluation of selection criteria for deicing materials. In the participants' backgrounds category, all three variables were included in the analysis. Similarly, both variables in the category addressing deicing/anti-icing materials used by INDOT were selected. These questions allowed respondents to indicate all applicable options. Details of the eight variable categories and their distribution are presented in Table 5.1. The full list of variables is provided in Appendix H.

In the category "Practices for Deicing," 13 of the 16 variables were chosen. All 10 variables related to awareness of chloride impacts were included, emphasizing the importance of understanding the environmental implications of deicing activities. Within the "Leftover Salt Management" category, six of the nine variables were selected. Both variables concerning the tradeoff between public safety and the impacts on corrosion or natural environments were included in the analysis. Additionally, all ten variables under the "Perceptions" category, based on the AASHTO framework, were incorporated. Finally, the single variable focused on the evaluation of perceived priority for selecting deicing materials was also included in the analysis. This comprehensive approach to variable selection ensures that the survey data provide a robust foundation for analyzing deicing operations and their implications for enhancing INDOT's operational procedures.

5.2 Backgrounds of Respondents

The distribution of respondents was analyzed based on their region, role, and years of work experience. Among the 67 respondents, 24 worked in Northern Indiana, 23 in the Central region, and 17 in Southern Indiana (Figure 5.1). Regarding their roles, a majority of 51 respondents identified as supervisors, while 13 were field crew, and 3 held supporting or administrative positions (Figure 5.1). In terms of their years of work experience at INDOT, 30 respondents reported having more than 10 years of experience. An equal number, 16 respondents, indicated they had worked for either 6 to 10 years or 3 to 5 years. Only 5 respondents had 0 to 2 years of work experience at INDOT (Figure 5.2).

Questions 1–3 of the survey constituted the background questions of the survey, meant gathering information about the respondent. Respondents were asked to identify which region of the state they operated from, as well as their position within INDOT and duration of their work within INDOT's winter operations.

Figure 5.1 shows the distribution of roles among respondents within INDOT's winter operations. The results show that most of the respondents held a supervisory role (manager, supervisor, director, etc.). The overrepresentation of supervisory roles in the responses was primarily due to the overall lack of access for field crew to email and internet during work hours. The survey was distributed via email and text message; however, many field crew members do not get access to emails or their phones during work hours. As a result, the majority of the respondents were in supervisory positions. Supervisors were encouraged to

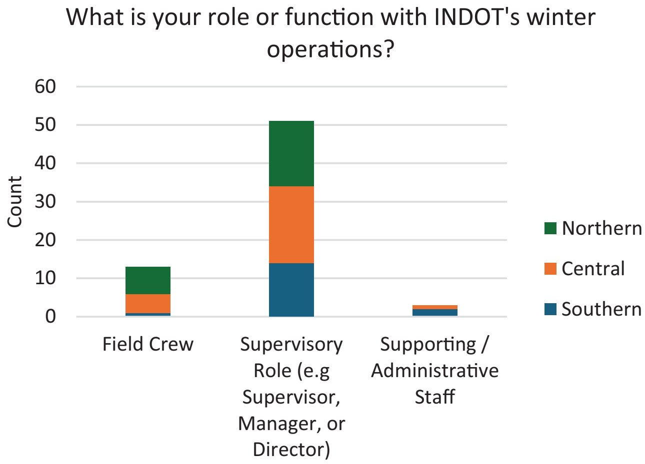

Figure 5.1 Respondent Roles in INDOT Winter Operations By Region.

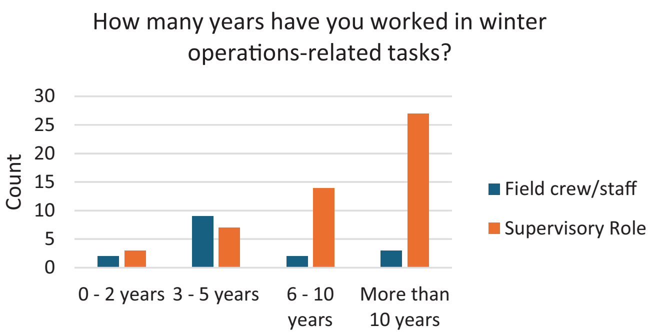

Figure 5.2 Respondent Tenure in INDOT Winter Operations.

distribute the survey to field crew within their units and encourage them to complete the survey at their convenience. However, response rates from field crew remained relatively low.

The duration of the respondents' work with INDOT's winter operations is presented in Figure 5.2. The results show that 44% of the respondents have been involved with winter operations for more than 10 years, while nearly 25% have worked in winter operations between 6 and 10 years. Among those in supervisory roles, 53% have worked for more than 10 years, while that number is less 20% for field crew/ staff in our sample. A majority (56%) of the field crew respondents in our sample have been involved in winter operations for 3 to 5 years. This disparity in the duration of work may be due to a higher turnover rate among lower-level staff compared with senior level staff such as supervisors. Furthermore, many supervisors may have started their career as lower-level employers and later ascended through the ranks, hence the higher number of years of work among supervisors compared with field crew.

5.3 Materials

We asked a question about the types of deicing and anti-icing materials commonly used by respondents. For this question, participants were allowed to select all the materials they use. Sodium chloride emerged as the most commonly used material across all three regions, followed by calcium chloride and magnesium chloride. Other materials, including potassium acetate and CMA, and sodium acetate, were reported as being used far less frequently.

Figure 5.3 shows survey results for the materials used for deicing/anti-icing in winter operations by region of the state. Across all the regions, sodium chloride is the most used de/anti-icing materials. The widespread use of sodium chloride as an anti-icing agent can be attributed to its low procurement cost and general availability. Compared with other salts, sodium chloride is generally cheap and widely available. Magnesium and calcium chloride are the second most used salts. While calcium chloride is used across the state, magnesium chloride appears to be used significantly only in the central region of the state. The northern and southern regions appear to use magnesium chloride only sparingly, along with other salts such as Potassium Chloride and Sodium Acetate. In addition to the salts, other items such as Beetheet are used for anti-icing across the state. Beetheet is used alongside the chlorides primarily for its anti-corrosion characteristics that helps counteract the corrosive nature of chlorides on vehicles and highway infrastructure.

5.4 Operational Practices

There are a total of 16 variables (i.e., survey questions) under the category of "Practices for Deicing" (see Appendix H for further details). Of these, ten variables are qualitatively assessed as *Good Practice* or *Bad Practice*. For a variable to be qualitatively assessed, it must meet all three of the following conditions: (1) the practice must be identified as recommendable in other states' documents; (2) the survey question must be a single-choice question rather than a multiple-response question; and (3) the question must be identified as an ordinal variable, meaning its response options must have ordered categories, such as Never, Often, and Always. Consequently, six variables that do not meet these conditions were excluded from the qualitative assessment.

To illustrate how we qualitatively assess the outcomes of deicing practice variables, consider an example. One survey

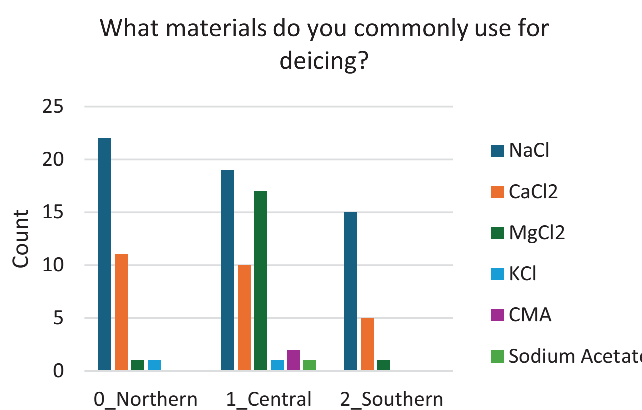

Figure 5.3 Commonly Used Deicing Materials.

question asked respondents: "How do you approach the application of deicing materials on the road?" Participants could choose from the following options: "I am not sure," "No overuse," "Occasionally overuse," "Sometimes overuse," or "Usually overuse." For the analysis, we first excluded responses of "I am not sure," as they were not useful for drawing meaningful conclusions.

We then conducted a qualitative evaluation of overuse. If more than 50% of respondents reported "no overuse" across all regions in Indiana, we assessed this practice as "Good Practice." If fewer than 50% reported "no overuse," the practice was assessed as "Bad Practice." It should be noted that in our report, we may use more precise terminology than "Good Practice" and "Bad Practice." Additionally, there is no universally standardized way to objectively assess these practices; our 50% threshold serves as a guideline to provide intuitive insights.

After completing the qualitative evaluation, a Chi-Square test was conducted to examine whether there were differences in responses based on region or role. The Chi-Square test is particularly suitable for this analysis because it is designed to evaluate relationships between categorical variables, making it an ideal choice for assessing whether response patterns vary across groups, such as regions or job roles.

One of the key merits of using the Chi-Square test is its ability to identify statistically significant differences in distributions without requiring assumptions about the underlying population, such as normality. By applying this test, we gain insights into whether observed variations in responses are likely due to random chance or reflect meaningful differences in practices or perceptions among subgroups. This information helps ensure a more thorough understanding of how practices may vary across different segments of the workforce or geographic areas.

5.4.1 Five "Bad" Practices

5.4.1.1 Bad Practice 1: Excessive Material Use. The survey question regarding the overuse of deicing materials is as follows:

- How do you approach the application of deicing materials on the road?
  0. **not sure**: I am not sure
  1. **no overuse:** I think that I always apply just enough salt to loosen the bond between the road and the ice, avoiding overuse of materials.
  2. **occasionally overuse**: I think that I often apply just enough salt to loosen the bond between the road and the ice, but occasionally overuse.
  3. **sometimes overuse**: I think that I sometimes overuse salt to ensure all snow and ice are melted
  4. **usually overuse**: I think that I usually overuse salt to ensure all snow and ice are melted.

A recommendable practice is as follows: You do not need to melt all the snow or ice on the road with salt. This is an overuse of materials. Apply just enough to loosen the bond between the road and the ice so it can be plowed off. (MnDOT, 2022).

The survey results revealed that only 35% of respondents reported "no overuse," while 65% indicated "occasional overuse," "sometimes overuse," or "usual overuse" of deicing materials. Since the proportion of respondents reporting "no overuse" is below our 50% threshold, we assessed the current practice in Indiana as a "Bad Practice."

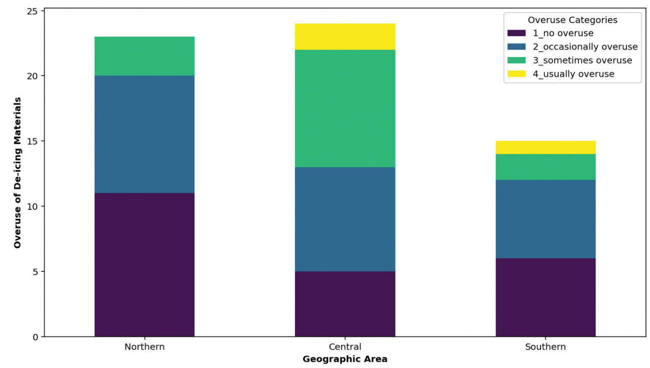

Figure 5.4 Overuse of Deicing Materials, By Region (Frequency).

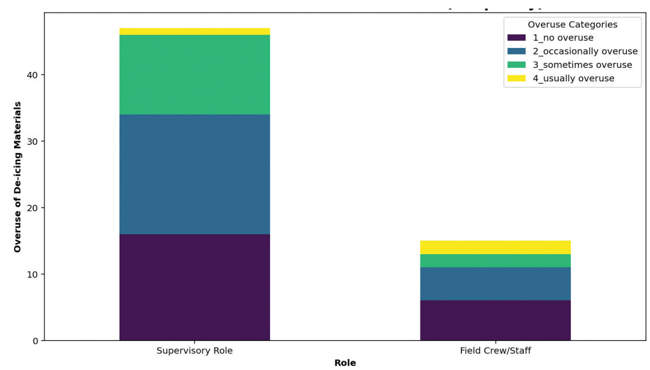

Figure 5.5 Overuse of Deicing Materials, By Role (Frequency).

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.4 and Figure 5.5 present self-reported salt overuse during application across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.1.2 Bad Practice 2: Application Rate—Multiple Passes. The survey question regarding the application rate during multiple passes is as follows:

- How frequently do you adjust your application rate of anti-/deicing materials during multiple passes when treating snow and ice?
  0. **not sure**: I am not sure
  1. **always adjust**: I always use a higher application rate on the first pass and reduce the rate on subsequent passes.
  2. **often adjust**: I often use a higher application rate on the first pass, but occasionally do not reduce the rate on subsequent passes.

3. **sometimes adjust**: I sometimes use a higher application rate on the first pass, depending on conditions, and adjust accordingly for subsequent passes.
4. **rarely adjust**: I rarely adjust my application rate based on the number of passes.

A recommendable practice is as follows: Generally, the first pass will require an application rate at the higher end of the range, with subsequent passes requiring less and less (MnDOT, 2022).

The survey results revealed that 43% of respondents reported "always adjust" or "often adjust," while 57% indicated "sometimes adjust" or "rarely adjust." Since the proportion of respondents reporting "always adjust" or "often adjust" is below our 50% threshold, we assessed the current practice in Indiana as a "Bad Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.6 and Figure 5.7 present the self-reported salt application rate during multiple passes across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions. However, there is a significant difference between roles: only 40% of supervisors reported only 40% of supervisors reported "always adjust" or "often adjust," compared to 54% of field crew/staff.

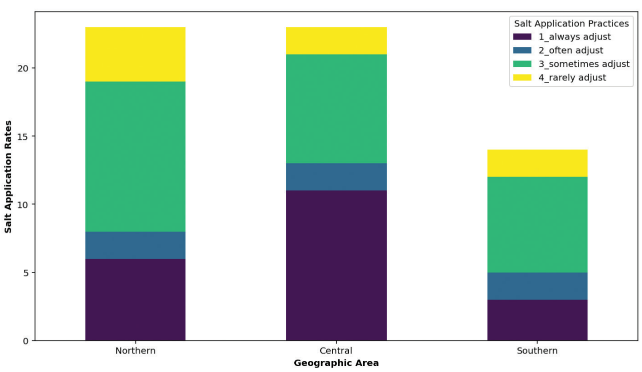

Figure 5.6 Salt Application Rates During Multiple Passes, By Region (Frequency).

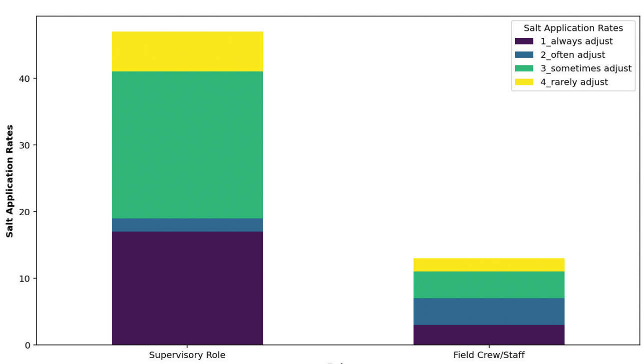

Figure 5.7 Salt Application Rates During Multiple Passes, By Role (Frequency).

5.4.1.3 Bad Practice 3: Application Rate—One-Pass Long Routes. The survey question regarding the application rate on long routes is as follows:

- How do you handle anti-/deicing material applications on long routes where only one pass is possible?
  0. **not sure**: I am not sure
  1. **always more**: I always apply more material than what's recommended in my organization's guideline.
  2. **often more**: I often apply more material on long routes but consider other factors before doing so.
  3. **sometimes more**: I sometimes apply more material on long routes, depending on the severity of the conditions.
  4. **rarely more**: I rarely apply more material, sticking to the recommended amounts regardless of route length.

A recommendable practice is as follows: On long routes where you will only be able to make one pass, you may have to apply more material than what's recommended in the charts (MnDOT, 2022).

The survey results revealed that only 17% of respondents reported "always more" or "often more" while 83% indicated "sometimes more" or "rarely more." Since the proportion of respondents reporting "always more" or "often more" is below our 50% threshold, we assessed the current practice in Indiana as a "Bad Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.8 and Figure 5.9 present the self-reported salt application rate on one-pass long routes across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

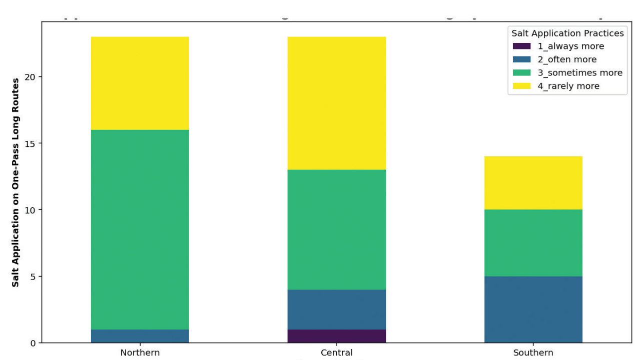

Figure 5.8 Salt Application on One-Pass Long Routes, By Region (Frequency).

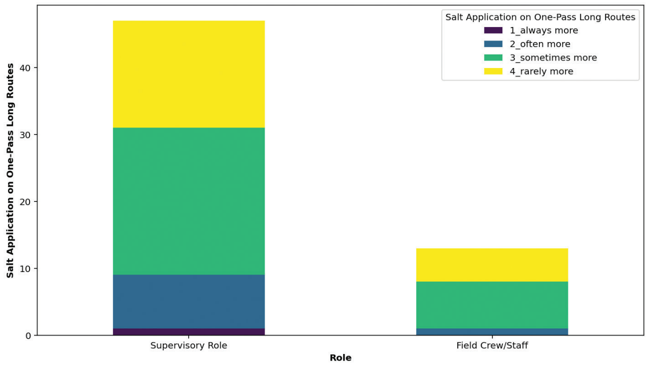

Figure 5.9 Salt Application on One-Pass Long Routes, By Role (Frequency).

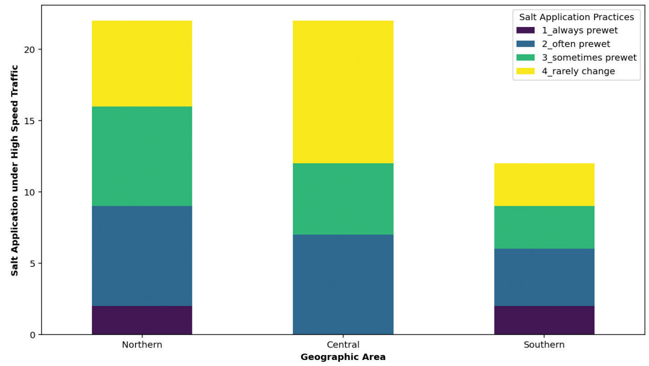

Figure 5.10 Salt Application at Higher Traffic Speeds, By Region (Frequency).

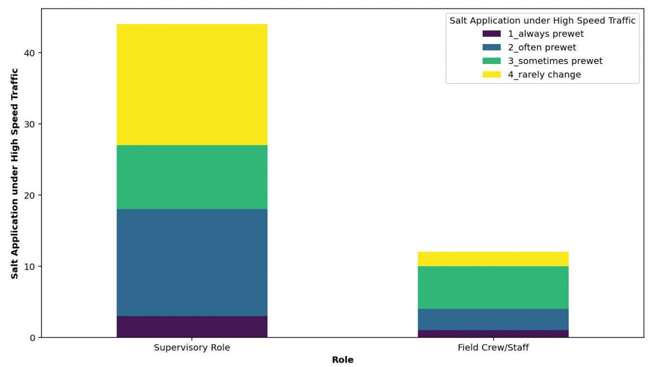

Figure 5.11 Salt Application at Higher Traffic Speeds, By Role (Frequency).

5.4.1.4 Bad Practice 4: Application Rate at Higher Traffic Speeds. The survey question regarding the application rate at higher traffic speeds is as follows:

- How do you adjust your use of anti-/deicing materials when dealing with higher traffic speeds?
  0. **not sure**: I am not sure
  1. **always prewet**: I always increase the use of prewetted materials instead of dry salt.
  2. **often prewet**: I often increase the use of prewetted materials but occasionally use dry salt depending on conditions.
  3. **sometimes prewet**: I sometimes use prewetted materials, but not consistently.
  4. **rarely change:** I rarely change my material usage based on traffic speeds.

A recommendable practice is as follows: Higher traffic speeds will blow salt off the road and hinder melting—so increase the use of prewetted materials. (MnDOT, 2022).

The survey results revealed that 37% of respondents reported "always prewet" or "often prewet" while 57% indicated "sometimes prewet" or "rarely change." Since the proportion of respondents reporting "always prewet" or "often prewet" is below our 50% threshold, we assessed the current practice in Indiana as a "Bad Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.10 and Figure 5.11 present the self-reported salt application rate at higher traffic speeds across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.1.5 Bad Practice 5: Spinner Speed. The survey question about the spinner speed for spreading deicing materials is as follows:

- How do you adjust your spinner speed when spreading materials?
  0. **not sure**: I am not sure
  1. **always the lowest**: I always adjust the spinner speed to the lowest setting possible.
  2. **often the lowest**: I often adjust the spinner speed to the lowest setting but sometimes keep it higher depending on the situation.
  3. **sometimes the lowest**: I sometimes adjust the spinner speed to the lowest setting, frequently keeping it at a moderate setting.
  4. **rarely adjust**: I rarely adjust the spinner speed, maintaining a consistent setting regardless of the situation.

A recommendable practice is as follows: Adjust your spinner speed to the lowest setting possible, except at intersections where a wider spread pattern may be helpful. (MnDOT, 2022).

The survey results revealed that 48% of respondents reported "always the lowest" or "often the lowest," while 52% indicated "sometimes the lowest" or "rarely adjust." Since the proportion of respondents reporting "always the lowest" or "often the lowest," is below our 50% threshold, we assessed the current practice in Indiana as a "Bad Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.12 and Figure 5.13 present self-reported spinner speed across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

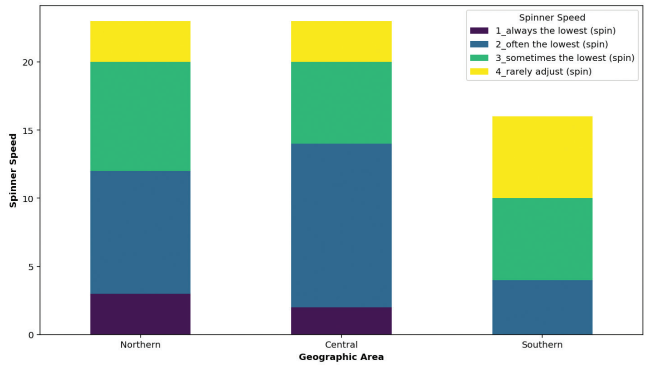

Figure 5.12 Spinner Speed, By Region (Frequency).

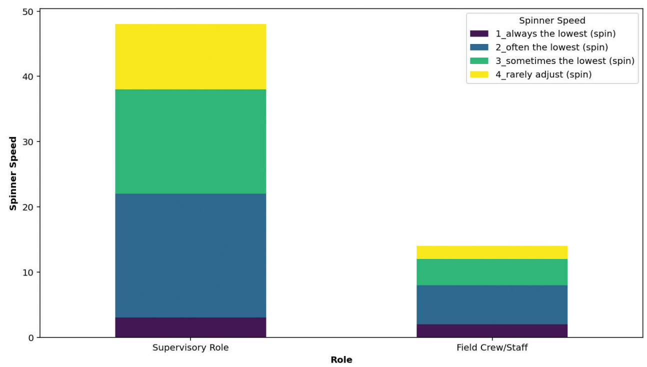

Figure 5.13 Spinner Speed, By Role (Frequency).

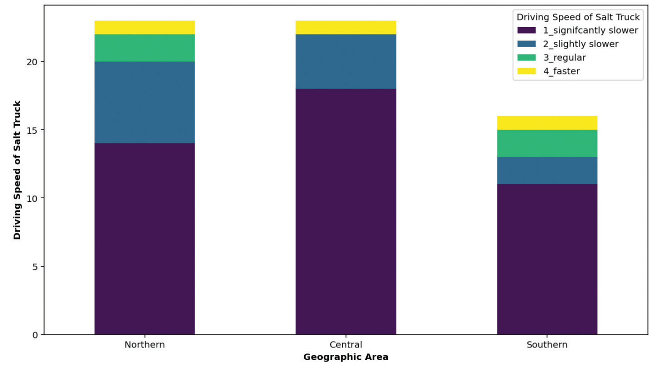

Figure 5.14 Driving Speed When Applying Dry Materials, By Region (Frequency).

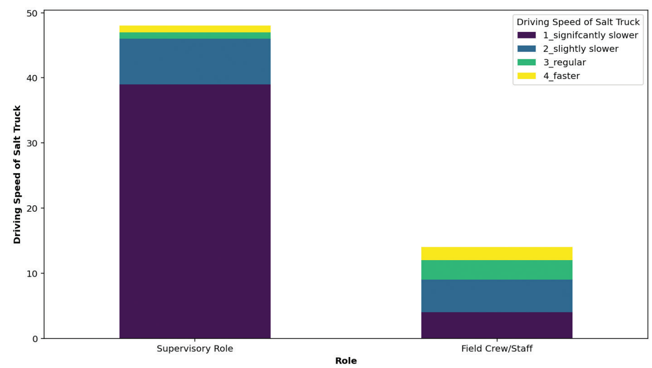

Figure 5.15 Driving Speed When Applying Dry Materials, By Role (Frequency).

5.4.2 Five "Good" Practices

5.4.2.1 Good Practice 1: Driving Speed When Applying Dry Materials. The survey question regarding the driving speed during the application of dry materials is as follows:

- When applying dry material for anti-/deicing, what speed do you typically drive at?
  0. **not sure**: I am not sure
  1. **significantly slower**: I drive at a significantly reduced speed compared to normal to ensure proper application.
  2. **slightly slower**: I usually drive slightly slower than normal when applying dry material.
  3. **regular**: I maintain my regular driving speed when applying dry material.
  4. **faster**: I sometimes drive faster than normal when applying dry material to cover more ground quickly.
  5. **not sure about the optimal speed**: I am not sure about the optimal driving speed when applying dry material.

A recommendable practice is as follows: If you must use dry material, drive slowly, apply on centerline, and turn off spinner to reduce bounce and scatter (MnDOT, 2022).

The survey results revealed that 89% of respondents reported "significantly slower" or "slightly slower," while 11% indicated "regular" or "faster." Since the proportion of respondents reporting "significantly slower" or "slightly slower" is greater than our 50% threshold, we assessed the current practice in Indiana as a "Good Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.14 and Figure 5.15 present self-reported driving speeds during material application across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions. However, there is a significant difference between roles: 98% of supervisors reported "significantly slower" or "slightly slower," compared to 60% of field crew/staff.

5.4.2.2 Good Practice 2: Plowing Prior to the Application of Deicing or Anti-Icing Materials. The survey question about plowing before applying the materials is as follows:

- How do you incorporate plowing into your snow and ice management routine before applying anti-/deicing materials?
  0. **not sure**: I am not sure
  1. **always plow**: I always plow before applying the materials.
  2. **often plow**: I often plow before applying the materials, but occasionally make exceptions based on conditions.
  3. **sometime plow**: I sometimes plow before applying the materials, depending on the severity of the snow and ice.
  4. **rarely plow**: I rarely plow before applying the materials.

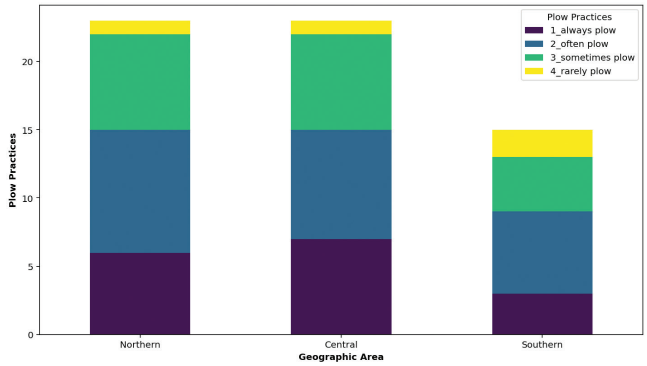

Figure 5.16 Plowing Prior to Material Application, By Region (Frequency).

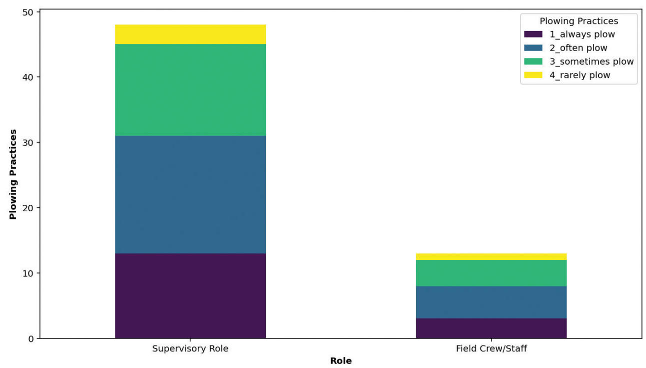

Figure 5.17 Plowing Prior to Material Application, By Role (Frequency).

A recommendable practice is as follows: Always plow before applying chemical (MnDOT, 2022).

The survey results revealed that 64% of respondents reported "always plow" or "often plow," while 36% indicated "sometimes plow" or "rarely plow." Since the proportion of respondents reporting "always plow" or "often plow" is greater than our 50% threshold, we assessed the current practice in Indiana as a "Good Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.16 and Figure 5.17 present self-reported plowing prior to material application across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.2.3 Good Practice 3: Application Rate Under High Volume Traffic. The survey question regarding the application rate of anti-/deicing materials under high volume traffic is as follows:

- How do you adjust your application rate of anti-/deicing material when encountering high traffic volume conditions?
  0. **not sure**: I am not sure

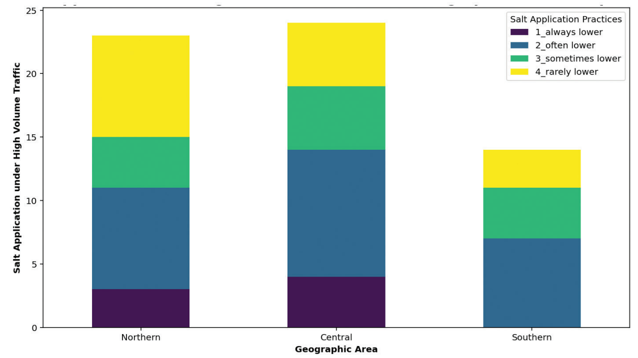

Figure 5.18 Application Rate Under High Volume Traffic, By Region (Frequency).

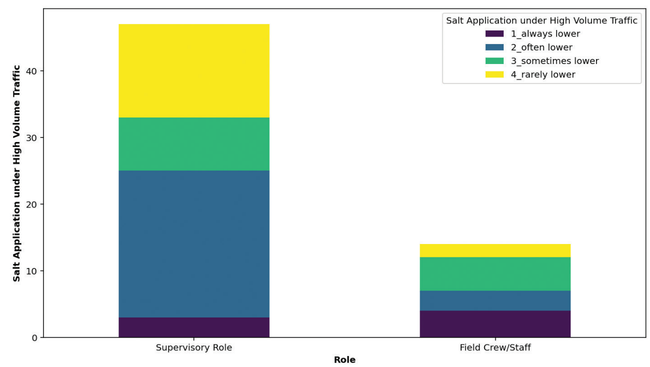

Figure 5.19 Application Rate Under High Volume Traffic, By Role (Frequency).

  1. **always lower**: I always use a lower rate.
  2. **often lower**: I often use a lower rate, depending on other factors like temperature and snow thickness.
  3. **sometimes slower**: I sometimes use a lower rate.
  4. **rarely lower**: I rarely use a lower rate regardless of traffic volume.

A recommendable practice is as follows: High traffic volume will work salt into the snow and aid in melting—so use a lower rate (MnDOT, 2022).

The survey results revealed that 52% of respondents reported "always lower" or "often lower," while 48% indicated "sometime lower" or "rarely lower." Since the proportion of respondents reporting "always lower" or "often lower" is greater than our 50% threshold, we assessed the current practice in Indiana as a "Good Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.18 and Figure 5.19 present the self-reported application rate under high volume traffic across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions. However, there is a significant difference between roles: 53% of supervisors reported "always lower" or "often lower," compared to 50% of field crew/staff.

5.4.2.4 Good Practice 4: Use of Dry Salt. The survey question regarding the use of dry salt based on pavement temperatures is as follows:

- How do you decide whether to apply dry salt based on pavement temperatures?
  0. **not sure**: I am not sure
  1. **always avoid (dry salt)**: I always avoid applying dry salt at below 15 °F pavement temperature.
  2. **often avoid (dry salt)**: I often avoid applying dry salt below 15 °F but occasionally apply it depending on other factors.
  3. **sometimes apply (dry salt)**: I sometimes apply dry salt at below 15 °F pavement temperature.
  4. **usually apply (dry salt)**: I usually apply dry salt regardless of pavement temperatures, focusing on immediate road safety.

A recommendable practice is as follows: It is usually not cost-efficient to apply salt (sodium chloride) at pavement temperatures below 15 °F (MnDOT, 2022). Do not apply dry salt at below 15 °F pavement temperature. It will not melt fast enough to help, and it will blow off the road into the ditch (MnDOT, 2022).

The survey results revealed that 75% of respondents reported "always avoid (dry salt)" or "often avoid (dry salt)," while 25% indicated "sometimes apply (dry salt)" or "usually apply (dry salt)." Since the proportion of respondents reporting "always avoid (dry salt)" or "often avoid (dry salt)" is greater than our 50% threshold, we assessed the current practice in Indiana as a "Good Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.20 and Figure 5.21 present the self-reported use of dry salt across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.2.3 Good Practice 5: Material Switch Below 15 °F. The survey question regarding the selection of materials based on pavement temperatures is as follows:

- How do you adjust your choice of materials when pavement temperatures are below 15F?
  0. **not sure**: I am not sure

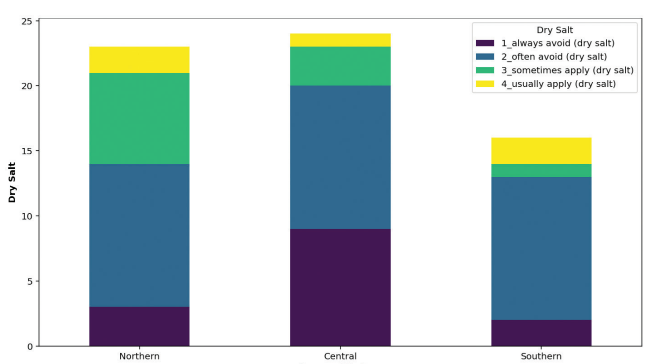

Figure 5.20 Use of Dry Salt, By Region (Frequency).

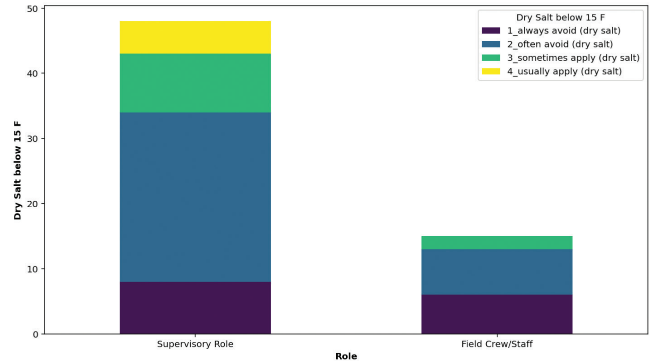

Figure 5.21 Use of Dry Salt, By Role (Frequency).

  1. **always switch**: I always switch to other tools such as calcium chloride, magnesium chloride, or other additives to obtain maximum melting when pavement temperatures are below 15 °F.
  2. **often switch**: I often switch to other materials below 15 °F, but occasionally use dry salt depending on conditions.
  3. **sometimes switch**: I sometimes switch to other materials below 15 °F, if necessary, but mostly stick to dry salt.
  4. **rarely switch**: I rarely switch materials based on pavement temperatures, continuing to use dry salt regardless.

A recommendable practice is as follows: Below 15 °F, switch to other tools such as calcium chloride, magnesium chloride, or other additives to obtain maximum melting (MnDOT, 2022).

The survey results revealed that 66% of respondents reported "always switch" or "often switch," while 34% indicated "sometimes switch" or "rarely switch." Since the proportion of respondents reporting "always switch" or "often switch" is greater than our 50% threshold, we assessed the current practice in Indiana as a "Good Practice."

Following this qualitative evaluation, a statistical test (Chi-Square test) was performed to determine whether differences existed in responses by region or role. Figure 5.22 and Figure 5.23 present the self-reported selection of materials below 15 °F across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff),

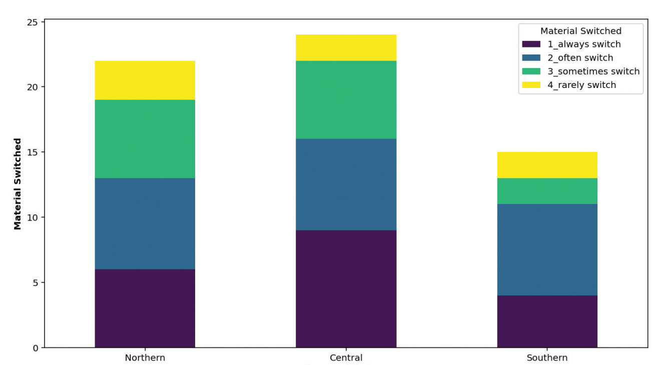

Figure 5.22 Material Selection Below 15 °F, By Region (Frequency).

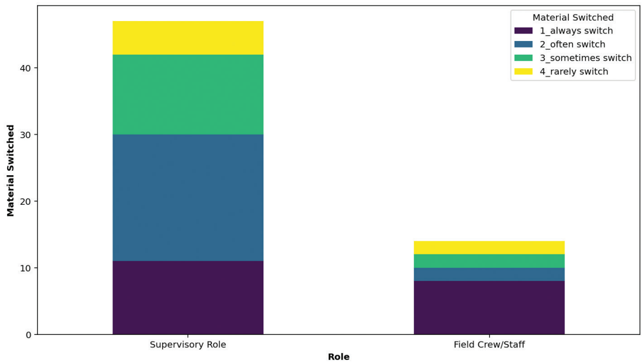

Figure 5.23 Material Selection Below 15 °F, By Role (Frequency).

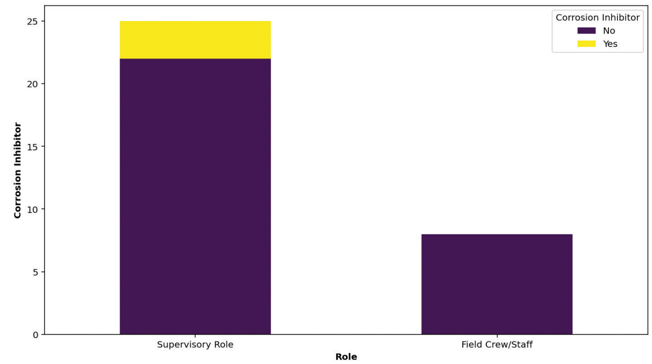

Figure 5.25 Corrosion Inhibitors, By Role (Frequency).

respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.3 Other Practices for Deicing

5.4.3.1 Use of Corrosion Inhibitors. The survey question regarding the use of corrosion inhibitors is as follows:

- Are you using any corrosion inhibitors along with the materials used for deicing and anti-icing?
  0. I am not aware of any
  1. Yes
  2. No

No recommendable practices for corrosion inhibitors were identified in other states' winter road maintenance documents. Therefore, we did not qualitatively assess the current practice in Indiana.

Of the 67 total responses, we excluded 34 that indicated "I am not aware of any," as they were not useful for drawing meaningful conclusions in a statistical test (Chi-Square test). The survey results showed that 4.5% of respondents reported "Yes," while 95.5% indicated "No."

A Chi-Square test was conducted to determine whether differences existed in responses based on region or role. Figure 5.24 and Figure 5.25 present self-reported the use of corrosion inhibitors across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.3.2 Use of Sand-Salt Mix. The survey question regarding the use of sand/salt mix is as follows:

- In which situations do you consider using a sand-salt mix, despite it generally not being advised?
  0. **not sure**: I am not sure
  1. **freezing rain (sand mix)**: I use a sand-salt mix only during freezing rain, as it can help improve traction.
  2. **instructed (sand mix)**: I use a sand-salt mix only when specifically instructed to do so by my supervisor.
  3. **never use (sand mix)**: I never use sand-salt mix.

A recommendable practice is as follows: Sand-salt mix is not advised but may help in some situations such as freezing rain (MnDOT, 2022). However, the response options are not in ordered categories. Therefore, we did not qualitatively assess the current practice in Indiana.

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.26 and Figure 5.27 present the

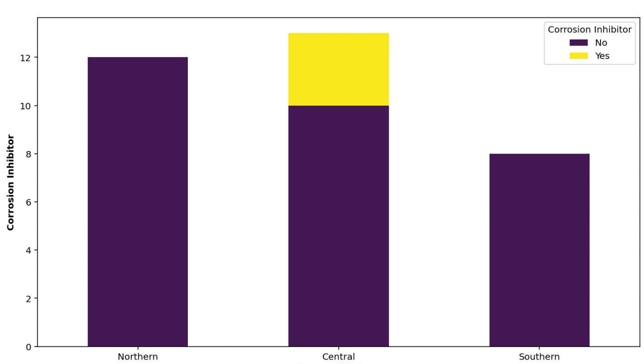

Figure 5.24 Corrosion Inhibitors, By Region (Frequency).

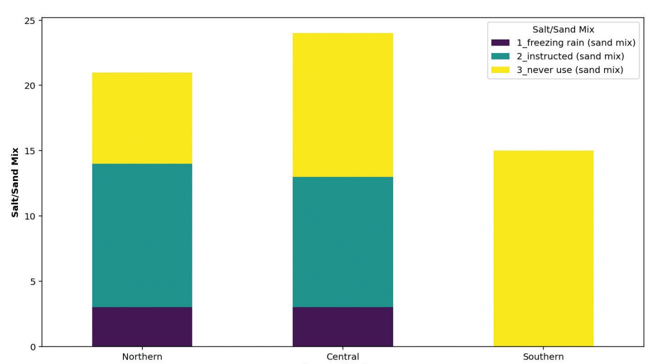

Figure 5.26 Sand-Salt Mix, By Region (Frequency).

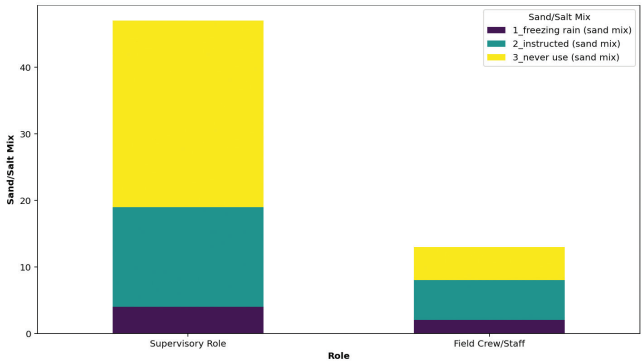

Figure 5.27 Sand-Salt Mix, By Role (Frequency).

self-reported use of sand-salt mix across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate a significant difference across the three regions: all responses from Southern Indiana were “never use.” However, no significant differences were observed between the two roles.

5.4.3.3 Use of Sand. The survey question regarding the use of sand is as follows:

- How do you utilize sand in your snow and ice management practices?
  0. **not sure**: I am not sure
  1. **always use**: I always use sand only for short-term traction, knowing it will not melt anything.
  2. **often use**: I often use sand for short-term traction, but occasionally mix it with salt for additional effects.
  3. **sometimes use**: I sometimes use sand for traction, but also rely on it for other purposes.
  4. **never use**: I never use sand.

A recommendable practice is as follows: Use sand for short-term traction only. It will never melt anything (MnDOT, 2022). However, it is problematic to interpret this question as a purely ordered variable for the use of sand because some response options assume the use of a sand-salt mix. Therefore, we did not qualitatively assess the current practice in Indiana.

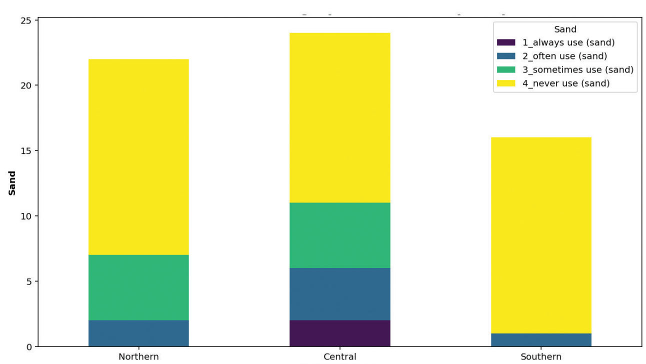

Figure 5.28 Use of Sand, By Region (Frequency).

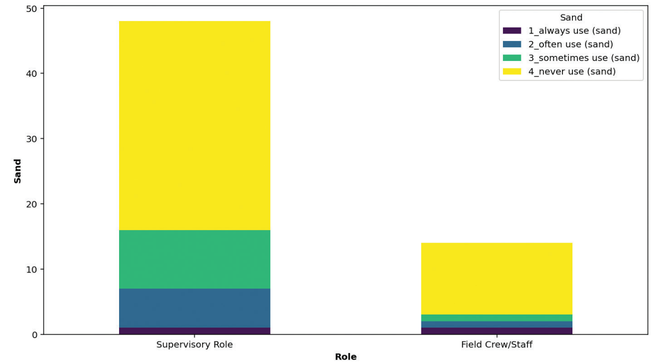

Figure 5.29 Use of Sand, By Role (Frequency).

A Chi-Square test was conducted to determine whether differences existed in responses based on region or role. Figure 5.28 and Figure 5.29 present the self-reported use of sand across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.3.4 Salt Storage The survey question regarding the storage of road salts is as follows:

- How do you manage the storage of road salts and other deicing materials in your area of operation? (**Select all that apply**)
  0. **not sure**: I am not sure
  1. **covered storage**
  2. **uncovered storage**
  3. **enclosed containers**
  4. **other (specify)**

No recommendable practices for corrosion inhibitors were identified in other states’ winter road maintenance documents. In addition, this question cannot be understood as an ordinal variable. Lastly, the current question is a multiple-response question. Hence, we did not qualitatively assess the current practice in Indiana. Therefore, we did not qualitatively assess the current practice in Indiana.

A Chi-Square test was conducted to determine whether differences existed in responses based on region or role. Figure 5.30

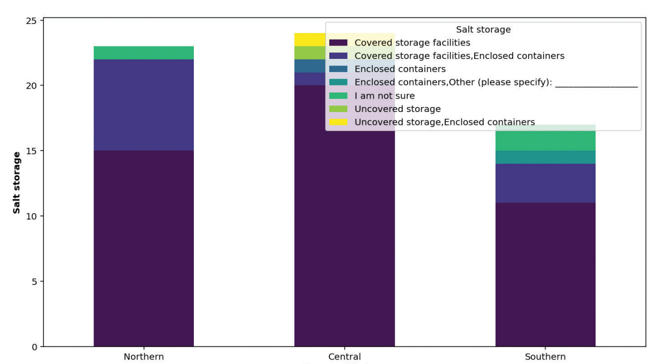

Figure 5.30 Salt Storage, By Region (Frequency).

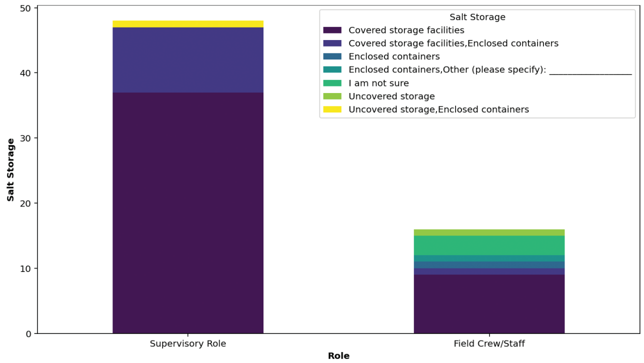

Figure 5.31 Salt Storage, By Role (Frequency).

and Figure 5.31 present the self-reported salt storage across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.4 Awareness of Chloride Impacts

There are a total of ten variables (i.e., survey questions) under the category of "Awareness of Chloride Impacts (see Appendix H for further details). These variables are qualitatively assessed as "High Awareness" or "Low Awareness." To illustrate how we qualitatively assess the outcomes of awareness variables, consider an example. One survey question asked respondents: "How aware are you that chlorides in road salts can increase soil salinity, leading to compaction and erosion?" Participants could choose from the following options: "not aware or not sure about this," "somewhat aware," "aware," "very aware."

If more than 50% of respondents reported "very aware" or "aware" across all regions in Indiana, we assessed it as "High Awareness." If fewer than 50% reported "very aware" or "aware," it was assessed as "Low Awareness." It should be noted that in our report, we may use more precise terminology than "High Awareness" and "Low Awareness." Additionally, there is no universally standardized way to objectively assess these practices; our 50% threshold serves as a guideline to provide intuitive insights.

After completing the qualitative evaluation, a Chi-Square test was conducted to examine whether there were differences in responses based on region or role. The Chi-Square test is particularly suitable for this analysis because it is designed to evaluate relationships between categorical variables, making it an ideal choice for assessing whether response patterns vary across groups, such as regions or job roles.

One of the key merits of using the Chi-Square test is its ability to identify statistically significant differences in distributions without requiring assumptions about the underlying population, such as normality. By applying this test, we gain insights into whether observed variations in responses are likely due to random chance or reflect meaningful differences in awareness of chloride impacts among subgroups. This information helps ensure a more thorough understanding of how awareness of chloride impacts may vary across different segments of the workforce or geographic areas.

5.4.4.1 Low Awareness (Two Variables)

5.4.4.1.1 Harmful metals. The survey question regarding metal awareness is as follows:

- How aware are you that many deicing materials might contain trace amounts of metals like cyanide, arsenic, lead, and mercury?
  0. not aware or not sure about this
  1. somewhat aware
  2. aware
  3. very aware

The survey results revealed that 41% of respondents reported "very aware" or "aware," while 59% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is lower than our 50% threshold, we assessed the current practice in Indiana as a "Low Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.32 and Figure 5.33 present self-reported metal awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

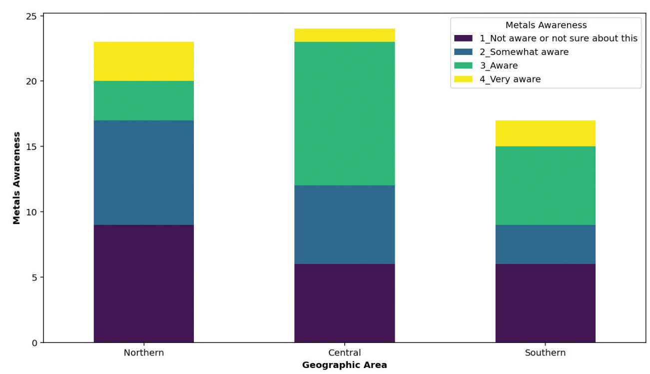

Figure 5.32 Harmful Metals, By Region (Frequency).

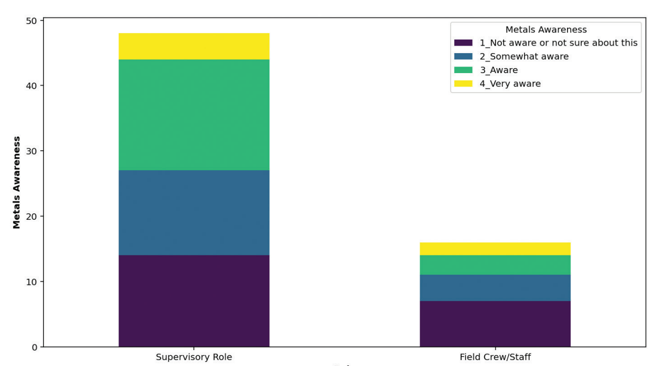

Figure 5.33 Harmful Metals, By Role (Frequency).

5.4.4.1.2 Impacts on aquatic organisms. The survey question regarding awareness of aquatic organisms is as follows:

- How aware are you that sand used for winter operations can smother fish eggs and other aquatic organisms if it washes into streams or lakes?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 37% of respondents reported "very aware" or "aware," while 63% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is lower than our 50% threshold, we assessed the current practice in Indiana as a "Low Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.34 and Figure 5.35 present self-reported awareness of aquatic organisms across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

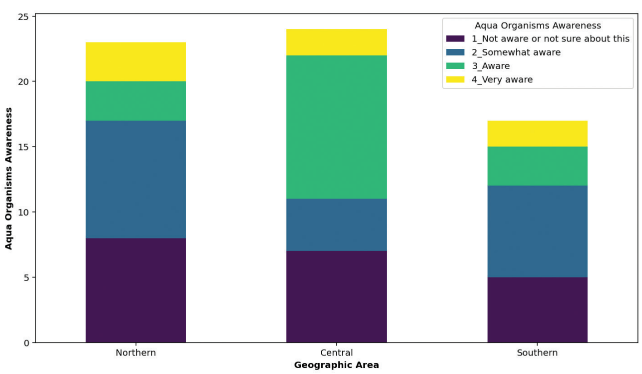

Figure 5.34 Impacts on Aquatic Organisms, By Region (Frequency).

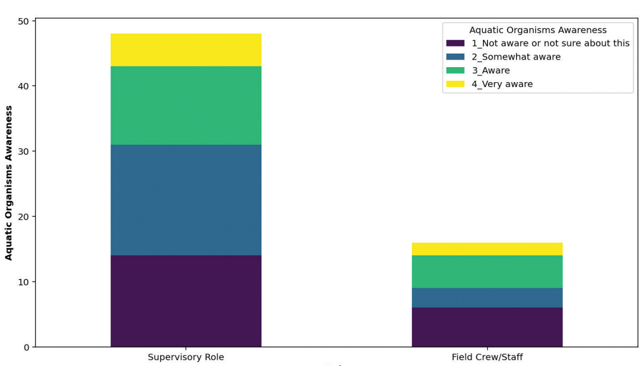

Figure 5.35 Impacts to Aquatic Organisms, By Role (Frequency).

5.4.4.2 High Awareness (Eight Variables)

5.4.4.2.1 Soil salinity. The survey question regarding soil salinity awareness is as follows:

- How aware are you that chlorides in road salts can increase soil salinity, leading to compaction and erosion?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 67% of respondents reported "very aware" or "aware," while 33% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.36 and Figure 5.37 present self-reported soil salinity awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.4.2.2 Water quality. The survey question regarding water awareness is as follows:

- How aware are you that excess chlorides from road salt can soak into groundwater or run off to nearby bodies of water?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 83% of respondents reported "very aware" or "aware," while 17% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

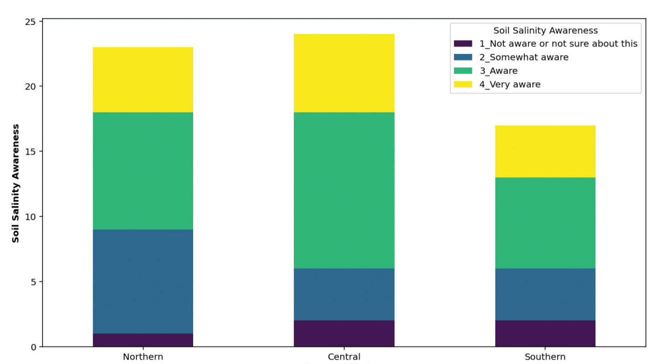

Figure 5.36 Soil Salinity, By Region (Frequency).

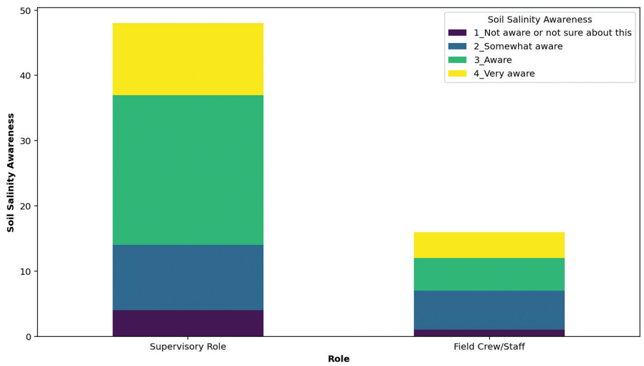

Figure 5.37 Soil Salinity, By Role (Frequency).

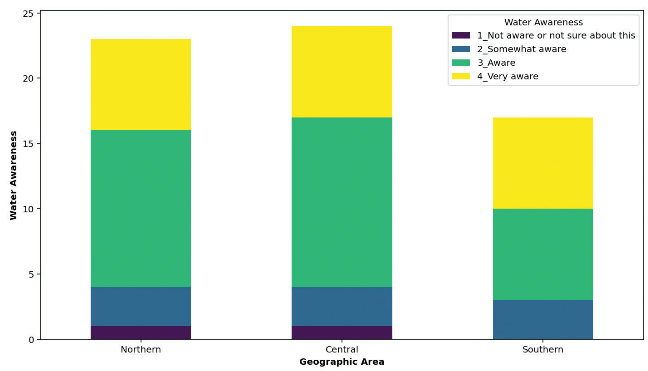

Figure 5.38 Water Quality, By Region (Frequency).

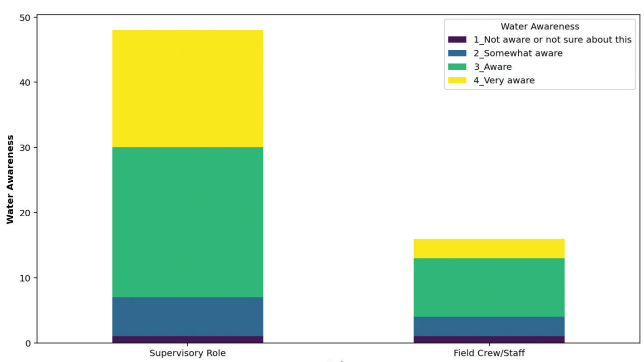

Figure 5.39 Water Quality, By Role (Frequency).

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.38 and Figure 5.39 present self-reported water awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.4.2.3 Aquatic life—Oxygen levels. The survey question regarding aquatic life (oxygen) awareness is as follows:

- How aware are you that chlorides in road salts can reduce oxygen levels in waterways, affecting aquatic life?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 64% of respondents reported "very aware" or "aware," while 36% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.40 and Figure 5.41 present self-reported aquatic life (oxygen) awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

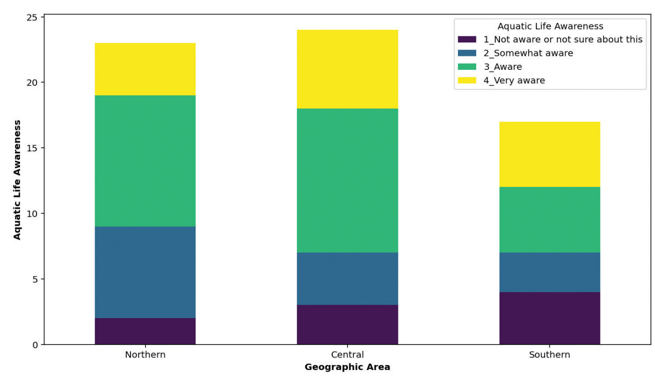

Figure 5.40 Aquatic Life, By Region (Frequency).

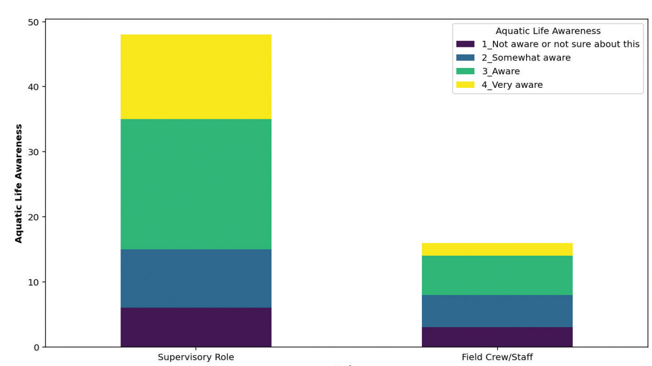

Figure 5.41 Aquatic Life, By Role (Frequency).

5.4.4.2.4 Aquatic systems. The survey question regarding aquatic systems awareness is as follows:

- How aware are you that calcium chloride is extremely toxic to aquatic systems and should not be used near open drains?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 55% of respondents reported "very aware" or "aware," while 45% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.42 and Figure 5.43 present self-reported aquatic systems awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

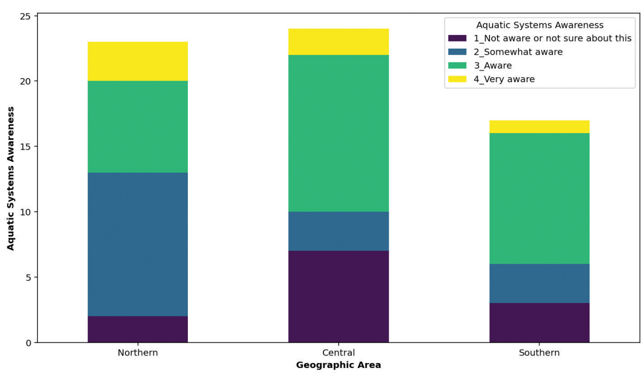

Figure 5.42 Aquatic Systems, By Region (Frequency).

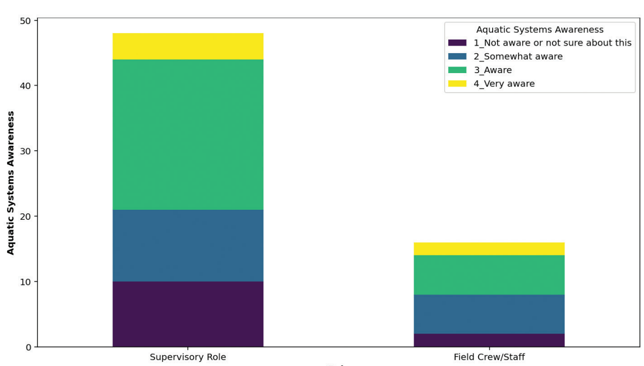

Figure 5.43 Aquatic Systems, By Role (Frequency).

5.4.4.2.5 Persistence of chlorides. The survey question regarding chloride persistence awareness is as follows:

- How aware are you that once chlorides enter waterways, they can persist for a long time due to the lack of biological removal processes?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 55% of respondents reported "very aware" or "aware," while 45% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.44 and Figure 5.45 present self-reported chloride persistence awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

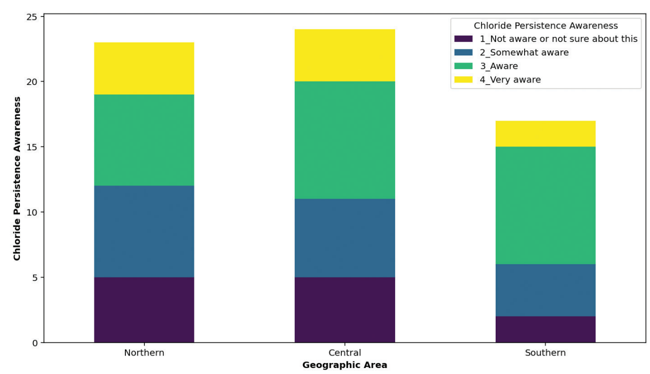

Figure 5.44 Persistence of Chlorides, By Region (Frequency).

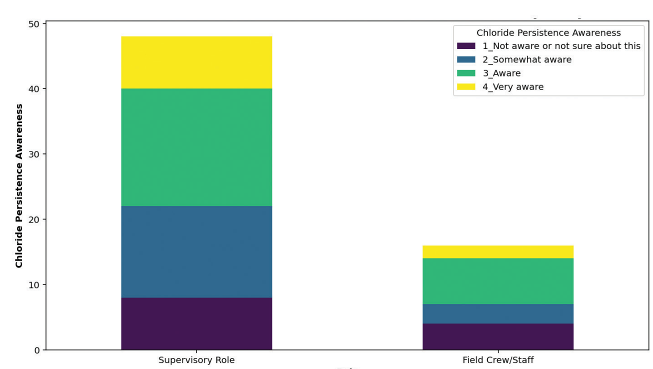

Figure 5.45 Persistence of Chlorides, By Role (Frequency).

5.4.4.2.6 Vegetation. The survey question regarding vegetation awareness is as follows:

- How aware are you that salt spray from road salts can damage roadside vegetation?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 77% of respondents reported "very aware" or "aware," while 23% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.46 and Figure 5.47 present self-reported vegetation awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

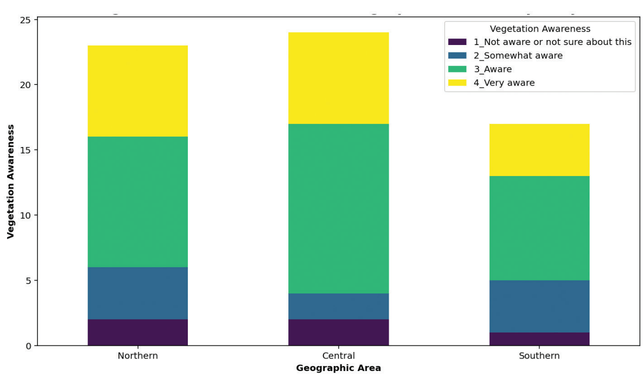

Figure 5.46 Vegetation, By Region (Frequency).

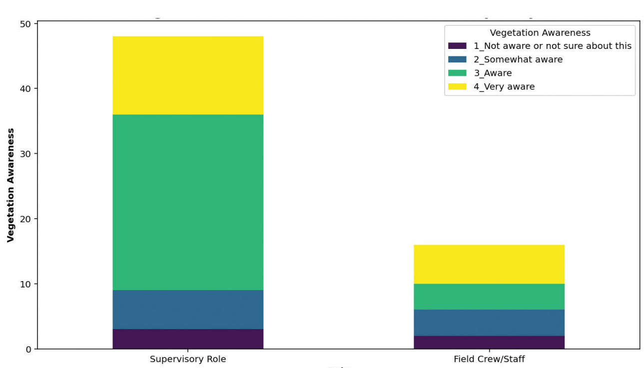

Figure 5.47 Vegetation, By Role (Frequency).

5.4.4.2.7 Corrosion. The survey question regarding corrosion awareness is as follows:

- How aware are you that road salts can corrode vehicles and bridges?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 83% of respondents reported "very aware" or "aware," while 17% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.48 and Figure 5.49 present self-reported corrosion awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

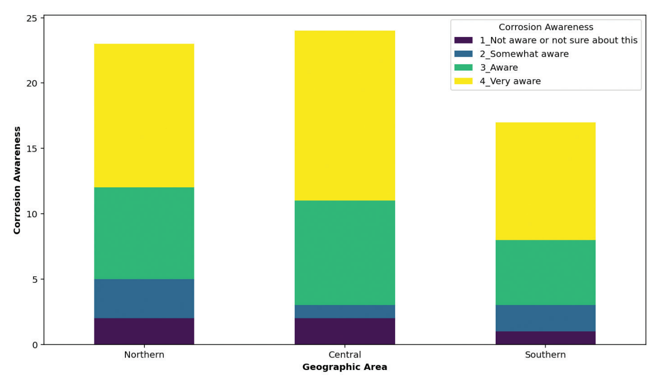

Figure 5.48 Corrosion, By Region (Frequency).

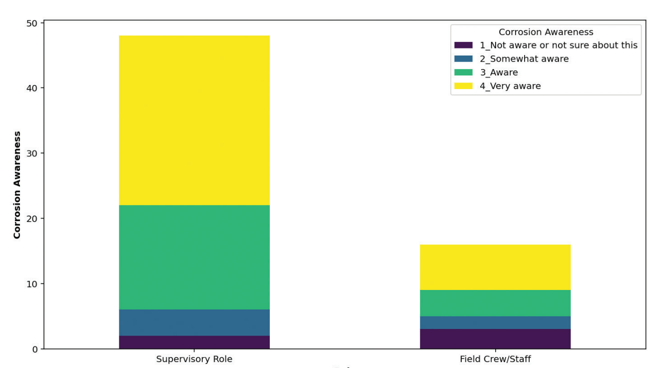

Figure 5.49 Corrosion, By Role (Frequency).

5.4.4.2.8 Drinking water contamination. The survey question regarding drinking water awareness is as follows:

- How aware are you that road salts can contaminate drinking water reservoirs and wells?
  1. not aware or not sure about this
  2. somewhat aware
  3. aware
  4. very aware

The survey results revealed that 64% of respondents reported "very aware" or "aware," while 36% indicated "somewhat aware" or "not aware or not sure about this." Since the proportion of respondents reporting "very aware" or "aware" is higher than our 50% threshold, we assessed the current practice in Indiana as a "High Awareness."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.50 and Figure 5.51 present self-reported drinking water awareness across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

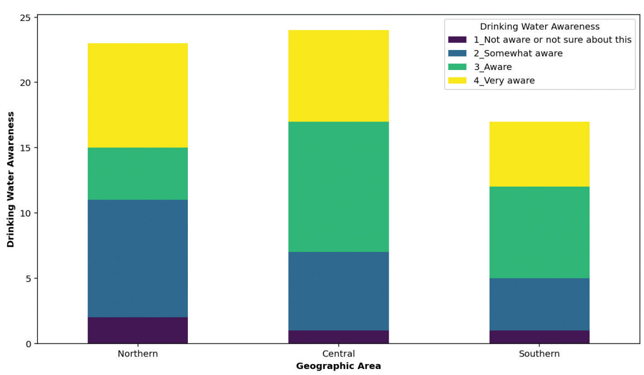

Figure 5.50 Drinking Water Contamination, By Region (Frequency).

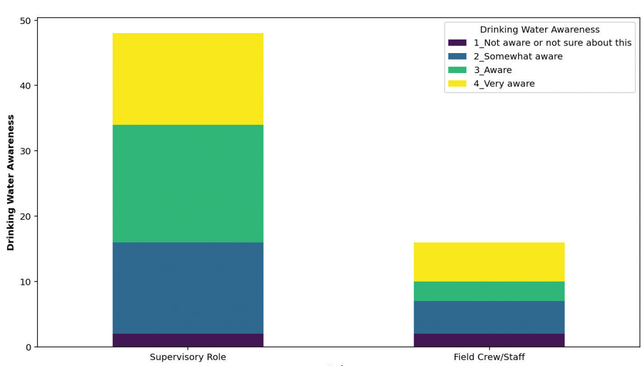

Figure 5.51 Drinking Water Contamination, By Role (Frequency).

5.4.5 Leftover Salt Management

The survey included questions that investigates how INDOT staff manage and perceive leftover salt after a snow event, examining factors such as storage, reuse, and potential overuse. Drawing on survey responses from across Indiana's regions (Northern, Central, and Southern) and job roles (supervisors vs. field crew/staff), we analyze whether these factors influence decisions about residual salt handling. The questions and results also touch on staff practices, guidelines in place, and the effectiveness of those guidelines in minimizing waste and maintaining safe operations.

5.4.5.1 Leftover Salt Across Geographic Areas. The survey question regarding Leftover Salt Across Geographic areas is as follows:

- How often do you find yourself with leftover salt in your truck after completing a snow event?
  0. Not sure
  1. Always
  2. Often
  3. Sometimes
  4. Rarely
  5. Never

The survey results revealed that 18% of respondents reported "Always" engaging in the activity, 40% indicated they do so "Often," while 31% reported "Sometimes." Additionally, 8% of participants stated they "Rarely" engage, and 3% mentioned they "Never" do.

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.52 and Figure 5.53 present self-reported leftover salt details across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

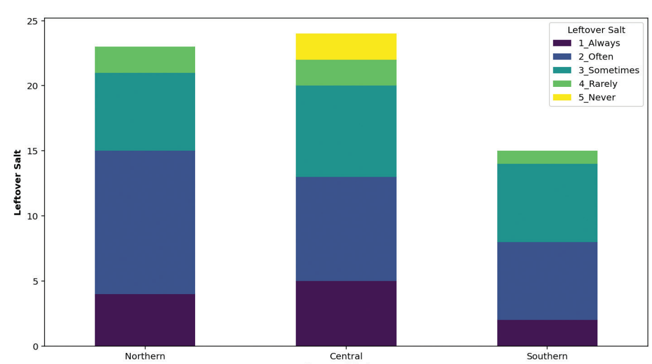

Figure 5.52 Leftover Salt Management, By Region (Frequency).

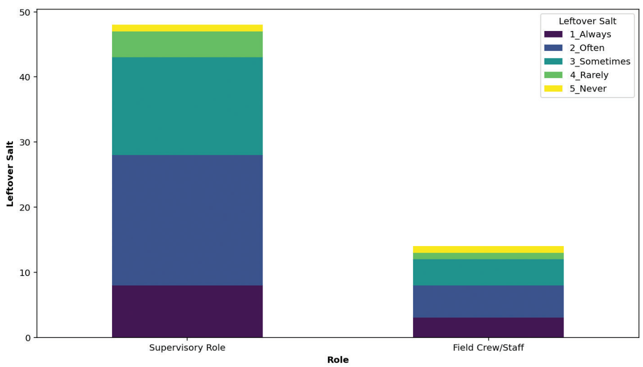

Figure 5.53 Leftover Salt Management, By Role (Frequency).

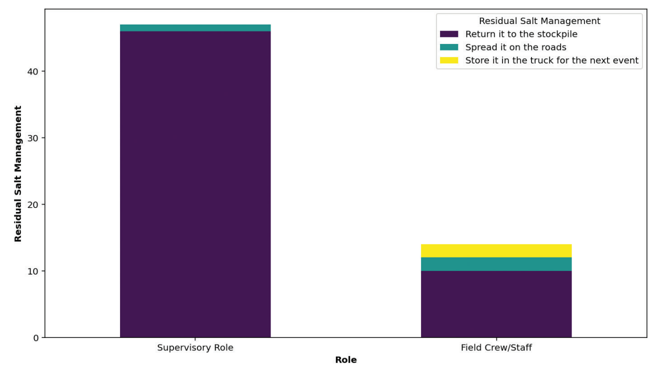

Figure 5.55 Residual Salt Management, By Role (Frequency).

5.4.5.2 Residual Salt Management Across Geographic Areas. The survey question regarding residual salt management across geographic areas is as follows:

- What do you typically do with residual salt left in your truck after a snow event?
  0. I am not sure
  1. Return it to the stockpile
  2. Spread on the roads
  3. Store it in the truck for the next event

The survey results revealed that 92% of respondents reported "Return it to the stockpile," 5% "Spread on the roads," and 3% "Store it in the truck for the next event."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.54 and Figure 5.55 present self-reported residual salt management across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant difference across the three regions.

However, a significant difference was observed between the two roles. Respondents in the Supervisory Role predominantly selected "Return it to the stockpile" (46 responses), and there were no instances of selecting "Store it in the truck." In contrast, respondents in the Field Crew/Staff role provided more diverse responses, including ten responses for "Spread it on the road" and two responses for "Store it in the truck for the next event." The results of the Chi-Square test are as follows: the Chi-Square statistic is 10.78, with a p-value of 0.0046 and 2 degrees of freedom. Since the p-value is less than the standard significance threshold of 0.05, this indicates a statistically significant relationship between respondents' roles and their actions regarding residual salt.

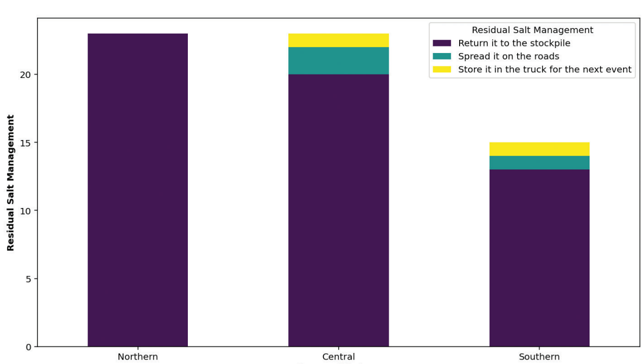

Figure 5.54 Residual Salt Management, By Region (Frequency).

5.4.5.2.1 Interpretation of the relationship. The results suggest that respondents' roles significantly influence how they handle leftover salt. Supervisors are far more likely to return the residual salt to the stockpile, while field crew/staff show greater variability in their actions, with some spreading it on roads or storing it in the truck for future use. The difference in responses could reflect variations in responsibilities, decision-making authority, or operational guidelines based on role.

5.4.5.2.2 Implications. The significant relationship highlights a need to consider roles when assessing or improving leftover salt management practices. Differences in practices might stem from disparities in training, resources, or communication about standard operating procedures.

5.4.5.3 Leftover Salt Return Across Geographic Areas. The survey question regarding leftover salt return across geographic areas is as follows:

- If you return residual salt to the stockpile, how frequently do you do so?
  0. Not sure
  1. Always
  2. Often
  3. Sometimes
  4. Rarely
  5. Never

The survey results revealed that 48% of respondents reported "Always" engaging in the activity, 31% indicated they do so "Often," while 13% reported "Sometimes." Additionally, 6% of participants stated they "Rarely" engage, and 2% mentioned they "Never" do.

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.56 and Figure 5.57 present self-reported

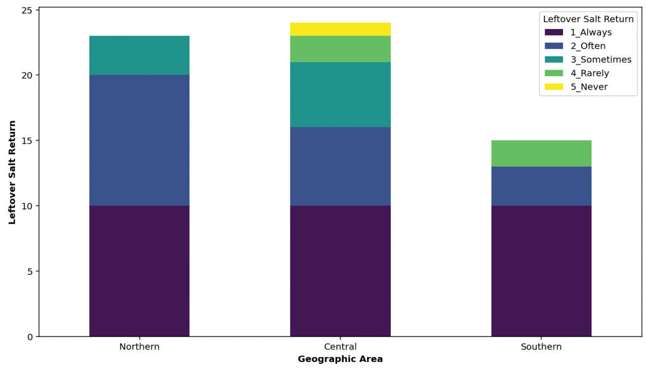

Figure 5.56 Leftover Salt Return, By Region (Frequency).

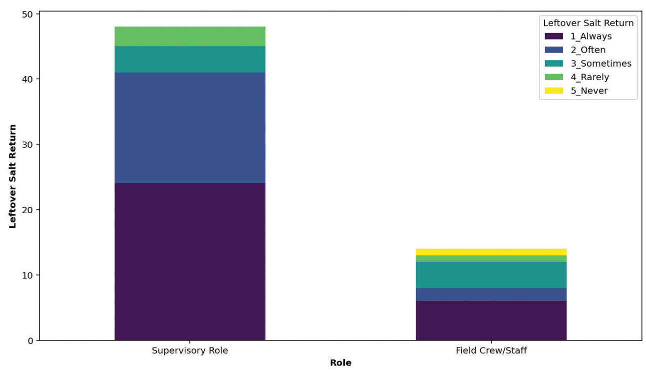

Figure 5.57 Leftover Salt Return, By Role (Frequency).

leftover salt across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.5.4 Leftover Overuse Concern Across Geographic Areas. The survey question regarding leftover overuse concern across geographic areas is as follows:

- How concerned are you about the potential for excessive salt use due to residual salt left in trucks?
  1. Very concerned
  2. Concerned
  3. Somewhat concerned
  4. Not concerned
  5. I don't think this is an issue

The survey results revealed that 19% of respondents reported "I don't think this is an issue," 14% indicated they are "Very concerned," while 23% reported being "Concerned." Additionally, 23% of participants stated they are "Somewhat concerned," and 20% mentioned they are "Not concerned."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.58 and Figure 5.59 present self-reported details on leftover overuse concern across the three regions (Northern, Central, and Southern Indiana) and between the two roles

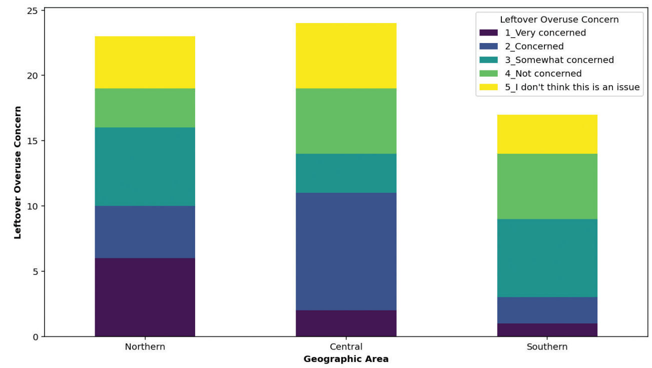

Figure 5.58 Leftover Overuse Concern, By Region (Frequency).

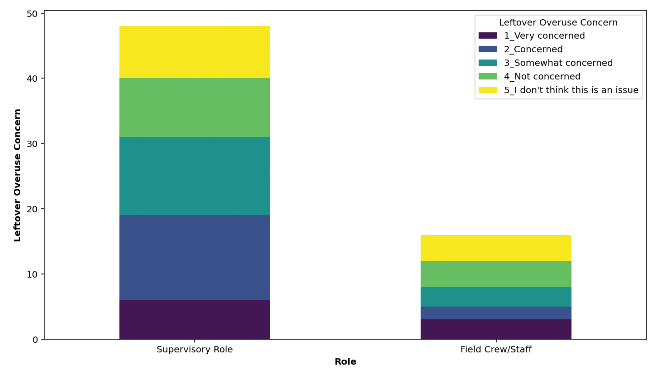

Figure 5.59 Leftover Overuse Concern, By Role (Frequency).

(supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.5.5 Leftover Salt Guidelines Across Geographic Areas. The survey question regarding leftover salt guidelines across geographic areas is as follows:

- Are there organizational guidelines on how to manage leftover salts after a snow event?
  0. Not sure
  1. Yes, detailed guidelines
  2. Yes, but they are vague
  3. No, there are no guidelines

The survey results revealed that 64% of respondents reported "Yes, detailed guidelines" are available, 32% indicated that "Yes, but they are vague," while 4% reported "No, there are no guidelines" in place.

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.60 and Figure 5.61 present self-reported data on awareness of leftover salt guidelines across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

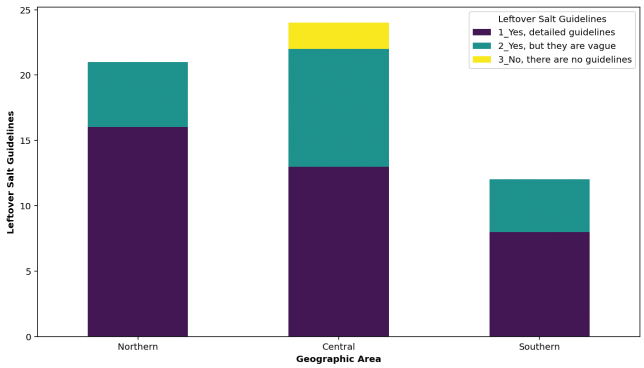

Figure 5.60 Leftover Salt Guidelines, By Region (Frequency).

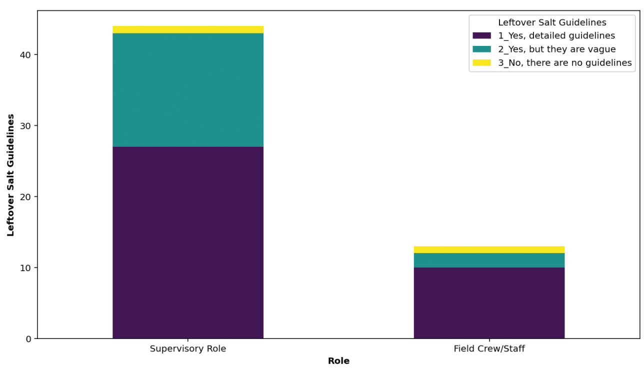

Figure 5.61 Leftover Salt Guidelines, By Role (Frequency).

5.4.5.6 Effectiveness of Guidelines Across Geographic Areas. The survey question regarding the effectiveness of guidelines across geographic areas is as follows:

- In your opinion, how effective are these guidelines in managing residual salts?
  0. No guidelines
  1. Very effective
  2. Effective
  3. Somewhat effective
  4. Not effective

The survey results revealed that 21% of respondents reported the measure as "Very effective," 48% indicated it is "Effective," while 21% stated it is "Somewhat effective." Additionally, 10% of participants reported it as "Not effective."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.62 and Figure 5.63 present self-reported effectiveness of guidelines across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

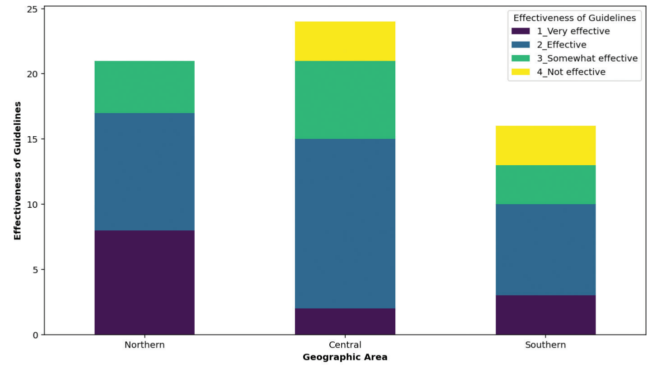

Figure 5.62 Effectiveness of Guidelines, By Region (Frequency).

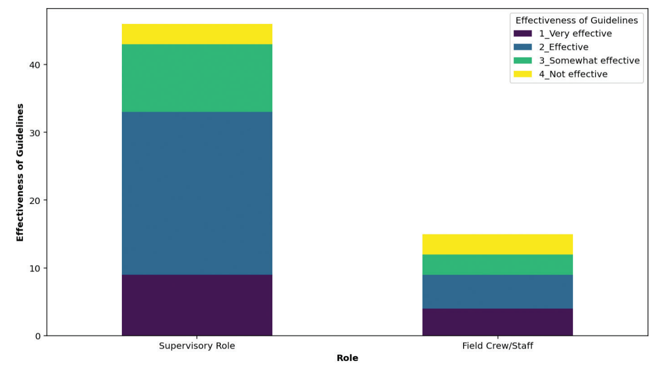

Figure 5.63 Effectiveness of Guidelines, By Region (Frequency).

5.4.6 Balancing Traffic Safety With Corrosion and Environmental Impacts

The survey included questions that examine how INDOT staff weigh the importance of traffic safety against potential corrosion and environmental impacts associated with deicing materials. Two survey questions gauged agreement on whether maintaining safe, passable roads should take priority over preventing infrastructure deterioration and protecting the natural environment. The responses were then analyzed for potential differences across regions and between supervisors and field crew, providing insight into how various roles and locations within INDOT perceive these tradeoffs.

5.4.6.1 Traffic Safety Versus Infrastructure Corrosion. The survey question regarding tradeoff between traffic safety and corrosion is as follows:

- To what extent do you agree with the following statement? The priority of applying deicing materials to maintain road safety and traffic flow should outweigh the potential for corrosive damage to infrastructure, including bridges, roads, vehicles, and underground utilities.
  1. Strongly agree
  2. Agree
  3. Neither
  4. Disagree
  5. Strongly disagree

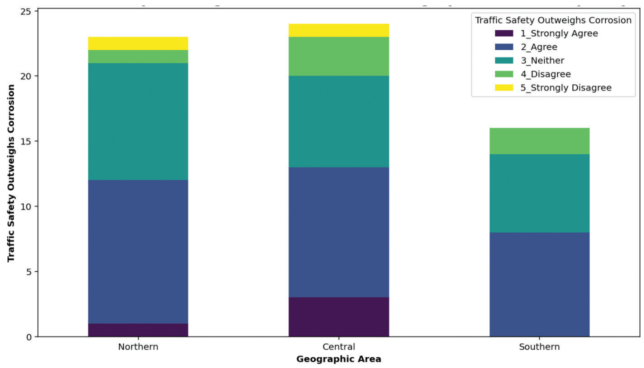

Figure 5.64 Traffic Safety Versus Infrastructure Corrosion, By Region (Frequency).

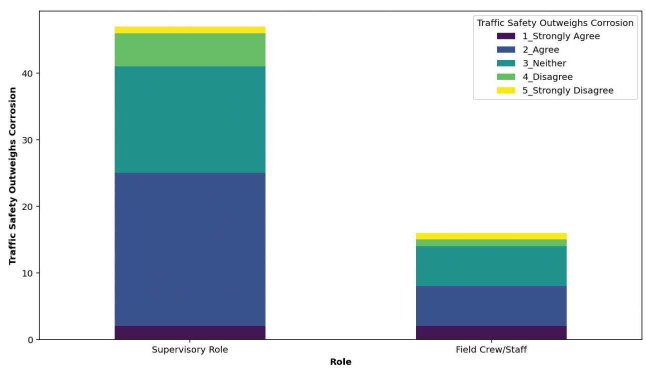

Figure 5.65 Traffic Safety vs. Infrastructure Corrosion, By Role (Frequency).

The survey results revealed that 52% of respondents reported "Strongly agree" or "Agree," 13% indicated "Disagree" or "Strongly disagree," while 35% of respondents selected "Neither."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.64 and Figure 5.65 present self-reported tradeoff between traffic safety and corrosion across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant differences across the three regions and between supervisors and field crew/staff.

5.4.6.2 Traffic Safety Versus Natural Environment. The survey question regarding tradeoff between traffic safety and natural environment is as follows:

- To what extent do you agree with the following statement? The use of anti-/deicing materials on roads is essential for maintaining traffic flow and safety during winter weather events, despite the potential negative impacts on the natural environment.
  1. Strongly agree
  2. Agree
  3. Neither
  4. Disagree
  5. Strongly disagree

The survey results revealed that 60% of respondents reported "Strongly agree" or "Agree," 10% indicated "Disagree" or "Strongly disagree," while 30% of respondents selected "Neither."

A statistical test (Chi-Square test) was conducted to determine whether differences existed in responses based on region or role. Figure 5.66 and Figure 5.67 present the self-reported tradeoff between traffic safety and natural environment across the three regions (Northern, Central, and Southern Indiana) and between the two roles (supervisors and field crew/staff), respectively. The results indicate no significant difference across the three regions.

However, a significant difference was observed between the two roles. Among those in the Supervisory Role, most respondents selected "Agree" (24 responses), followed by "Neither" (ten responses) and "Disagree" (four responses), with smaller counts for "Strongly Agree" (three responses) and none for "Strongly Disagree." Conversely, for the Field Crew/Staff, the responses were more evenly distributed, with "Agree" receiving six responses, "Strongly Agree" receiving five responses, "Neither" receiving three responses, "Disagree" receiving one response, and "Strongly Disagree" receiving one response.

The Chi-Square test results indicate a Chi^2 statistic of 10.21 with a *p*-value of 0.0370 and 4 degrees of freedom. Since the *p*-value is below the conventional significance threshold of 0.05, the test reveals a statistically significant relationship between the respondents' roles and their responses to the question on traffic safety versus natural environments.

5.4.6.2.1 Interpretation of the significant relationship. This indicates that the two roles perceive or prioritize the tradeoff between safety and protecting the natural environment differently. Supervisors were more likely to agree or strongly agree with the statement (with higher counts in the "Agree" and "Strongly Agree" categories), while field crew/staff responses were more evenly distributed across all options, including disagreement and strong disagreement. This difference suggests that supervisors may prioritize safety over natural considerations more consistently, whereas field crew members have more diverse or conflicted views on this tradeoff.

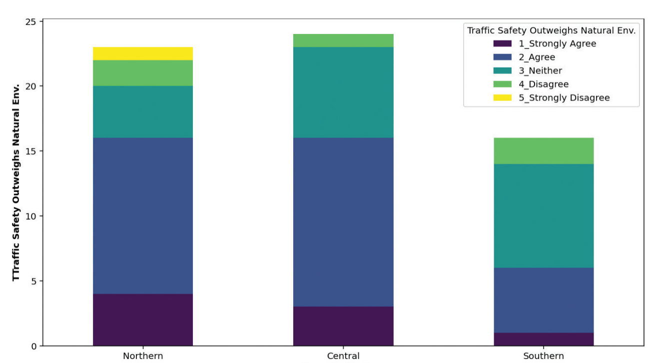

Figure 5.66 Traffic Safety Versus Natural Environment, By Region (Frequency).

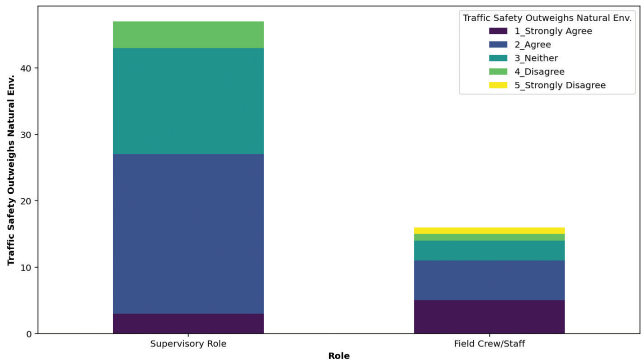

Figure 5.67 Traffic Safety vs. Natural Environment, By Role (Frequency).

5.4.7 Assessment of the Perceptions of Winter Maintenance Practices

The survey questionnaire also included a section on the assessment of the perceptions of winter maintenance guidelines by the staff. The questions were based on the AASHTO's survey on *State of Practice in Winter Maintenance Operations* (AASHTO, 2023). The survey evaluates the implementation of key winter maintenance concepts including sustainable practices, accurate weather forecasting, optimal route planning, equipment reliability, preventative maintenance, operational efficiency, effective communication, comprehensive snow plans, performance standards, and defined service levels. The survey aims to identify gaps in implementation by categorizing responses into fully implemented, partially implemented, being researched, or not implemented. The findings are aimed at helping determine the focus areas and guide the development of tools and strategies to enhance winter maintenance operations.

5.4.7.1 Sustainable Winter Maintenance Practices. The survey question regarding sustainable winter maintenance practices is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Using sustainable winter maintenance practices.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.68) revealed that 62% of respondents reported the measure as "Fully implemented in my area," 24% indicated it is "Partially implemented in my area," while 2% stated it is "Not implemented at all." Additionally, 13% of participants mentioned it is "Being researched."

5.4.7.2 Utilization of Accurate and Timely Weather Forecasts. The survey question regarding weather forecasts is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Utilization of accurate and timely weather forecasts.

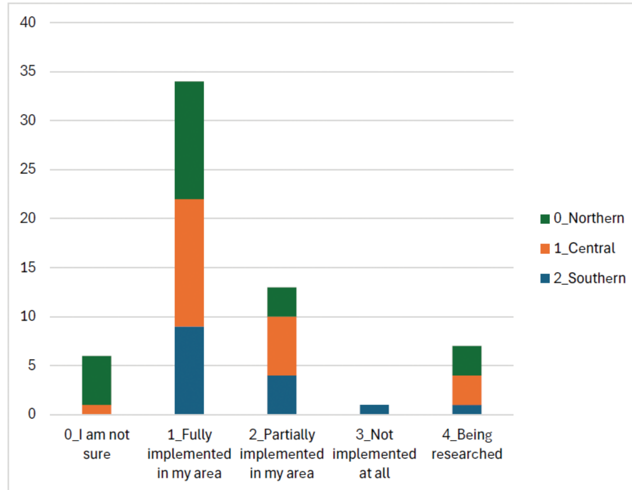

Figure 5.68 Using Sustainable Winter Maintenance Practices (Frequency).

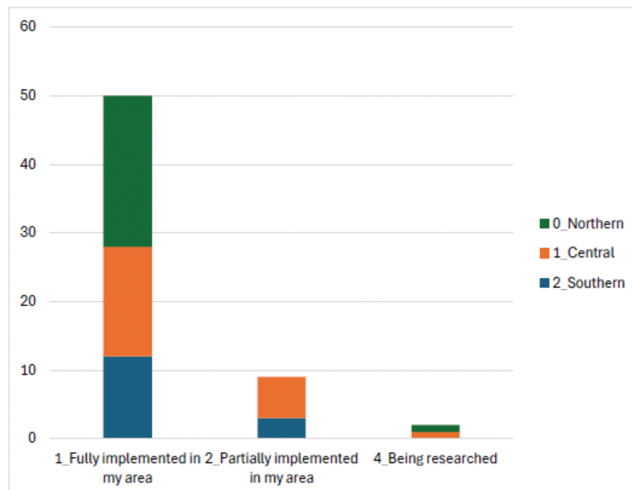

Figure 5.69 Utilization of Accurate and Timely Weather Forecasts (Frequency).

1. Fully implemented in my area
2. Partially implemented in my area
3. Being researched
4. Not implemented at all

The survey results (Figure 5.69) revealed that 82% of respondents reported the measure as "Fully implemented in my area," 15% indicated it is "Partially implemented in my area," while 3% mentioned it is "Being researched."

5.4.7.3 Optimal Route Planning or Route Optimization Programs. The survey question regarding optimal route planning is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Optimal route planning or route optimization programs.
  1. Fully implemented in my area

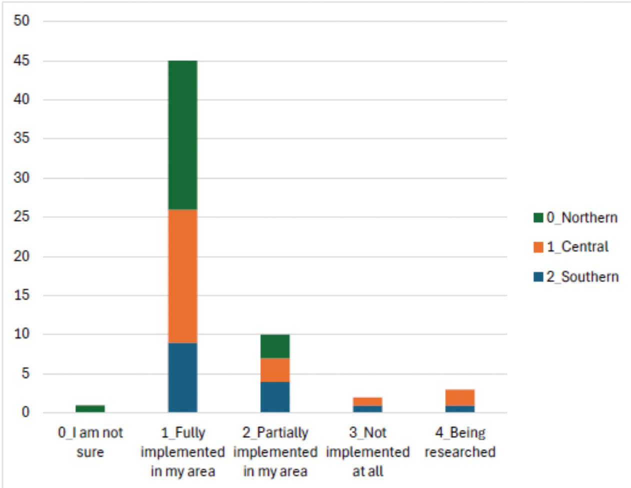

Figure 5.70 Optimal Route Planning or Route Optimization Programs (Frequency).

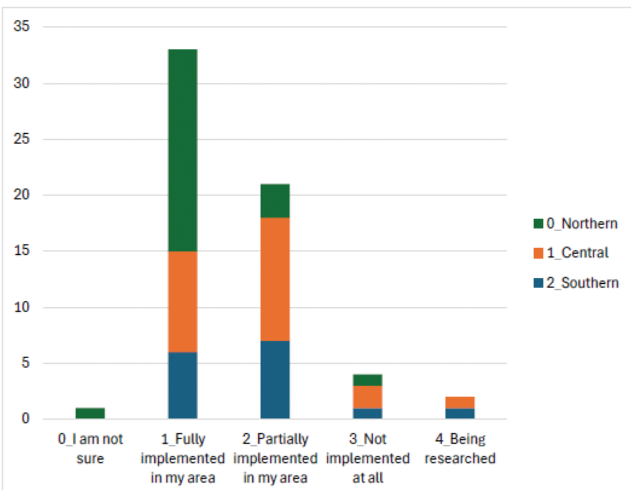

Figure 5.71 Reliable Equipment and Equipment Calibration Programs (Frequency).

2. Partially implemented in my area
3. Being researched
4. Not implemented at all

The survey results (Figure 5.70) revealed that 75% of respondents reported the measure as "Fully implemented in my area," 17% indicated it is "Partially implemented in my area," while 3% stated it is "Not implemented at all." Additionally, 5% of participants mentioned it is "Being researched."

5.4.7.4 Reliable Equipment and Equipment Calibration Programs. The survey question regarding equipment and equipment calibration is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Reliable equipment and equipment calibration programs.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.71) revealed that 55% of respondents reported the measure as "Fully implemented in my area," 35% indicated it is "Partially implemented in my area," while 7% stated it is "Not implemented at all." Additionally, 3% of participants mentioned it is "Being researched."

5.4.7.5 Equipment Maintenance Program (Preventative and Routine). The survey question regarding equipment maintenance program is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Equipment maintenance program (preventative and routine).
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.72) revealed that 66% of respondents reported the measure as "Fully implemented in my area," 28% indicated it is "Partially implemented in my area," while 3% stated it is "Not implemented at all." Additionally, 3% of participants mentioned it is "Being researched."

5.4.7.6 Efficiency in Operations: Intelligent Use of Resources. The survey question regarding efficiency in operations is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Efficiency in operations: intelligent use of resources.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

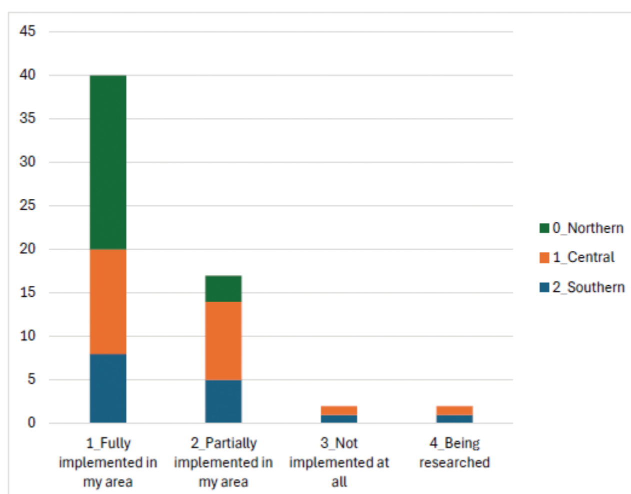

Figure 5.72 Equipment Maintenance Program: Preventative and Routine (Frequency).

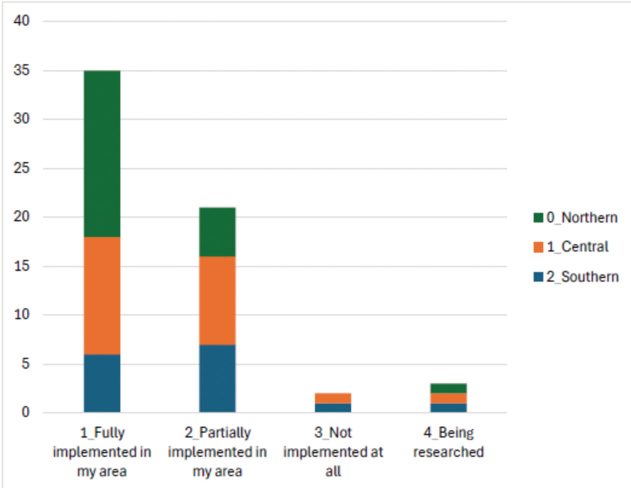

Figure 5.73 Efficiency in Operations: Intelligent Use of Resources (Frequency).

The survey results (Figure 5.73) revealed that 57% of respondents reported the measure as "Fully implemented in my area," 34% indicated it is "Partially implemented in my area," while 3% stated it is "Not implemented at all." Additionally, 5% of participants mentioned it is "Being researched."

5.4.7.7 Communication Between Operation Controllers and Drivers. The survey question regarding communication is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Communication between operation controllers and drivers.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.74) revealed that 80% of respondents reported the measure as "Fully implemented in my area," 13% indicated it is "Partially implemented in my area," while 3% stated it is "Not implemented at all." Additionally, 5% of participants mentioned it is "Being researched."

5.4.7.8 Snow Plans (Include Operational Evaluation/ Continuous Improvement). The survey question regarding snow plans is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Snow plans (Include operational evaluation/continuous improvement).
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.75) revealed that 79% of respondents reported the measure as "Fully implemented in my area," 11% indicated it is "Partially implemented in my area," while

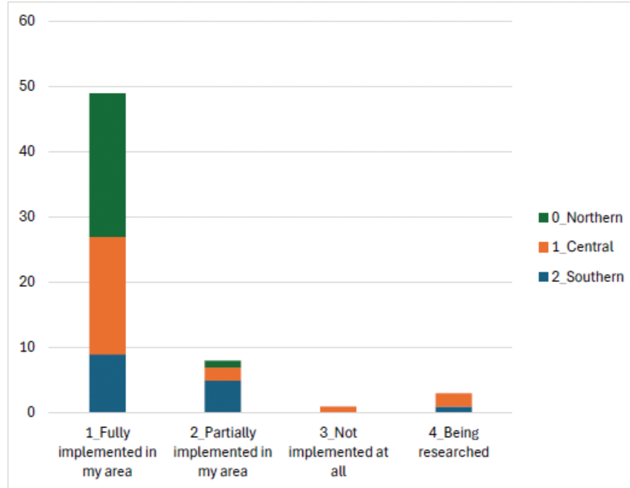

Figure 5.74 Communication Between Operation Controllers and Drivers (Frequency).

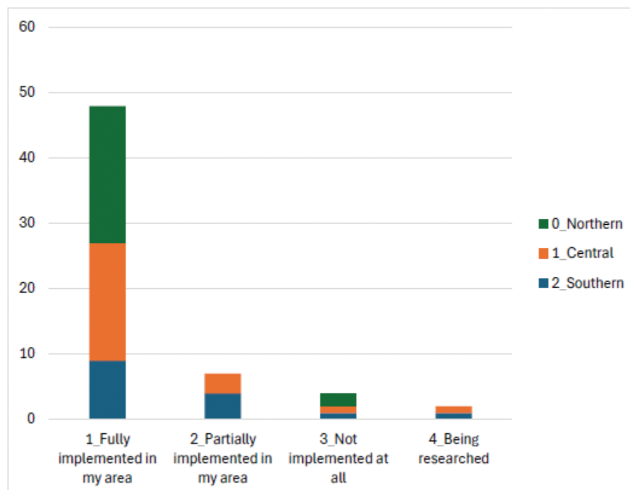

Figure 5.75 Snow Plans: Include Operational Evaluation/ Continuous Improvement (Frequency).

7% stated it is "Not implemented at all." Additionally, 3% of participants mentioned it is "Being researched."

5.4.7.9 Performance Standards for Winter Service. The survey question regarding performance standards is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Performance standards for winter service are in place.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.76) revealed that 73% of respondents reported the measure as "Fully implemented in my area,"

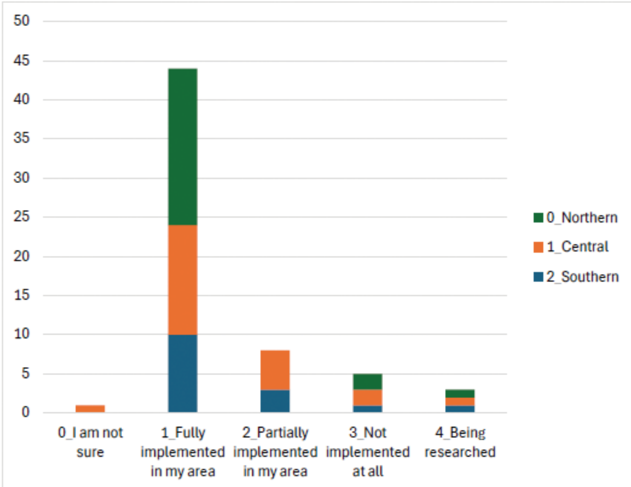

Figure 5.76 Performance Standards for Winter Service Are in Place (Frequency).

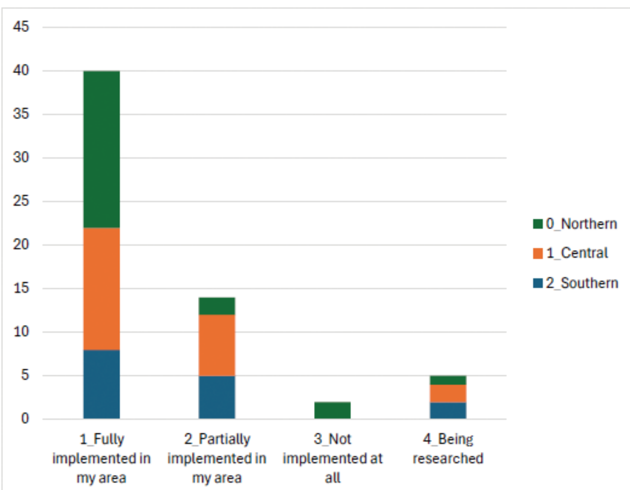

Figure 5.77 Defined Levels of Service (Frequency).

13% indicated it is "Partially implemented in my area," while 8% stated it is "Not implemented at all." Additionally, 5% of participants mentioned it is "Being researched."

5.4.7.10 Defined Levels of Service. The survey question regarding defined levels of service is as follows:

- From your perspective, are you utilizing these concepts in your winter maintenance program? Defined levels of service.
  1. Fully implemented in my area
  2. Partially implemented in my area
  3. Being researched
  4. Not implemented at all

The survey results (Figure 5.77) revealed that 66% of respondents reported the measure as "Fully implemented in my area," 23% indicated it is "Partially implemented in my area," while 5% stated it is "Not implemented at all." Additionally, 8% of participants mentioned it is "Being researched."

5.4.7.11 Summary of the Perceptions on Winter Maintenance (AASHTO). The results of survey questions on the perceptions of winter maintenance practices (based on the AASHTO's survey on *State of Practice in Winter Maintenance Operations*) are summarized in Table 5.2. The results indicate strong implementation of key winter maintenance practices in Indiana as indicated by the respondents, with areas like accurate weather forecasting (82%), communication between controllers and drivers (80%), and snow plans (79%) being widely adopted. However, gaps remain in sustainable winter maintenance practices, where only 61% report full implementation, and reliable equipment calibration programs, with only 55% fully implemented. Additionally, efficiency in operations (57%) and optimal route planning (75%) show room for improvement. While performance standards and defined service levels are in place for most agencies, partial implementation and ongoing research suggest a need for further development. These insights highlight the importance of enhancing sustainability efforts, improving equipment reliability, and optimizing operational efficiency to create a more effective winter maintenance program.

TABLE 5.2
Summary of Findings From Winter Maintenance Practices.

Question	Fully Implemented in My Area	Partially Implemented in My Area	Being Researched	Not Implemented at All	Total
Using sustainable winter maintenance practices	61%	24%	2%	13%	100%
Utilization of accurate and timely weather forecasts	82%	15%	0%	3%	100%
Optimal route planning or route optimization programs	75%	17%	3%	5%	100%
Reliable equipment and equipment calibration programs	55%	35%	7%	3%	100%
Equipment maintenance program: Preventative and routine	66%	28%	3%	3%	100%
Efficiency in operations: Intelligent use of resources	57%	35%	3%	5%	100%
Communication between operation controllers and drivers	80%	13%	2%	5%	100%
Snow plans	79%	11%	7%	3%	100%
Performance standards for winter service are in place	74%	13%	8%	5%	100%
Defined levels of service	66%	23%	3%	8%	100%

6. INDOT INTERVIEWS: PERSPECTIVES ON OPERATIONAL PRACTICES AND IMPACTS

In addition to the survey, this study also carried out interviews with INDOT personnel involved in winter operations to gather insights into the practice. The interview questionnaire was designed in tandem with the survey questionnaire and was meant to serve as a supplement to the survey results. The interview questionnaire and survey were structured similarly and were similar in content. However, the interview questionnaire was designed to allow for a more in-depth discussion of the concepts covered by allowing for follow-up questions and clarifications were necessary. Additionally, interviews were conducted before the survey was conducted. This was so that insights drawn from the interviews could be used to enhance and improve the survey questionnaire. A copy of the interview questionnaire is included in Appendix H.

With the help of INDOT personnel, fifteen supervisors overseeing winter operations units were identified and contacted with a request for an interview. Three responded favorably and two ultimately participated in the interview with the research team. The interview was conducted via video platforms such as Zoom and Microsoft Teams.

Like the survey questionnaire, the interview questionnaire was divided into different sections including the introductory section, decision making for operations, salt management, postevent evaluation and challenges, and relative ranking of various criteria related to winter operations. The introductory questions were meant to establish rapport between the interviewers and the interviewee and asked questions related to the interviewee's name, position, and role to winter operations. The section on decision-making for operations focused on understanding the typical decisions and the process followed when supervising deicing and anti-icing operations in response to a snow event, from start to finish.

The section on salt management sought to understand how INDOT manages salt at the tail end of a snow event. These included questions related to the kind of salts used, the frequency of loading, and the handling of residual salts. Postevent evaluation, challenges, and suggestions section sought to understand the interviewee's thoughts on the postevent evaluation of the winter operations, environmental concerns, common challenges, and suggestions for improvement. The final section of the interview questionnaire asked the interviewee to rank the relative importance of various criteria related to salt and winter operations. The criteria included material cost, availability, residual effectiveness, ease of application, environmental impact, corrosiveness, safety, and melting capacity. The rankings obtained from this section are meant to aid in the development of the multi-criteria analysis and recommendations.

6.1 Key Lessons Learned

The interviews provided several key insights into Indiana's winter road maintenance practices. A primary takeaway was the importance of proactive monitoring and coordination. Effective operations rely heavily on monitoring weather conditions through tools like the MDSS and weather applications, combined with seamless communication among supervisors and operators to guide decisions on timing and material application. Flexibility in operations was also emphasized, as supervisors highlighted the need for dynamic decision-making during storms. Shifting resources and adjusting strategies based on real-time conditions were identified as critical practices for maintaining road safety and ensuring material efficiency. The following excerpts from interviewees highlight the importance of monitoring and coordination.

> *"So, during an event. Communications are done. In several different ways, you know whether it's by phone or by radio or sometimes it's group text messages. Sometimes it's emails, depending on who I'm trying to get this information to."*
>
> *"We have to make sure we're talking to our operators like 'hey, you know, slow your speeds down because if you're driving too fast, then obviously the granular salts just gonna go off to the edge of the road.'"*
>
> *"Yeah. I mean, there are adjustments made all the time for every event."*

Salt management emerged as a well-established practice, with proper storage and handling of residual salt being standard across most units. Covered domes are commonly used to protect materials from weather exposure, and operators frequently employ calibrated application rates and return unused salt to storage facilities for future use. However, challenges in consistency were noted. While some units excel in aligning with best practices, variability in plowing routines, material application rates, and the use of sand were areas identified for improvement. Training programs and the standardization of practices across units could help address these inconsistencies.

Environmental and cost considerations were recurring themes throughout the interviews. Concerns about the environmental impact of salt usage, particularly chloride runoff into water systems, were highlighted. Interviewees also stressed the importance of balancing cost efficiency with operational effectiveness and public safety. These insights collectively underscore the strengths of Indiana's winter operations while identifying areas where improvements could enhance sustainability and consistency.

The interviews with INDOT personnel offered valuable qualitative insights into Indiana's winter road maintenance practices, supplementing the survey data with in-depth perspectives. These findings underscored the strengths and challenges of current practices while highlighting areas for improvement, including enhanced use of technology, operator training, and environmental sustainability measures.

6.1.1 Summary of Interviewee Comments on Decision-Making During Operations

Some of the major comments and insights that interviewees shared about the decision-making process are summarized as follows:

- Effective decision-making in winter operations is crucial for maintaining road safety, minimizing disruptions, and optimizing resource utilization. The decision-making process involves multiple factors, including weather forecasting, resource allocation, real-time adjustments, and interagency coordination. Supervisors rely on multiple weather monitoring tools such as MDSS, National Weather Service updates, and local weather forecasts. These sources provide critical data on storm severity, precipitation type, temperature fluctuations, and wind conditions, influencing pretreatment, deicing, and snow removal strategies.

- Once forecasts indicate an impending weather event, operations meetings are held to develop an action plan. Roads are classified into priority levels: Class 1 (interstates and highways), which receive the highest priority due to traffic volume and safety concerns; Class 2 (US highways and major roads), which have moderate traffic and require secondary priority; and Class 3 (state roads and local routes), which are lower priority but still managed as conditions allow. Personnel and equipment allocation depends on expected snowfall, road priority, and available resources. During minor events, limited crews are deployed, whereas major storms require an all-hands-on-deck approach.
- Winter events are unpredictable, and adjustments are made as conditions evolve. Supervisors monitor road conditions, and if unexpected rainfall washes away pretreatment or wind causes snowdrifts, new strategies are implemented. For example, if a flash freeze is imminent, granular salt may be prewet with magnesium chloride to enhance effectiveness. Another example is when snow accumulation exceeds manageable levels, plowing is prioritized over spreading material to avoid waste.
- Continuous communication occurs via radio, phone, phone, emails, and group text messages among supervisors, field crews, and external agencies. Coordination with State Police, emergency responders, and traffic management centers ensures a unified response, particularly in high-impact scenarios like highway accidents or road closures. After a weather event, teams assess material usage, accident rates, and road conditions to determine operational effectiveness. The success of the response is often measured by accident rates and public safety rather than rigid metrics. Supervisors also review equipment performance, crew efficiency, and material application rates to improve future responses.
- The main challenges in decision making include equipment failures, particularly electronic and hydraulic issues caused by salt exposure, balancing environmental concerns with effective deicing strategies, and ensuring adequate salt reserves while avoiding unnecessary stockpiling. Continuous training for operators, leveraging new technologies, and optimizing material use is crucial for improving winter operations.

6.1.2 Summary of Interviewee Comments on Salt Management and Application

The interviewees shared several comments and insights about salt management and application. These comments are summarized as the following:

- Salt management is a critical aspect of winter road maintenance, ensuring both effective deicing and environmental sustainability. Proper handling, storage, and application of salt play a vital role in maintaining road safety while minimizing waste and environmental impact. To ensure a consistent supply throughout the winter, salt is stockpiled in salt domes or barns, protecting it from weather exposure. It is replenished year-round, with agencies maintaining contracts to secure stock before the winter season begins. In cases of surplus, redistribution between districts is practiced, balancing inventory levels. Proper storage prevents leaching, which can lead to environmental contamination. After snow events, any unused salt in trucks is returned to storage facilities, preventing unnecessary waste. Salt brine, used for pretreatment, is stored separately and applied strategically based on weather conditions. The following response touches on these points: "So that in the event, if our trucks still have salt on them, they're supposed to come back and unload into our salt barns or our salt buildings."
- Salt is applied according to real-time weather conditions and the specific needs of the roadway. Supervisors adjust application rates depending on factors such as snow intensity, where heavier snowfall may require plowing before applying salt, and temperature, as traditional rock salt (sodium chloride) is effective down to 15 °F, while magnesium or chloride blends are used for colder conditions. Wind conditions also play a role since high winds can blow salt off roads, reducing its effectiveness. Pretreatment with salt brine, typically a 23.3% sodium chloride solution, is commonly used before snowfall to prevent ice from bonding to the pavement. Blended solutions, such as salt brine mixed with calcium chloride or organic additives, enhance performance in extreme cold.
- Excessive salt use can increase corrosion on vehicles and infrastructure while also contaminating waterways. Agencies follow best practices to mitigate these effects by calibrating trucks to ensure precise salt distribution, using live updates from the MDSS to optimize application rates, and reducing reliance on abrasives like sand, which can clog drainage systems. After a storm, material use is assessed to determine efficiency and reduce excess usage in future events. Salt management improvements focus on operator training, enhanced storage utilization, and new technologies like automated spreaders and GPS-controlled brine application systems. Efficient salt management ensures safe roads, reduces costs, and minimizes environmental impact, making it a crucial component of winter operations.

6.1.3 Summary of Interviewee Comments on Postevent Evaluation, Challenges, and Suggestions

The following major points were raised by the interviewees regarding postevent evaluation, challenges and suggestions for improvement:

- Postevent evaluation is an essential step in winter road operations, allowing agencies to assess effectiveness, optimize resource usage, and identify areas for improvement. After a snow or ice event, supervisors analyze factors such as material consumption, road conditions, accident rates, and equipment performance to refine future strategies. The effectiveness of a snow event response is often measured by several key indicators. Road conditions and pass-ability are assessed to ensure roads are cleared efficiently and remain safe for motorists. Accident rates serve as a primary measure of operational success, as a reduction in incidents suggests proper material application and timely interventions. Salt and material usage are evaluated by comparing actual usage with expected amounts to prevent over-application and unnecessary costs. Equipment performance is reviewed to identify breakdowns or failures in plows, spreaders, and electronic systems, allowing for improved maintenance schedules. Additionally, environmental impact is considered by examining the effectiveness of salt application in minimizing runoff and infrastructure corrosion.

- Several challenges impact decision-making and overall efficiency during and after an event. Unpredictable weather conditions, such as sudden temperature shifts, unexpected precipitation, and wind, can change treatment needs midevent. Equipment failures are common due to salt exposure, which leads to corrosion and frequent mechanical issues in plows and spreaders. For example, the following excerpt from the interview transcription highlights these equipment issues: "Let's say a truck may have electronic issues or the tanker that we use or the system that communicates from the truck in the tankers having electronic issues, that's probably our most common issue to deal with throughout the winter."
- Limited personnel and resources pose another challenge, as ensuring adequate staffing and equipment availability, particularly during major storms, remains difficult. This concern is highlighted in the following excerpt:

  > *"I just want us to continue to do it and maybe do it better and it's just educating our operators because we use, we've used all kinds of people when it comes to winter OPS, we're not just using our unit personnel. We're using people that are under construction that don't typically even sit inside of a truck and you know every winner. We do snow school training, and we go over all the different things with the equipment that they're gonna be using and the material that they're gonna be using. And as long as we can continue to really try to educate our operators about our equipment. That's gonna do nothing but help us send. And then once they get a little experience, hopefully, you know, we get the results that we need."*

- Overuse or underuse of materials must also be managed, as determining the optimal amount of salt, brine, or abrasives is crucial to avoiding environmental harm or inefficiency. Additionally, traffic management requires coordination with law enforcement and emergency responders to handle road closures and incidents effectively.
- To enhance future winter operations, agencies can implement several strategies. Advanced technology integration, such as GPS-based salt application systems, live road condition monitoring, and automated brine spreaders, allows for precision treatment. Enhanced operator training ensures that crews understand optimal material application rates and best practices to reduce waste. Improved equipment maintenance, including regular service of trucks, spreaders, and plows, helps prevent failures during critical operations. Data-driven decision making is another essential practice, as leveraging postevent data refines response strategies, minimizes costs, and improves road safety. The following comment highlights INDOT's need and appreciations for advanced technologies in winter operations:

  > *"I would say probably the newest thing that I've experienced hands on, and I think Purdue played a role in it as well, is we have a semi tanker that has a salt brine that has a GPS on it, and it can, you know, turn itself on and off depending on what you're doing, and calculate how much material you're putting down and things like that. So, I have that based out of my unit. So that's a kind of cool thing that we have. . ."*

- Environmental considerations should also be considered, including reducing chloride dependency by incorporating blended deicing materials and monitoring runoff impact. By continuously refining postevent evaluation methods and addressing operational challenges, agencies can increase efficiency, enhance safety, and reduce environmental impact in winter road management.

6.1.4 Summary of Interviewee Comments on the Relative Importance of Different Criteria for Selecting Deicing Materials

During the interviews, interviewees were asked about their thoughts regarding the relative importance of various criteria when selecting deicing materials. Interviewee comments can be summarized as follows:

- Selecting the most effective deicing material involves balancing several critical factors, each influencing the efficiency, cost, and environmental impact of winter road operations. Among these criteria, safety is the most important, as the primary goal of deicing is to ensure roads remain passable and reduce accident risks. Materials must effectively prevent ice bonding and maintain traction to protect motorists and pedestrians. Melting capacity is another crucial factor, as a material's ability to lower the freezing point of water determines its effectiveness in different temperature conditions. Sodium chloride is widely used but loses efficiency below 15 °F, requiring alternative materials such as calcium chloride or magnesium chloride for extreme cold.
- Availability also plays a key role in decision-making, as materials need to be readily accessible to maintain continuous winter operations. Common deicers like rock salt are preferred due to their widespread availability, while specialized alternatives may be used selectively based on supply chain constraints. Residual effectiveness is another consideration, as materials that remain active longer reduce the need for frequent reapplication, conserving resources and labor. However, ease of application must also be factored in, as certain materials require prewetting, blending, or specific application techniques, impacting operational efficiency.
- While performance-driven criteria are prioritized, environmental impact is increasingly influencing material selection. High chloride concentrations can contaminate water bodies, degrade vegetation, and accelerate infrastructure corrosion. Blends incorporating agricultural by-products or corrosion inhibitors help mitigate these effects while maintaining deicing efficiency. Corrosiveness is particularly relevant for protecting bridges, vehicles, and roadways from damage, with some agencies opting for treated salts to minimize infrastructure deterioration. Cost, while an important factor, is generally considered secondary to safety and effectiveness, as ensuring public safety and mobility outweighs financial savings. However, optimizing material use through data-driven decision making and technological advancements helps balance cost-effectiveness with performance.
- Ultimately, the selection of deicing materials requires a holistic approach, where safety, effectiveness, and sustainability are carefully weighed. Agencies must adapt their strategies based on weather conditions, road priorities, and resource availability, ensuring optimal winter road maintenance while minimizing negative environmental and economic impacts.

7. SYNTHESIS AND FINAL SUMMARY

7.1 Deicing Materials: Summary of Findings

7.1.1 Introduction

The use of deicing materials is essential for winter highway management, ensuring safety and mobility during adverse weather conditions. Across the United States, a variety of materials are used, each with distinct properties, advantages, and limitations. The selection of deicers depends on factors such as cost, effectiveness at low temperatures, environmental impact, and infrastructure considerations.

Sodium chloride remains the most widely used deicer due to its affordability and effectiveness above 15 °F. It is available in various forms, including dry salt and brine solutions, with prewetted applications improving performance. However, sodium chloride is highly corrosive and loses efficiency at lower temperatures, necessitating alternatives for extreme winter conditions. calcium chloride and magnesium chloride perform better in colder conditions, with calcium chloride effective down to −20 °F and magnesium chloride to −10 °F. Both attract moisture, accelerating the melting process, though they present concerns related to cost and infrastructure corrosion.

Acetates, such as CMA and potassium acetate, provide environmentally friendly, noncorrosive alternatives suitable for sensitive areas like airports and steel infrastructure. However, their high cost and limited availability restrict widespread adoption. Blends and abrasives, such as sand-salt mixtures, enhance traction in extreme cold where chemical deicers become ineffective, though they require extensive cleanup and may pose environmental concerns. Enhanced brines, fortified with calcium chloride or magnesium chloride, improve deicing performance while reducing scatter loss but still pose chloride-related environmental risks. Innovative solutions, such as agricultural by-products (e.g., beet juice additives), improve deicing efficiency while minimizing environmental impact. These materials enhance adhesion, reducing material runoff and salt usage. However, their cost and regional availability present challenges to widespread adoption.

In conclusion, the effectiveness of deicing materials varies based on temperature, environmental considerations, and economic factors. While sodium chloride remains dominant, states increasingly adopt blended and alternative materials to mitigate its limitations. The balance between performance, cost, and sustainability continues to drive advancements in winter road maintenance, ensuring safer and more efficient transportation systems during winter conditions.

7.1.2 Tools for Winter Road Maintenance

Effective winter road maintenance relies on a diverse set of tools designed to manage snow and ice accumulation, improve roadway safety, and optimize resource usage. These tools enhance operational efficiency and minimize environmental impacts while ensuring road accessibility during severe weather conditions. Snowplows, including front-mounted, underbody, and wing plows, serve as the primary tool for clearing snow, with wing plows increasing clearing width and tow plows enabling a single truck to clear multiple lanes. Snow blowers are deployed in areas with heavy snowfall where plows alone are insufficient. Deicing and anti-icing tools include prewetting systems that mix liquid deicers with solid materials for improved adherence, slurry generators that create supersaturated salt solutions for quick activation, and brine makers that prepare salt brine solutions for anti-icing applications. Abrasive spreaders are used in extreme cold to enhance traction when chemical deicers are less effective.

Advanced technology and monitoring tools such as RWIS collect real-time pavement and atmospheric data, while AVL systems track plow trucks and optimize resource deployment. MDSS integrate AI-driven weather forecasting and road condition data to recommend optimal treatments, complemented by temperature sensors and ESSs that monitor crucial weather factors. Safety and visibility tools include plow truck lighting systems with high-visibility LED and blue lights to reduce collision risks, HFST for improved traction in high-risk areas, and Dynamic Message Signs alongside Traveler Information Systems to keep motorists informed about road conditions and maintenance operations. These tools, combined with state-specific strategies and advanced data analytics, form the backbone of effective winter road maintenance, ensuring safety and efficiency while minimizing environmental impacts.

7.1.3 Impact Assessment of Deicing Materials

Deicing materials impact the environment and infrastructure differently. Chloride-based deicers (sodium chloride, calcium chloride, magnesium chloride) are widely used but contribute to water contamination, soil degradation, and corrosion. Alternative deicers like CMA and potassium acetate are less corrosive but costly and can harm aquatic ecosystems. Sand and abrasives improve traction but cause sediment accumulation and require cleanup. Agricultural by-products help reduce chloride usage but may still pose corrosion risks. In Indiana, sodium chloride is the primary deicer due to cost and availability, with calcium chloride and magnesium chloride used regionally. Beet juice additives help mitigate corrosion while maintaining deicing effectiveness. Balancing cost, effectiveness, and environmental impact is key to sustainable winter road maintenance.

7.1.4 MCDA on Deicing Material Choice

This section addresses the selection of deicing/anti-icing materials for Indiana using a MCDA that incorporates both quantitative and qualitative data. Although the technical details of the MCDA method are not the main focus, the analysis relies on feedback from INDOT personnel, as well as a synthesis of literature and reported best practices. Four commonly used materials, sodium chloride, calcium chloride, magnesium chloride, and acetates, were evaluated alongside abrasives (e.g., sand). The goal was to determine which of these alternatives best meets the specific needs and constraints identified by INDOT, given the importance of factors such as material cost, availability, safety, environmental impact, and other considerations.

An initial survey elicited from INDOT staff the relative importance of eight criteria: availability, safety, melting capacity, cost, environmental impact, residual effectiveness, corrosiveness, and ease of application. The responses were analyzed using the Rank Order Centroid (ROC) approach, which reflects the weighting of each criterion based on how respondents ranked the importance of these different concerns. Table 7.1 summarizes the resulting weights. Higher values signify criteria considered more influential in the selection process. Availability, safety, and melting capacity received some of the highest

TABLE 7.1
ROC Weighting of the Multicriteria.

Order of Relative Importance	Criterion	ROC Weight
1	Availability (Consistency of supply and ease of procurement)	0.339732
2	Safety (Impact on traction and road condition for drivers)	0.214732
3	Melting Capacity (Ability of material to melt ice at different temps.)	0.152232
4	Cost (Direct cost of material)	0.110565
5	Environmental Impact (Impact on water quality and aquatic life)	0.079315
6	Residual Effectiveness (Duration of effectiveness after application)	0.054315
7	Corrosiveness (Potential for causing damage to infrastructure)	0.033482
8	Ease of Application (Simplicity and speed for applying the material)	0.015625

weights, underscoring the significance of ensuring a steady supply, maintaining safe driving conditions, and achieving reliable ice-melting performance.

To gauge performance across these criteria, each material was assessed using data from multiple sources, including transportation research reports, state department guidelines, and previous deicing studies. Table 7.2 details the raw measurements drawn from these sources. For example, melting capacity is listed as the temperature down to which each material remains effective; sodium chloride is generally effective to about 15 °F, while calcium chloride can function at temperatures as low as −20 °F. Likewise, cost is reported in approximate dollars per 100 gal, revealing variations that may influence decisions where budget constraints are critical. Environmental impacts on water and soil health, based on documented ecological effects of each chemical, were also noted because unintended harm to roadside vegetation and aquatic ecosystems has become a growing concern in winter operations.

Since the raw measurements in Table 7.2 differ in scales and units (some reflect temperature, others reflect cost in dollars, still others rely on user-perceived scales), these values were normalized into a consistent ordinal scale (0–1), as presented in Table 7.3. This conversion allows direct comparisons among the various materials. The 0–1 scale is divided into five tiers: very low (0), low (0.25), medium (0.50), high (0.75), and very high (1.00). Thus, a material rated "high" or "very high" on safety or ease of application clearly outperforms one rated "low" or "very low," even if the original measures were expressed in different ways. These standardized ratings highlight how certain materials, such as acetates, stand out in areas like residual effectiveness and non-corrosiveness, while lagging in cost efficiency.

Applying the previously determined weights from Table 7.1 to the standardized ordinal data in Table 7.3 produces an aggregated performance score for each material. Table 7.4 illustrates these final scores and ranks. Notably, sodium chloride emerges at the top, reflecting strong performance in several areas that were weighted highly by INDOT staff (availability, cost efficiency, and sufficient safety measures). Calcium chloride and magnesium chloride are tied for second, partly due to their outstanding melting capacity at lower temperatures, which is an appealing feature in extremely cold conditions, even though their higher cost and moderate availability somewhat diminish their overall advantage. Abrasives rank fourth; although they do not directly melt snow and ice, their lower cost and favorable availability keep them competitive for certain use cases. Acetates, in spite of being more environmentally benign and very effective at lower temperatures, rank last overall due to cost and supply constraints which reduce their practicality within the scope of INDOT operations.

TABLE 7.2
Multiciteria Measurements of Deicing Materials.

Material	Availability[1]	Safety[2]	Melting Capacity[3]	Cost[4]	Env. Impact to Water[5]	Env. Impact to Soil[6]	Residual Effectiveness[7]	Corrosiveness[8]	Ease of Application[9]
NaCl	more available	4.3	15 °F	~$21	med.	med./ high	average effectiveness	3.8	4.3
$CaCl_2$	available	3.7	−20 °F	~$140	med.	low/ med.	> NaCl	3.4	3.1
$MgCl_2$	available	3.8	−10 °F	~$100	med.	low/ med.	> NaCl	3.3	3.2
Acetates	less available	3.8	−15 °F	> NaCl, $CaCl_2$, $MgCl_2$	high	low/ med.	> $CaCl_2$, $MgCl_2$	1	4
Abrasives	more available	2.3	do not melt snow	~$4 to $8	high	low	limited effectiveness	1	4.0

[1] Availability means consistency of supply and ease of procurement. The ratings shown are ordinal and based on Clear Roads (2019).
[2] Safety means impact on traction and road condition for drivers. The ratings are based on the average of a user-perceived ranking of deicer advantages, with 1 being the least advantageous and 5 being the most (Colorado Department of Transportation [CDOT], 2009, p. 144).
[3] Melting capacity means the ability of the materials to melt ice at various temperatures. The ratings shown are the lowest temperatures of different materials' melting capacity (MnDOT, 2022, p. 20).
[4] Cost means the cost of material (in USD) per 100 gal. The ratings are based on SDDOT (2024, p. 20) and Clear Roads (2019, pp. 13, 15–16).
[5] This criterion represents the materials' environmental impact on water quality and aquatic life. The ratings are based on (Casey et al., 2014, p. 62,).
[6] This criterion represents the materials' environmental impact on soil health. The ratings are based on (Casey et al., 2014, p. 62,).
[7] Residual effectiveness means how long the material remains effective after application. The ordinal ratings shown are based on Clear Roads (2019).
[8] This criterion represents the materials' potential for causing corrosive damage to metal structures. The ratings are based on the average of a user-perceived assessment, with 1 being the least impact and 5 being the greatest impact. (CDOT, 2009, p. 155,).
[9] Ease of application means the level of simplicity and speed for applying the material. The ratings are based on the average of a user-perceived ranking of deicer advantages, with 1 being the least advantageous and 5 being the most (CDOT, 2009, p. 144,).

TABLE 7.3
Conversion of the Multicriteria Measurements to an Ordinal 0–1 Scale.

Material	Availability	Safety	Melting Capacity	Cost Efficiency[1]	Environmental Friendliness[2] (Water)	Environmental Friendliness[2] (Soil)	Residual Effectiveness	Noncorrosiveness[3]	Ease of Application
NaCl	high	high	med.	high	med.	low	med.	low	high
$CaCl_2$	med.	high	very high	low	med.	med.	high	med.	med.
$MgCl_2$	med.	high	very high	low	med.	med.	high	med.	med.
Acetates	low	high	very high	very low	low	med.	very high	high	high
Abrasives	high	low	low	very high	low	high	low	high	high

[1] Cost efficiency signifies relative cost savings based on the cost of materials (in USD) per 100 gal, with very high (1.0) being the lowest cost and very low (0) being the most expensive.
[2] Environmental friendliness has two components: the levels of benign impact on water quality/aquatic life and soil health, respectively. Very high (1.0) means the lowest impact and very low (0) means the most impactful.
[3] Non-corrosiveness is the opposite of corrosiveness, with very high (1.0) being the least corrosive damage to the metal structures and very low (0) being the least corrosive damage.

TABLE 7.4
Overall Scores and Rankings Based on the MCDA.

Material	Aggregated Score	Rank
NaCl	0.651878	1
$CaCl_2$	0.615736	2
$MgCl_2$	0.615736	2
Acetates	0.519102	5
Abrasives	0.547172	4

These findings suggest that, under most typical conditions in Indiana, sodium chloride remains the recommended material for deicing. Its reliable availability, generally acceptable safety profile, and relatively low cost help it outperform other alternatives once INDOT's priorities are factored in. However, localized conditions, such as severe cold spells, environmental sensitivities, or special roadway segments, may still justify the use of calcium chloride, magnesium chloride, or acetates in niche applications. Likewise, abrasives can be valuable when traction is the primary concern or in remote areas where chemical supplies may be limited.

7.1.5 Recommendations for Deicing Material Choice in Indiana

Based on the survey results, MCDA, and performance rankings, the following recommendations are proposed for deicing material selection.

7.1.5.1 Primary Deicing Material

7.1.5.1.1 Continue the use of sodium chloride as the primary deicing agent. Sodium chloride remains the most widely used deicer due to its high availability, affordability, and adequate melting capacity at temperatures above 15 °F. Therefore, it is recommended to use sodium chloride as the standard deicing material for most conditions, especially where cost is a significant factor. It outperforms alternatives in terms of availability, cost efficiency, and ease of application.

7.1.5.2 Secondary and Niche Deicing Materials

7.1.5.2.1 Deploy calcium chloride and magnesium chloride in extremely cold conditions. Both calcium chloride and magnesium chloride are more effective than sodium chloride at lower temperatures, with calcium chloride functioning down to −20 °F and magnesium chloride down to −10 °F. Therefore, it is recommended to use calcium chloride and magnesium chloride in extreme cold conditions to improve deicing performance. However, their higher cost and moderate availability should be taken into consideration.

7.1.5.2.2 Limit the use of acetates due to high costs and limited availability. Acetates, such as CMA and potassium acetate, offer environmentally friendly benefits, particularly in reducing corrosion and minimizing environmental impact. However, their high costs and limited availability make them less practical for widespread use. Therefore, it is recommended to use acetates selectively in high-priority areas, such as sensitive locations like airports, steel infrastructure, and water-sensitive areas. Their noncorrosive properties should be prioritized, but usage should be limited due to cost and supply constraints.

7.1.5.2.3 Use abrasives for traction in low-temperature conditions. Abrasives such as sand provide immediate traction in low temperatures where chemical deicers are less effective. However, they do not melt ice and snow, and their cleanup requirements can be significant. Therefore, it is recommended to apply abrasives in areas where traction is the primary concern, such as intersections and steep grades, or when chemical deicing materials are unavailable. They are especially useful when cost is a concern, and salt-based materials may not be viable due to temperature limitations.

7.1.5.3 Environmental Considerations

7.1.5.3.1 Minimize Environmental Impact Through Targeted Deicer Application. While deicing chemicals like sodium chloride, calcium chloride, and magnesium chloride are effective, they pose environmental risks, particularly to water quality, vegetation, and infrastructure. Therefore, it is recommended to adopt optimized application strategies to reduce environmental damage. Using prewetting techniques can improve efficiency and minimize scatter loss, while incorporating blended materials can help balance performance and environmental impact.

7.1.5.4 Cost Considerations

7.1.5.4.1 Prioritize cost-effective deicing materials for routine use. Sodium chloride remains the most cost-effective option, while alternatives such as calcium chloride and magnesium chloride can be considerably more expensive. Therefore, it is recommended to continue relying on sodium chloride as the default material for routine applications due to its low cost and wide availability. More expensive materials should be reserved for situations requiring specialized performance, such as extreme cold or environmentally sensitive areas.

In Indiana, sodium chloride remains the recommended primary deicing material for its balance of availability, cost effectiveness, and adequate performance. However, calcium chloride and magnesium chloride are valuable for extreme cold conditions, while acetates should be reserved for high-priority sensitive locations. Abrasives can be beneficial for traction, and targeted strategies should be adopted to minimize environmental impact while maintaining cost-effectiveness.

7.2 Deicing Operations: Summary of Findings

The examination of winter maintenance practices across six states—Michigan, Idaho, Wisconsin, Minnesota, Alaska, and South Dakota—reveals several consistent strategies that contribute to effective deicing operations. These states, representing diverse winter climates and maintenance challenges, have developed comprehensive approaches that balance safety, cost efficiency, and environmental protection.

7.2.1 Key Common Practices

The study of a few states regarding deicing operations shows that all six states prioritized proactive winter preparation, including equipment calibration, route planning, and staff training. To improve efficiency, Michigan and South Dakota focus on snow trap management and snow fences. Anti-icing is the preferred strategy, using chemicals before storms to prevent ice bonding, reduce deicing needs, and enhance safety. States use advanced material application methods, such as prewetting salt with brine and employing liquid deicers, to improve efficiency and reduce waste. Tailored material selection optimizes performance and minimizes environmental impact. Slurry applications also help reduce salt usage and improve cost efficiency.

Environmental stewardship is prioritized with controlled material storage and application rates to minimize chloride runoff and protect ecosystems. South Dakota tests sustainable alternatives, like agricultural by-products, to reduce reliance on traditional deicers. Technology integration, such as RWIS, GPS tracking, and MDSS, enhances operational efficiency and resource allocation. Postevent evaluations track performance, material use, and equipment maintenance to improve future strategies and minimize environmental impact.

The most successful winter maintenance programs share several fundamental elements: they are proactive rather than reactive, they leverage technology for precision and efficiency, they prioritize environmental protection alongside road safety, and they continuously evaluate and improve their practices. The findings demonstrate that effective deicing operations require a balanced approach that considers the unique climatic challenges of each region while adhering to core best practices. By implementing these strategies, transportation agencies can maintain safe roadways during winter conditions while optimizing resource use and minimizing environmental impacts.

7.2.2 Application Rates for Deicing Materials

The effective management of winter road conditions relies heavily on the appropriate application rates of various deicing materials. Different states have developed specific guidelines based on their climate conditions, environmental concerns, and cost considerations.

The effectiveness of deicing materials depends on proper application techniques and regional conditions. Sodium chloride is widely used, with application rates varying by state—Idaho applies about 130 lb per lane mile, while Midwest states use 600–1,500 lb. Prewetted salt enhances efficiency, reducing overall material use. Calcium chloride, applied in lower quantities due to its higher efficacy, is recommended at 80–120 lb per lane mile, with lower rates for temperatures below 0 °F. Magnesium chloride is applied at rates between 60–300 lb per lane mile, with liquid applications of 15–25 gal per lane mile for anti-icing. Acetates, such as CMA and potassium acetate, are lesser corrosive alternatives but are more expensive. CMA is applied at 90–120 lb per lane mile, while potassium acetate is used in liquid form at 30–50 gal per lane mile, particularly for high-priority areas like bridges.

7.2.3 Analysis of Winter Maintenance Expenditures

The analysis of winter maintenance operations across multiple states reveals significant variations in expenditures relative to winter severity as measured by the AWSSI. States with higher AWSSI values generally allocate more resources to winter maintenance. For example, Minnesota (AWSSI: 1,646) spent $173.9 million, while Indiana (AWSSI: 290) spent $35.7 million during the 2022–2023 season. When comparing expenditure efficiency, Indiana demonstrates moderate cost-effectiveness at approximately $123,200 per AWSSI point, positioning it between highly efficient states like Minnesota ($105,668 per AWSSI point) and less efficient states like Kentucky ($386,000 per AWSSI point).

7.2.4 Material Usage Patterns

7.2.4.1 Solid Salt (Sodium Chloride) Application. Indiana applies 6.21 tons of sodium chloride per lane mile, which is moderate compared to neighboring states. This is higher than Pennsylvania (4.68 tons/mi) but significantly lower than Michigan (14.6 tons/mi) and Wisconsin (13.94 tons/mi), which experience more severe winters.

7.2.4.2 Liquid Materials. Indiana's sodium chloride brine usage (104.67 gal/mi) is moderate compared to regional neighbors. This is higher than Illinois (41.11 gal/mi) but substantially lower than Iowa (1,288.54 gal/mi) and Nebraska (703.53 gal/mi).

7.2.4.3 Alternative Materials. Unlike some neighboring states, Indiana does not incorporate potassium acetate, enhanced brine, agricultural products, or blended materials in its winter maintenance strategy. This contrasts with states like Illinois, which uses 625,259 gal of enhanced brine and 183,120 gal of agricultural products.

7.2.4.4 Cost Analysis. Indiana's average salt cost ($74.14/ton) is relatively economical compared to many states, below Illinois ($85.91) and Kentucky ($98.72) but slightly higher than Ohio ($60.20) and Michigan ($61.41). The state's total winter maintenance expenditure breaks down to $4,125,549 for labor, $17,087,999 for equipment, and $14,512,680 for materials. At $1,197.90 per lane mile, Indiana's cost is lower than Illinois ($1,750.19) and Ohio ($1,765.15), suggesting efficient resource allocation.

7.2.4.5 Infrastructure and Operations. Indiana maintains 120 salt facilities and 96 liquid facilities, with storage capacities of 423,952 tons of salt and 1,825,800 gal of liquid. While this is fewer facilities than some neighboring states, Indiana's liquid capacity exceeds many comparable states. Notably, Indiana conducts 100% of its winter maintenance operations in-house, similar to Iowa, Kansas, and Pennsylvania, providing centralized control and consistency in maintenance quality.

7.2.4.6 Historical Trends. From 2014–2015 to 2022–2023, Indiana's material usage and expenditures have fluctuated with winter severity. Rock salt usage peaked at 321,834 tons in 2020-21 (AWSSI: 440), while the highest expenditure ($41.8 million) occurred that same season. Storage capacity has increased steadily over this period, with salt capacity growing from 382,000 tons to 423,952 tons and liquid capacity expanding from 1,400,000 gal to 1,825,800 gal, indicating enhanced preparedness for winter conditions. Overall, Indiana demonstrates a balanced approach to winter maintenance, achieving moderate costs while maintaining effective operations through strategic resource allocation and operational efficiency.

7.2.5 Deicing Practices in Indiana

Based on a comprehensive survey of winter maintenance practices in Indiana, several key findings emerge regarding deicing operations, application techniques, and environmental awareness.

7.2.5.1 Current Deicing Practices. The survey of winter maintenance personnel identified five "good practices" widely implemented:

1. Driving at reduced speeds when applying dry materials (89% compliance)
2. Plowing prior to material application (64% compliance)
3. Reducing application rates in high traffic areas (52% compliance)
4. Avoiding dry salt at low temperatures (75% compliance)
5. Switching to alternative materials at low temperatures (66% compliance)

However, five "bad practices" were also identified:

1. Overuse of deicing materials (65% noncompliance)
2. Inconsistent adjustment of application rates during multiple passes (57% noncompliance)
3. Insufficient material application on one-pass long routes (83% noncompliance)
4. Inadequate use of prewetted materials at higher traffic speeds (63% noncompliance)
5. Suboptimal spinner speed adjustments (52% noncompliance)

7.2.5.2 Environmental Awareness. The survey revealed a high level of awareness among respondents regarding several environmental impacts of deicing materials. More than 50% of respondents recognized issues such as water contamination (83%), corrosion to vehicles and bridges (83%), damage to roadside vegetation (77%), soil salinity effects (67%), and drinking water contamination (64%). Additionally, concerns about reduced oxygen levels in waterways (64%), calcium chloride toxicity to aquatic systems (55%), and the persistence of chlorides in waterways (55%) were also noted. However, awareness was lower regarding the presence of trace metals in deicing materials (41%) and the impact of sand on aquatic organisms (37%), indicating areas where further education and outreach may be beneficial.

7.2.5.3 Leftover Salt Management. Most respondents (92%) return leftover salt to stockpiles rather than spreading it on roads (5%) or storing it in trucks (3%). Additionally, 64% reported having detailed guidelines for managing leftover salt, with 69% finding these guidelines effective or very effective.

7.2.5.4 Implementation of Winter Maintenance Concepts. The survey revealed that key winter maintenance practices are being strongly implemented, with 82% of respondents fully implementing accurate weather forecasting, 80% ensuring communication between controllers and drivers, 79% having snow plans in place, and 75% optimizing route planning. However, there are areas that need improvement, including sustainable winter maintenance practices (61% fully implemented), reliable equipment calibration programs (55%), and operational efficiency (57%). These findings highlight both strengths in current deicing practices and opportunities for improvement in material application rates, environmental awareness, and operational efficiency.

7.2.5.5 Previous Studies in Indiana. Other aspects of deicing operations in Indiana were studied by McCullouch (2010) who synthesized Indiana practices regarding snow and ice removal and anti-icing, Mahlberg et al. (2022) who developed and tested a connected vehicle for campus deicing, Iyer et al. (2022) who established optimal routes for snow removal in Indiana, and Brinster et al. (2024) who evaluated the robustness of forecasts from a winter maintenance decision support system. Zhang et al. (2024) developed a system for automated record keeping for statewide winter road maintenance using telematics tracks. At a national level, Fay et al. (2013) carried out a national study that identified strategies to mitigate the impacts of chloride roadway deicers on the natural environment, and

Desai et al. (2023) who analyzed connected vehicle data to quantify the impacts of winter storms on national mobility.

7.2.6 Interview Insights and Decision-Making

The study gathered valuable insights from interviews with INDOT personnel involved in winter operations. A key finding was that proactive monitoring and coordination are essential, with tools like the MDSS and weather applications helping guide decisions. Supervisors emphasized the importance of flexibility in operations, noting that dynamic decision-making during storms is critical. Communication methods used include phone, radio, group texts, and emails to coordinate responses efficiently. Road prioritization follows a classification system: Class 1 (interstates and highways), Class 2 (US highways and major roads), and Class 3 (state roads and local routes).

In terms of salt management practices, salt is stored in covered domes to protect it from weather exposure. Operators use calibrated application rates to ensure efficient material usage, and unused salt is returned to storage for future use. Pretreatment with salt brine, typically a 23.3% sodium chloride solution, prevents ice from bonding to the pavement, while blended solutions with calcium chloride or organic additives are used to enhance performance in extreme cold. Application rates are adjusted based on snow intensity, temperature, and wind conditions to optimize efficiency.

The interviews also highlighted several challenges and areas for improvement. Equipment failures, particularly electronic and hydraulic issues caused by salt exposure, are common. There are also consistency issues between units in plowing routines and material application rates. Environmental concerns were raised about chloride runoff into water systems, while staffing limitations, especially during major storms, require personnel from construction and other departments to assist. Additionally, balancing cost efficiency with operational effectiveness and public safety remains an ongoing challenge.

Evaluation of deicing and anti-icing operations is based on key performance indicators such as road conditions, accident rates, material usage, and equipment performance. To enhance effectiveness, future improvements should focus on integrating advanced technologies like GPS-based salt application and automated spreaders, strengthening operator training programs, improving equipment maintenance, and adopting data-driven decision-making strategies. Additionally, environmental considerations, such as reducing chloride dependency, should be prioritized. When selecting deicing materials, safety remains the most critical factor, followed by melting capacity, availability, residual effectiveness, environmental impact, and corrosiveness. While cost is an important consideration, it is secondary to safety and overall effectiveness in ensuring optimal winter road maintenance.

7.2.7 Recommendations for Deicing Operations in Indiana

Based on the literature review, surveys and interviews, there are several recommendations for improving deicing operations:

1. Enhance Prewinter Preparation and Planning
   a. *Continue proactive planning:* Maintain thorough prewinter preparation, including calibrating equipment, ensuring adequate training, and optimizing route planning. Consider expanding snow trap management and snow fence installations, as used in Michigan and South Dakota, to reduce drifting and improve operational efficiency.
   b. *Focus on snow and ice prediction:* Leverage RWIS to obtain real-time monitoring and incorporate them in the planning stages for better anticipation of storm impacts.
2. Maximize the use of Anti-Icing Strategies
   a. *Continue using anti-icing as the primary strategy:* Applying materials before a storm occurs is more effective than reactive deicing, as it prevents ice from bonding to the pavement. Ensure that anti-icing techniques are consistently applied to reduce the need for salt and other materials during storms.
   b. *Prewet salt to improve adhesion:* As seen in Michigan, prewetting salt improves its effectiveness and reduces the need for large quantities of material. This should be standard practice wherever possible.
3. Optimize Material Application Techniques
   a. *Use advanced material application techniques*: Maintain and expand the use of prewetting materials, slurries, and liquid deicers (e.g., magnesium chloride and sodium chloride brine) to reduce salt usage. Ensure materials are tailored to specific road conditions and temperature ranges for maximum effectiveness.
   b. *Implement precise material application:* Employ GPS-enabled systems and automated spreaders for better precision in applying deicing materials. This can help ensure that materials are applied at the right rates and locations, improving cost efficiency and minimizing environmental impact.
   c. *Adopt best practices in adjusting application rates:* Ensure that application rates are adjusted consistently, particularly in high traffic areas, to avoid overuse. Additionally, adjust rates based on weather conditions, such as temperature, snow intensity, and wind conditions, to ensure efficiency.
4. Prioritize Environmental Stewardship
   a. *Minimize environmental impact:* Adopt best practices to reduce chloride contamination, including controlled application rates, better storage, and regular monitoring of runoff. Continue efforts to test and use sustainable alternatives, such as agricultural by-products and enhanced brine solutions.
   b. *Develop and enforce better guidelines for leftover salt management:* Ensure all leftover salt is returned to stockpiles and reused rather than being spread unnecessarily on roads. Encourage the adoption of efficient leftover salt management programs, with clear and consistent guidelines.
5. Focus on Technology Integration
   a. *Enhance technology use in deicing operations:* Continue using MDSS and other weather-related applications for real-time decision making and ensuring that deicing strategies are dynamically adjusted during storms.
   b. *Invest in automated and data-driven technologies:* Invest in automated spreaders and data-driven systems to monitor real-time effectiveness, optimize salt usage, and minimize unnecessary applications.
6. Improve Equipment and Staff Training
   a. *Ensure consistent calibration and maintenance of equipment:* Regularly calibrate and maintain equipment to ensure consistency in material application, plowing routines, and operational performance. Proactively address equipment failures, particularly those caused by salt exposure.
   b. *Enhance training programs:* Focus on enhancing operator training for optimal equipment use and consistent application of materials. Provide targeted training on adjusting application rates, monitoring weather conditions, and making decisions during storms.
7. Monitor and Evaluate Poststorm Performance
   a. *Strengthen poststorm evaluation:* Maintain thorough postevent evaluations to assess performance, material usage, and equipment

condition. Use this data to refine strategies for future events, ensuring continuous improvement in deicing operations.
   b. *Track environmental impacts:* Regularly monitor and assess the environmental impact of deicing materials, particularly runoff into waterways and soil salinity, to ensure that deicing practices are as environmentally friendly as possible.
8. Adapt Material Choices for Cost and Effectiveness
   a. *Consider using more cost-effective and efficient materials:* Evaluate the use of materials like calcium chloride and magnesium chloride, which tend to be more effective than sodium chloride in certain conditions. While more expensive, they may provide better cost efficiency in the long run by reducing material usage and improving effectiveness at lower temperatures.
   b. *Continue evaluating sustainable materials:* Regularly assess the feasibility of using alternative deicing materials, such as potassium acetate and agricultural by-products, in high-priority areas like bridges and critical roadways, where cost effectiveness and sustainability are essential.

By focusing on these recommendations, INDOT can improve their deicing operations, reduce environmental impacts, increase operational efficiency, and maintain safer road conditions during winter months. Furthermore, it is recommended that INDOT develop a comprehensive manual or set of guidelines specifically for winter operations. This document should provide detailed guidance on the selection of deicing materials, taking into account factors such as effectiveness, cost, and environmental impact. The manual should outline best practices for operational procedures, including optimal application methods, timing, and equipment usage. By standardizing these practices and materials, INDOT can ensure consistency, improve the effectiveness of winter maintenance efforts, and reduce potential negative impacts on both the environment and infrastructure.

REFERENCES

Alaska Department of Transportation. (2014). *Alaska highway maintenance and operations handbook*. https://dot.alaska.gov/stwddes/research/assets/pdf/ak_maint-ops_hb.pdf

Alaska Department of Transportation. (2024). *Standard operating procedures for winter road maintenance*. https://dot.alaska.gov/stwdmno/documents/MnO_CR_Winter_Maintenance_Manual.pdf

Alleman, J. E., Partridge, B. K., & Yeung, L. (2004). *Innovative environmental management of winter salt runoff problems at INDOT yards* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2001/27). Purdue University. https://doi.org/10.5703/1288284313253

American Association of State Highway and Transportation Officials. (2023). *State of practice in winter maintenance operations*. https://transportation.org/winter-weather-management/surveys/

Bouchard, R. W. (2016). *Development of biological criteria for tiered aquatic life uses*. Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/wq-bsm4-02.pdf

Bright, D. A., & Addison, J. (2002). Addendum A: Technical options analysis for a soil chloride standard for drinking water protection (aesthetic). In *Derivation of matrix soil standards for salt under the British Columbia Contaminated Sites Regulation*. Retrieved from https://web.archive.org/web/20181220063246id_/https://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/requests-for-comments-archive/rev_add_a.pdf

Brinster, G. L., Desai, J., Overall, M. W., Gartner, C., Sakhare, R. S., Mathew, J. K., Evans, N., & Bullock, D. M. (2024). *Evaluating the robustness of MDSS forecast and compliance with recommendations* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/31). Purdue University. https://doi.org/10.5703/1288284317805

Casey, P. C., Alwan, C. W., Kline, C. F., Landgraf, G. K., & Lonsenmayer, K. R. (2014). *Impacts of using salt and salt brine for roadway deicing* (Idaho Transportation Department Report No. FHWA-ID-14-231). https://apps.itd.idaho.gov/apps/research/Completed/RP231.pdf

Clear Roads. (2018). *Utilization of AVL/GPS technology: Case studies final report*. Retrieved from https://www.clearroads.org/project/16-01/

Clear Roads. (2019). *Material application methodologies guidebook*. https://www.clearroads.org/download/guidebook/?tmstv=1741151138

Clear Roads. (2023). *Annual survey of state winter maintenance data: 2022-2023 state winter maintenance data and statistics.* https://clearroads.org/winter-maintenance-survey

Clear Roads. (2024) *Annual survey of state winter maintenance data: 2023-2024 state winter maintenance data and statistics*. https://clearroads.org/winter-maintenance-survey

Colorado Department of Transportation. (2009). *Evaluation of alternative anti-icing and deicing compounds using sodium chloride and magnesium chloride as baseline deicers – Phase I* (Report No. CDOT-2009-1). https://rosap.ntl.bts.gov/view/dot/36465

Cope, A., Bai, Q., Samdariya, A., & Labi, S. (2011). Assessing the efficacy of stainless steel for bridge deck reinforcement under uncertainty using Monte Carlo simulation. *Structure and Infrastructure Engineering*, *9*(7), 634–647. https://doi.org/10.1080/15732479.2011.602418

Corson, L. A. (2004). *Development of a strategy for preparing an INDOT storm water quality management plan* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2004/18). Purdue University. https://doi.org/10.5703/1288284313189

Desai, J., Mathew, J. K., Kim, W., Liu, M., Li, H., Brooks, J. D., & Bullock, D. M. (2020). *Dashboards for real-time monitoring of winter operations activities and after-action assessment* (JTRP Affiliated Reports Paper 33). Purdue University. https://doi.org/10.5703/1288284317252

Desai, J., Mathew, J. K., Li, H., Sakhare, R. S., Horton, D., & Bullock, D. M. (2023). Analysis of connected vehicle data to quantify national mobility impacts of winter storms for decision makers and media reports. *Future Transportation*, *3*(4), 1292–1309. https://doi.org/10.3390/futuretransp3040071

Farnam, Y., Dick, S., Wiese, A., Davis, J., Bentz, D., & Weiss, W. J., (2015). The influence of calcium chloride deicing salt on phase changes and damage development in cementitious materials. *Cement and Concrete Composites*, *64*(1), 1–15. https://doi.org/10.1016/j.cemconcomp.2015.09.006

Fay, L., Shi, X., & Huang, J. (2013). *NCHRP synthesis 449: Strategies to mitigate the impacts of chloride roadway deicers on the natural environment*. Transportation Research Board. https://doi.org/10.17226/22506

Frosch, R. J., Labi, S., & Sim, C. (2014). *Increasing bridge deck service life: Volume I—Technical evaluation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/16). Purdue University. https://doi.org/10.5703/1288284315516

Gardner, K. M., & Royer, T. V. (2010). Effect of road salt application on seasonal chloride concentrations and toxicity in south-central Indiana streams. *Journal of Environmental Quality*, *39*(3), 1036–1042. https://doi.org/10.2134/jeq2009.0402

Hashad, M. F., Sharma, S., Nies, L. F. & Alleman, J. E. (2006). *Study of salt wash water toxicity on wastewater treatment* (Joint Transportation

Research Program Publication FHWA/IN/JTRP-2005/21). Purdue University. https://doi.org/10.5703/1288284313386

Illinois Department of Transportation. (2017). *Snow & ice management in Southern Illinois*. https://uslawns.com/locations/il/southern-illinois/services/snow -ice-management/

Iyer, A. V., Dunlop, S. R., Senicheva, O., Thakkar, D. J., Yan, R., Subramanian, K., Vasu, S., Siddharthan, G., Vasandani, J., & Saurabh, S. (2021). *Improve and gain efficiency in winter operations* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/11). Purdue University. https://doi.org/10.5703/1288284317312

Iyer, A. V., Labi, S., Dunlop, S. R., Thakkar, D. J., Mishra, S., Kumar, L. K., Du, R., Gala, M., Banerjee, A., & Siddharthan, G. (2022). *Heavy fleet and facilities optimization* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2022/03). Purdue University. https://doi.org/10.5703/1288284317365

Ji, Y., McCullouch, B., & Zhou, Z. (2020). *Evaluation of anti-icing/de-icing products under controlled environmental conditions* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2020/22). Purdue University. https://doi.org/10.5703/1288284317253

Labi, S., Frosch, R. J., Samdariya, A., & Qing, Y. (2014). *Increasing bridge deck service life: Volume II—Economic evaluation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/17). Purdue University. https://doi.org/10.5703/1288284315517

Mahlberg, J. A., Manish R., Koshan, Y., Joseph, M., Liu, J., Malackowski, H. A., DeLoach, Z., Wells, T., McGuffey, J., Habib, A., & Bullock, D. M. (2023). *Salt monitoring and reporting technology (SMART) for salt stockpile inventory reporting* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/19). Purdue University. https://doi.org/10.5703/1288284317650

Mahlberg, J., Mathew, J. K., Horton, D., McGavic, B., Wells, T., Bullock, D. (2022). Intelligent sidewalk de-icing and pre-treatment with connected campus maintenance vehicles (Report No. 42). *Center for Connected and Automated Transportation Report.* Purdue University. https://doi.org/10.5703/1288284317572

Mahlberg, J., Zhang, Y., Jha, S., Mathew, J. K., Li, H., Desai, J., Kim, W., McGuffey, J., Wells, T., Krogmeier, J. V., & Bullock, D. M. (2021). *Development of an intelligent snowplow truck that integrates telematics technology, roadway sensors, and connected vehicle* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/27). Purdue University. https://doi.org/10.5703/1288284317355

McClellan, T., Coleman, M., Boone, P., & Carpenter, K. (2009). Implementing a winter maintenance decision support system: Indiana Department of Transportation's process, success, and savings. *TR News*, *265*, 35–37. https://onlinepubs.trb.org/onlinepubs/trnews/trnews265rpo.pdf

McCullouch, B. (2010). *Snow and ice removal and anti-icing synthesis study* (Joint Transportation Research Program Publication FHWA/IN/JTRP-2010/18). Purdue University. https://doi.org/10.5703/1288284314254

McCullouch, B., Partridge B., & Noureldin S. (2013). *Snow and ice performance standards* (Joint Transportation Research Program Publication FHWA/IN/JTRP-2013/21). Purdue University. https://doi.org/10.5703/1288284315223

Michigan Department of Transportation. (2013). *Michigan winter maintenance manual – Promoting safe roads and clean water*. Retrieved from https://miwintermaintenance.weebly.com/uploads/1/7/1/6/17161926/mi_winter_maintenance_manual_2013.pdf

Minnesota Department of Transportation. (2010). *Mn/DOT anti-icing guide*. https://www.dot.state.mn.us/maintenance/pdf/research/AntiIcingGuide8Full.pdf

Minnesota Department of Transportation. (2015). *Manufacturers' perspectives on Minnesota's transportation system: District 4*. https://www.dot.state.mn.us/mps/docs/d4report.pdf

Minnesota Department of Transportation. (2022). *Minnesota snow and ice control handbook for snowplow operators* (2022RIC01). https://mdl.mndot.gov/items/2022RIC01

Minnesota Department of Transportation. (2024). *Road weather information system*. https://www.dot.state.mn.us/maintenance/rwis.html

Moomen, M., Qiao, Y., Agbelie, B. R., Labi, S., & Sinha, K. C. (2016). *Bridge deterioration models to support Indiana's bridge management system* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/03). Purdue University. https://doi.org/10.5703/1288284316348

Nees, J. (2025). Deicer's impact on your landscape. https://extension.purdue.edu/news/county/putnam/2025/01/deicers-impact-on-your-landscape.html

New York State Department of Transportation. (2012). *Highway maintenance guidelines chapter 5: Snow and ice control*. https://www.dot.ny.gov/divisions/operating/oom/transportation-maintenance/repository/NYS_SI_Manual_Apr2006_RevJan2012.pdf

Olek, J., Janusz, A., Jain, J., & Ashraf, W. (2013). *Investigation of anti-icing chemicals and their interactions with pavement concretes* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2013/24). Purdue University. https://doi.org/10.5703/1288284315226

South Dakota Department of Transportation. (2023). *2022-2023 South Dakota Department of Transportation winter highway maintenance plan*. https://boardsandcommissions.sd.gov/bcuploads/Attach%204%20-%20Consideration%20of%20Winter%20Highway%20Maintenance%20Plan%202022%20-%2023.pdf

South Dakota Department of Transportation. (2024). *Winter highway maintenance plan 2024-2025*. https://boardsandcommissions.sd.gov/bcuploads/Attach%205%20-%20Consideration%20of%202024-25%20WHMP.pdf

Spragg, R. P., Castro, J., Li, W., Pour-Ghaz, M., Huang, P., Weiss, J. (2011). Wetting and drying of concrete using aqueous solutions containing deicing salts. *Cement and Concrete Composites*, 33(5), 535–542. https://doi.org/10.1016/j.cemconcomp.2011.02.009

Suraneni, P., Monical, J., Unal, E., Farnam, Y., Villani, C., Barrett, T. J., & Weiss, W. J. (2016). *Performance of concrete pavement in the presence of deicing salts and deicing salt cocktails* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/25). Purdue University. https://doi.org/10.5703/1288284316350

Tokpatayeva, R., Castillo, A., & Olek, J. (2025). *Interaction of cementitious systems containing nontraditional and natural pozzolans (NNPs) with chloride-based deicers* [Conference session]. Eighth International Conference on Durability of Concrete Structures, Heriot-Watt University, Edinburgh, United Kingdom. https://doi.org/10.5703/1288284318138

Town of Greenville Department of Public Works. (2015). *Snow and ice control manual*. https://cms3.revize.com/revize/greenvillewi/Snow%20Manual%20-%202019%20WEBSITE.pdf

Vermont Agency of Transportation. (2020). *Snow and ice control plan for state and interstate highways.* https://vtrans.vermont.gov/sites/aot/files/documents/Snow%20and%20Ice%20Control%20Plan.pdf

Vermont Agency of Transportation. (2024). *Road weather information system (RWIS)*. https://vtrans.vermont.gov/operations/rwis

Vermont Agency of Transportation. [VTrans]. (2015, March 24). *Vermont's snow and ice control plan* [Video]. YouTube. https://www.youtube.com/watch?v=rmnYab85DBc

Wilcox, D. A. (1982). *The effects of deicing salts on water chemistry and vegetation in Pinhook Bog, Indiana* [Doctoral dissertation, Purdue University]. https://docs.lib.purdue.edu/dissertations/AAI8300976/

Wright, J. R. (1988). Development of a prototype system for snow route design and management (Joint Highway Research Project Publication FHWA/IN/JHRP-88/17). Purdue University. https://doi.org/10.5703/1288284314156

Zhang, Y., Ault, A., Krogmeier, J. V. (2024). Automated record keeping for statewide winter road maintenance using telematics tracks [Conference session]. 2024 IEEE 99th Vehicular Technology Conference, Singapore. https://doi.org/10.1109/VTC2024-Spring62846.2024.10683171

APPENDICES

Appendix A. List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ADOT	Alaska Department of Transportation
AVL	Automated Vehicle Location
AWSSI	Accumulated Winter Season Severity Index
BOD	Biochemical Oxygen Demand
$CaCl_2$	Calcium Chloride
CMA	Calcium Magnesium Acetate
COD	Chemical Oxygen Demand
DOT	Department of Transportation
EPA	Environmental Protection Agency
EMS	Equipment Management System
ESS	Environmental Sensor Stations
FHWA	Federal Highway Administration
HFST	High Friction Surface Treatments
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
ITD	Idaho Transportation Department
JTRP	Joint Transportation Research Program
KAc	Potassium Acetate
KCl	Potassium Chloride
MCDA	Multicriteria Decision Analysis
MDCs	Mobile Data Collectors
MDOT	Michigan Department of Transportation
MnDOT	Minnesota Department of Transportation
MDSS	Maintenance Decision Support System
$MgCl_2$	Magnesium Chloride
MPCA	Minnesota Pollution Control Agency

NaCl	Sodium Chloride
NYSDOT	New York State Department of Transportation
ROC	Rank Order Centroid
RWIS	Road Weather Information System
SDDOT	South Dakota Department of Transportation
VTrans	Vermont Agency of Transportation

Appendix B. Generalized Potential Environmental Impairment Related to Common Snow and Ice Control Chemicals (Casey et al., 2014)

Table B.1 *Generalized Potential Environmental Impairment Related to Common Snow and Ice Control Chemicals (Casey et al., 2014).*

Environmental Impact	**Road Salt (NaCl)**	**Calcium Chloride ($CaCl_2$)**	**Magnesium Chloride ($MgCl_2$)**	**Acetates (CMA and KA)**	**Organic Biomass Products**	**Abrasives**
Water Quality/ Aquatic Life	Moderate: Excessive chloride loading, metal contaminants; ferrocyanide additives.	Moderate: Excessive chloride loading; heavy metal contamination.	Moderate: Excessive chloride loading; heavy metal contamination.	High: Organic content leading to oxygen demand.	High: Organic matter leading to oxygen demand; nutrient enrichment by phosphorus and nitrogen; heavy metals.	High: Turbidity; increased sedimentation.
Air Quality	Low: Leads to reduced abrasive use.	Low: Leads to reduced abrasive use.	Low: Leads to reduced abrasive use.	Low: Leads to reduced abrasive use.	Low: Leads to reduced abrasive use.	High: Fine particulate degrades air quality.
Soils	Moderate/High: Sodium accumulation breaks down soil structure and decreases permeability and soil stability; potential for metals mobilization.	Low/Moderate: Improves soil structure; increases permeability; potential for metals mobilization.	Low/Moderate: Improves soil structure; increases permeability; potential for metals mobilization.	Low/Moderate: Improves soil structure; increases permeability; potential for metals mobilization.	Low: Probably little or no effect; limited information available.	Low: Probably little or no effect.

Environmental Impact	Road Salt (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium Chloride ($MgCl_2$)	Acetates (CMA and KA)	Organic Biomass Products	Abrasives
Vegetation	High: Spray causes foliage damage; osmotic stress harms roots; chloride toxicosis.	High: Spray causes foliage damage; osmotic stress harms roots; chloride toxicosis.	High: Spray causes foliage damage; osmotic stress harms roots; chloride toxicosis.	Low: Little or no adverse effect; osmotic stress at high levels.	Low: Probably little or no effect.	Low: Probably little or no effect.
Animals	Low: Sodium linked to salt toxicosis, and vehicle kills; magnitude unclear.	Low: Probably little or no effect.	Low: Probably little or no effect.	Low: Probably little or no effect.	Low: Probably little or no effect; limited toxicity information available.	Low: Probably little or no

Appendix C. Impact Assessments of Chlorides

Table C.1 *Impact Assessments of Chlorides.*

Impact Category	Description	References
Chlorides in Ecosystems	Chlorides persist in ecosystems, contaminating water bodies, reducing biodiversity, and harming aquatic life and vegetation.	MDOT, 2013; Casey et al., 2014
	Long-term chloride accumulation elevates salinity in soil and water, affecting sensitive plants and aquatic organisms.	ITD, 2014; SDDOT, 2023
	Chloride runoff causes significant harm to ecosystems. Agricultural byproducts present a lower environmental impact compared to traditional chlorides.	ADOT, 2014; Brown County Public Works Department, 2020
Public Health Concerns	Chloride levels in drinking water may pose risks to individuals with hypertension or heart disease. Sodium and chloride contamination raise ecological and public health concerns.	MDOT, 2013; Casey et al., 2014
Infrastructure Impacts	Chlorides, particularly sodium chloride, accelerate corrosion of vehicles, bridges, and steel structures. Corrosion inhibitors in brines and treated salts mitigate damage but increase costs.	SDDOT, 2023; ADOT, 2014
Sedimentation Issues	High sedimentation levels from chlorides and abrasives clog stormwater systems, degrading aquatic habitats and requiring significant cleanup efforts in spring.	MDOT, 2013; Walworth County, 2022
Air Quality and Health	Fine particulates from abrasives/sand-salt mixes contribute to air quality issues and secondary health effects.	Casey et al., 2014; MnDOT, 2022
Road and Pavement Wear	Sand and abrasives cause abrasion and wear on pavements, increasing the need for maintenance and repair.	VTrans, 2015; Brown County Public Works Department, 2020

Appendix D. Tools and Equipment Used in Various States

***Table D.1** Tools and Equipment Used in Various States.*

Tools and Equipment	Minnesota	Michigan	Idaho	Wisconsin	South Dakota	Vermont	Alaska	Indiana
Plow Trucks	✓	✓	✓	✓	✓	✓	✓	✓
Wing Plows	✓	✓	✓	✓	✓	✓	✓	✓
Tow Plows	✓	✓	✓	✓	✓	✓	✓	✓
Scrapers	✓	✓		✓				✓
Prewetting	✓	✓	✓	✓	✓	✓	✓	✓
Slurry Systems	✓	✓	✓		✓			
Brine Makers	✓	✓	✓	✓	✓	✓	✓	✓
MDSS	✓	✓		✓	✓			✓
AVL	✓	✓	✓	✓	✓	✓	✓	✓
Belly Plows	✓	✓		✓	✓	✓	✓	✓
Spreaders	✓	✓	✓	✓	✓	✓	✓	✓
Blowers	✓	✓	✓	✓	✓	✓	✓	✓
RWIS	✓	✓	✓	✓	✓	✓	✓	✓
Road Graders	✓	✓	✓	✓	✓	✓	✓	✓
Snow Fences	✓	✓	✓	✓	✓	✓	✓	✓
Carbide Blades	✓	✓	✓		✓		✓	✓
MDC	✓	✓	✓	✓	✓	✓	✓	✓
Temp. Sensors	✓	✓	✓	✓	✓	✓	✓	✓

Appendix E. Average Use of Deicing Materials by State and Method

Table E.1 *Five Year (2019-2023) Average of Use of Solid Deicing Materials.*

State	NaCl Dry (tons)	$CaCl_2$ Dry (tons)	$MgCl_2$ Dry (tons)	Abrasives (tons)	Other Dry (tons)	Other Material
Alabama	2,425	180		1,388	59	
Alaska	12,255	11,256	15,010	30,312	62,840	
Arizona	25,522	11		9,021		
Arkansas	60,281	94		2,828		
California	15,457		1,333	75,699		
Colorado	226,420	237	111	42,071		
Connecticut	157,976		50,875			
Delaware	23,728					
Florida						
Georgia	12,381	27		527		
Hawaii						
Idaho	145,519			3,311	15,338	Antiskid with salt
Illinois	408,800			15		
Indiana	238,173			625		
Iowa	122,250			11,420		
Kansas	91,234			14,257		
Kentucky	138,908					
Louisiana						
Maine	128,614	10		2,898		
Maryland	115,107		1,077	14,673		
Massachusetts	306,721	243		8,992	101	
Michigan	436,023			56,163	55	
Minnesota	190,242			20,406		
Mississippi						
Missouri	106,928	239		95,534	18,175	Treated NaCl + MgCl2
Montana	25,070			222,809	318	
Nebraska	95,544			7,100	3,750	
Nevada	6,491			48,336	100,135	Salt & Sand mix
New Hampshire	194,191	1,694		13,266		

State	NaCl Dry (tons)	$CaCl_2$ Dry (tons)	$MgCl_2$ Dry (tons)	Abrasives (tons)	Other Dry (tons)	Other Material
New Jersey	254,333	206,667		5,000		
New Mexico	19,800		2,678	63,000		
New York	830,406			3,030	65,944	Treated NaCl + CaCl2
North Carolina						
North Dakota	41,179			9,302		
Ohio	507,635	654		510		
Oklahoma					25,550	
Oregon	8,420			153,888		
Pennsylvania	597,611			449,666		
Rhode Island	82,006			6,222		
South Carolina	1,700			2,220		
South Dakota	49,210			2,706	150	
Tennessee	78,040					
Texas	20,329		2,183	7,911		
Utah	249,406	6,659	19,913	2,210		
Vermont	118,428			2,299		
Virginia						
Washington	71,703			57,532	34,316	Sand Salt Mix
West Virginia	236,417	1,114		53,857		
Wisconsin	375,290			15,939		
Wyoming	6,657		2,096	219,180	4,288	

Table E.2 Five Year (2019-2023) Average of Use of Liquid Deicing Materials.

State	NaCl Brine (gal)	$CaCl_2$ Brine (gal)	$MgCl_2$ Brine (gal)	Kac (gal)	Enhanced Brines (gal)	Agri. By-product (gal)	Other (gal)	Other Material
Alabama	257,000	30,500	113	7,375				
Alaska	3,100				40			
Arizona	327,526		208,172					
Arkansas	3,939,857				4,000			
California	1,135,253							
Colorado	1,400,821		11,613,572					
Connecticut	60,740		562,348					
Delaware	669,027							
Florida								
Georgia	522,145	2,700				1,250		
Hawaii								
Idaho	4,896,835		900,814		42,200			
Illinois	1,352,654	124,720			897,938	175,204	580,000	10% $CaCl_2$
Indiana	3,540,092	27,695	14,136			32,315	26,583	Beet Heet
Iowa	27,310,036	17,727						
Kansas	6,078,200		30,950			40,217		
Kentucky	668,718	517,246						
Louisiana								
Maine	330,756		242,890		238,269			
Maryland	1,939,261		70					
Massachusetts	329,000		1,256,480					
Michigan	1,340,836	423,422					2,117,147	Uncategorized
Minnesota	8,631,507	665,116	5,254	124,867	11,619			
Mississippi								
Missouri	2,066,010	14,472	24,428			404,706		

State	NaCl Brine (gal)	$CaCl_2$ Brine (gal)	$MgCl_2$ Brine (gal)	Kac (gal)	Enhanced Brines (gal)	Agri. By-product (gal)	Other (gal)	Other Material
Montana	4,734,661		2,265,741	9,436				
Nebraska	9,368,000		2,379,249	10,819		326,930		
Nevada	764,210		3,038	10,596				
New Hampshire	109,174	7,144	29,705					
New Jersey	42,333	515,333				20,000		
New Mexico			500					
New York	3,500,001	3,299	106,151	1,672				
North Carolina								
North Dakota	3,075,683			3,519		637,979		
Ohio	12,206,877	208,096				248,284	832,861	Brine + Beet
Oklahoma	1,000,000							
Oregon			3,384,625		2,954			
Pennsylvania	8,950,851							
Rhode Island	11,209	6,923	2,288					
South Carolina	1,700	1,700						
South Dakota	1,428,086		196,713		22,560	9,054	75,159	Beet Heet
Tennessee	2,177,623	137,170						
Texas	9,986,605		12,688					
Utah	2,467,541		211,227	125				
Vermont	1,461,344		69,089					
Virginia								
Washington	357,776	597,423	695,054	4,188				
West Virginia	778,494	46,898						
Wisconsin	13,906,288	171,821	14,255		95,256	269,211		
Wyoming	719,055		51,624		384,924	65,318	2,359	

Appendix F. Best Practices for Winter Operations by State

Table F.1 *Best Practices in Michigan Winter Operations.*

Category	Best Practices
Winter Maintenance Plan	• Develop and share a comprehensive winter maintenance plan with all staff involved. Define levels of service for snow routes based on traffic, safety, and environmental factors.
Preparation	• Inspect and clear ditches, culverts, and snow traps before winter. • Assign and familiarize operators with specific routes to enhance performance. • Use snow fences to trap snow and reduce the need for plowing.
Equipment Calibration	• Calibrate equipment annually or after major repairs. • Maintain a calibration worksheet for accurate material application.
Deicer Application	• Use prewetting and pretreating methods to enhance salt effectiveness and reduce application rates. • Apply deicers based on pavement temperature and conditions, not air temperature.
Anti-Icing	• Use liquid deicers before winter events to prevent ice bonding and reduce chemical use. • Apply during low traffic periods and during regular work hours; this saves product and reduces staff costs.
Snow Removal	• Prioritize mechanical removal (plowing/blading) to minimize chemical use. • Use wing plows for efficiency and reduce passes.
Environmental Protection	• Store salt in covered, water-tight buildings with impervious floors. • Maintain secondary containment for liquid deicers to prevent spills. • Avoid overuse of salt to minimize environmental contamination.
Weather Monitoring	• Utilize Road Weather Information Systems (RWIS) for real-time data on pavement temperatures and conditions. • Use weather forecasts to plan pre-treatment and response strategies.
Post-Event Evaluation	• Conduct end-of-event meetings to review performance and refine procedures. • Properly store unused materials and clean vehicles after use.

Table F.2 Best Practices in Idaho Winter Operations.

Category	Best Practices
Material Management	• Use a mix of solid salt, salt brine, magnesium chloride, and sand for specific road conditions. • Apply corrosion inhibitors to reduce damage to vehicles and infrastructure.
Application Rate	• Adjust material application rates based on pavement temperature, storm severity, and expected traffic. • Employ automated systems and GPS tracking for precise application.
Plowing and Anti-Icing	• Prioritize plowing before applying chemicals to minimize dilution and waste. • Use liquid anti-icers proactively to prevent ice bonding to pavement.
Environmental Protection	• Store materials in covered facilities with impervious floors to prevent runoff. • Monitor material usage to minimize environmental contamination.
Wildlife Collision Mitigation	• Assess risks related to salt attracting wildlife and implement measures like draining roadside salt pools.
Corrosion Prevention	• Use corrosion-resistant materials and coatings for equipment. • Encourage public education on vehicle washing to mitigate chemical corrosion.
Post-Storm Evaluation	• Conduct detailed reviews after major winter events to assess material usage, costs, and performance.
Operator Training	• Train staff on material application, environmental risks, and proper equipment use to enhance efficiency and safety.

Table F.3 Best Practices in Wisconsin Winter Operations.

Category	Best Practices
Weather Monitoring	• Utilize weather forecasts from the National Weather Service, RWIS (Road Weather Information Systems), and other sources to guide operations.
Snow Plowing Operations	• Prioritize primary and secondary roads, followed by residential streets and parking lots. • Full-width plowing of primary roads within 8 hours of storm cessation, secondary roads within 8 hours, and residential roads within 12 hours.
Anti-Icing Practices	• Apply liquid deicers before storms to prevent the bonding of snow and ice. • Use pretreated salts to enhance effectiveness in colder conditions.
Material Use and Storage	• Use rock salt as the primary deicing agent; apply abrasives for traction in colder temperatures.
Shift Management	• Implement two 12-hour shifts during major snowstorms to ensure continuous coverage.
Equipment Maintenance	• Regularly inspect and maintain equipment for operational readiness before and during winter. • Utilize a range of equipment, including wing plows and liquid dispensing systems, to adapt to varied conditions.
Emergency Procedures	• Provide support for emergency vehicles and prioritize emergency access during snowstorms.
Public Communication	• Inform the public about parking bans and snow removal schedules via media notifications.
Post-Event Evaluations	• Conduct post-storm reviews to assess the effectiveness of the response and refine practices.

Table F.4 *Best Practices in Minnesota Winter Operations.*

Category	**Best Practices**
Preparation	• Conduct pre-season route inspections and address snow traps and obstructions. • Calibrate equipment yearly to ensure accurate application rates for salt and sand.
Anti-Icing Practices	• Apply liquid deicers before storms to prevent bonding snow and ice to pavement. • Use appropriate chemicals for specific pavement temperatures.
Deicing Operations	• Apply only the required amount of material to break the bond between ice and pavement. • Use prewetted or treated salts for enhanced performance.
Material Management	• Store salt and sand in covered facilities with impermeable pads to prevent runoff. • Utilize pretreated stockpiles to reduce material loss.
Equipment Use	• Equip trucks with plows, underbody blades, and liquid dispensing systems. • Use closed-loop controllers for precise material spreading.
Environmental Protection	• Limit the use of abrasives to critical areas and minimize overspreading of salt. • Avoid using materials that can contribute to runoff into sensitive areas.
Public Communication	• Notify residents of snow removal schedules and parking bans. • Share updates on road conditions and ongoing operations.
Evaluation and Training	• Conduct post-storm meetings to assess performance and improve practices. • Train operators on environmental impacts and proper application techniques.

Table F.5 *Best Practices in Alaska Winter Operations.*

Category	Best Practices
Preparation	• Conduct pre-season inspections of routes, ditches, and culverts to ensure readiness. • Train all staff on standard operating procedures, including equipment calibration and material application.
Anti-Icing	• Apply anti-icing chemicals before a storm to prevent bonding snow and ice to the pavement. • Use stream nozzles for precise application and avoid fan sprays to reduce material waste.
Deicing	• Use chemicals only as needed to break the bond between ice and pavement. • Avoid oversalting and use materials effectively to minimize waste.
Abrasive Use	• Apply sand only for traction in critical areas such as intersections, curves, and hills. • Limit the amount of sand used to prevent environmental contamination and reduce cleanup costs.
Plowing	• Plow snow before applying chemicals to reduce material dilution and enhance efficiency. • Use underbody blades to remove compacted snow and ice.
Environmental Protection	• Store salt and sand on impermeable pads and under cover to prevent runoff. • Minimize the use of chlorides near sensitive ecosystems and water sources.
Post-Storm Evaluation	• Conduct meetings to review storm response and refine strategies. • Record material usage and assess environmental and operational impacts.
Public Safety	• Provide real-time road condition updates to the public. • Ensure the safety of operators and the traveling public through proactive hazard identification and response.

Table F.6 Best Practices in South Dakota Winter Operations.

Category	Best Practices	Details
Preparation Before Winter	Snow Fence Installation	Erect temporary snow fences in October-November and dismantle them in March-April to minimize snowdrift. Living snow fences, such as rows of trees or corn, are also encouraged to reduce blowing snow.
	Equipment Inspections	Use a standardized checklist (Form 825) to inspect and address maintenance needs for snowplows, sanders, and related equipment before the season starts.
Material Management	Anti-Icing Practices	Apply chemicals like salt brine before storms to prevent snow and ice from bonding to the road. Anti-icing is generally more cost-effective than deicing, though it is limited by weather conditions.
	Deicing Strategies	Use materials like sodium chloride and magnesium chloride during and after storms to break the bond of ice and snow. Adjust application rates based on road and weather conditions.
	Material Handling	Train staff in safe handling practices to minimize spillage and contamination. Maintain accurate inventory records to plan future material needs.
Equipment Deployment	Use of Tow Plows	Deploy tow plows equipped with deicing tanks or sanders for efficient clearing of wide road sections, particularly on interstates.
	Equipment Maintenance	Conduct preventive maintenance regularly using an Equipment Management System (EMS) to track and schedule maintenance. After storms, clean equipment thoroughly, to remove corrosive residues.
Technology Integration	Maintenance Decision Support System (MDSS)	Utilize MDSS to predict road conditions, recommend treatment strategies, and optimize resource deployment. The system integrates data from weather stations, snowplows, and road sensors.

Category	Best Practices	Details
Communication	Traveler Information System (SD511)	Provide real-time updates on road conditions, closures, and weather forecasts via the SD511 website, mobile app, and phone system.
	Public Outreach	Use social media platforms (e.g., Facebook, Twitter) and dynamic message signs to keep the public informed. Provide specific messaging during severe weather events.
Environmental Practices	Use of Agricultural Byproducts	Test and deploy chloride-free agricultural deicers derived from corn and sugar beet production to lower environmental impact.
Safety Enhancements	High Friction Surface Treatments (HFST)	Apply HFST at critical locations like curves and intersections to improve traction and reduce winter-related crashes.
	Blue Lights on Equipment	Equip snowplows with blue lights for better visibility during low-visibility conditions.

Appendix G. State Comparison of Usage per Lane Mile

Table G.1 *State-Wise Comparison of solid Chloride Per Lane Mile with AWSSI.*

State DOT	Solid Chlorides (tons) Per Lane Miles	Average Accumulated Winter Season Index (AWSSI)
Kentucky	2.858	119
Oklahoma	0.112	121
West Virginia	10.697	184
Rhode Island	26.492	204
Missouri	15.604	224
Ohio	7.090	238
Massachusetts	6.211	244
Pennsylvania	5.256	281
Indiana	2.638	290
Illinois	4.925	327
Connecticut	17.017	368
Kansas	19.991	388
Arizona	14.600	416
California	8.672	421
New York	1.867	462
Washington	1.161	572
Iowa	8.624	653
Nebraska	12.622	726
Colorado	23.517	780
Utah	19.302	795
Nevada	2.664	801
Oregon	9.493	836
Vermont	0.838	847
New Hampshire	0.569	916
Idaho	4.682	1006
Wisconsin	17.896	1053
Michigan	3.894	1080
Montana	31.238	1368
Maine	17.486	1408
Wyoming	8.339	1466
South Dakota	1.751	1478
Minnesota	13.935	1646
North Dakota	0.292	2272

Table G.2 State-Wise Comparison of Liquid Brine Per Lane Mile with AWSSI.

State DOT	Liquid Chlorides (gallons) per lane miles	Average Accumulated Winter Season Index (AWSSI)
Kentucky	57.071	119
Oklahoma	15.939	121
West Virginia	550.467	184
Rhode Island	18.721	204
Missouri	527.956	224
Ohio	42.430	238
Massachusetts	105.677	244
Pennsylvania	1289.175	281
Indiana	235.574	290
Illinois	50.876	327
Connecticut	72.685	368
Kansas	108.973	388
Arizona	72.590	416
California	503.050	421
New York	28.309	462
Washington	286.631	572
Iowa	902.810	653
Nebraska	87.801	726
Colorado	15.281	780
Utah	31.731	795
Nevada	183.866	801
Oregon	230.322	836
Vermont	39.379	847
New Hampshire	282.230	916
Idaho	95.312	1006
Wisconsin	2.904	1053
Michigan	136.962	1080
Montana	24.883	1368
Maine	250.853	1408
Wyoming	106.635	1466
South Dakota	8.444	1478
Minnesota	567.439	1646
North Dakota	44.390	2272

Appendix H. List of Survey Questions and Variables

Table H.1 *List of Survey Questions and Variables.*

QueID	Variable Names	Category	Theme	Question	Choices
Q1 (1)	role_1	background	role1	What is your role or function in INDOT's winter operations? - Selected Choice	0 (field crew/staff), 1 (supervisory role)
Q1_6_TEXT (1)		background	role2	What is your role or function in INDOT's winter operations? - Other (please specify): - Text	
Q2 (2)	years_1	background	years	How many years have you worked in winter operations-related tasks?	1 (0-2 years), 2 (3-5), 3 (6, 10), 4 (more than 10)
Q3 (3)	area_1	background	area	What is your geographic area of operation?	North, Central, South
Q4_1 (4)		material	NaCl (sodium chloride)	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Sodium Chloride (NaCl)	
Q4_2 (4)		material	CaCl2 (calcium chloride)	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Calcium Chloride (CaCl2)	
Q4_3 (4)		material	MgCl2 (magnesium chloride)	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Magnesium Chloride (MgCl2)	

QueID	Variable Names	Category	Theme	Question	Choices
Q4_4 (4)		material	KCl (potassium chloride)	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Potassium Chloride (KCl)	
Q4_5 (4)		material	CMA (calcium magnesium acetate)	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Calcium Magnesium Acetate (CMA)	
Q4_6 (4)		material	Sodium Acetate	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Sodium Acetate	
Q4_7 (4)		material	other	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Other (please specify)	
Q4_7_TEXT (4)		material	other	What de-icing/anti-icing materials do you commonly use in your area of operation? (Select all that apply) - Other (please specify) .... - Text	
Q47 (5)		material	Salt and Abrasives; Salt and Sand Mix: Organic; Others	Do you use any of the following de-icing/anti-icing materials? (Select all that apply) - Selected Choice	
Q47_4_TEXT (5)		material	other	Do you use any of the following de-icing/anti-icing materials? (Select all that apply) - Other (please specify) - Text	

QueID	Variable Names	Category	Theme	Question	Choices
Q5 (6)		practice	pre-treatment before snowfall; during snowfall; post-treatment after snowfall; combination of the above	How are these materials applied in your area of operation? (Select all that apply) - Selected Choice	
Q5_5_TEXT (6)		practice	other	How are these materials applied in your area of operation? (Select all that apply) - Other (please specify): _______________ - Text	
Q6 (7)	inhibitor	practice	corrosion inhibitor	Are you using any corrosion inhibitors along with the materials used for de-icing and anti-icing?	Yes, No, I am not aware of any
Q7 (8)	overuse_1	practice	overuse of materials	How do you approach the application of de-icing materials on the road?	0 (not sure), 1 (no overuse), 2 (occasionally overuse), 3 (sometimes overuse), 4 (usually overuse)
Q8 (9)	speed_1	practice	speed	When applying dry material for anti-/de-icing, what speed do you typically drive at?	0 (not sure), 1 (significantly slower), 2 (slightly slower), 3 (regular), 4 (faster), 5 (not sure about the optimal speed)

QueID	Variable Names	Category	Theme	Question	Choices
Q9 (10)	plow_1	practice	plow	How do you incorporate plowing into your snow and ice management routine before applying anti-/de-icing materials?	0 (not sure), 1 (always plow), 2 (often plow), 3 (sometimes plow), 4 (rarely plow)
Q10 (11)	multipasses_1	practice	adjustment (multipasses)	How frequently do you adjust your application rate of anti-/de-icing materials during multiple passes when treating snow and ice?	0 (not sure), 1 (always adjust), 2 (often adjust), 3 (sometimes adjust), 4 (rarely adjust)
Q11 (12)	longroutes_1	practice	long routes	How do you handle anti-/de-icing material application on long routes where only one pass is possible?	0 (not sure), 1 (always more), 2 (often more), 3 (sometimes more), 4 (rarely more)
Q12 (13)	highvol_traf_1	practice	adjustment (high traffic volume)	How do you adjust your application rate of anti-/de-icing material when encountering high traffic volume conditions?	0 (not sure), 1 (always lower), 2 (often lower), 3 (sometimes lower), 4 (rarely lower)
Q13 (14)	highspeed_traf_1	practice	adjustment (high traffic speed)	How do you adjust your use of anti-/de-icing materials when dealing with higher traffic speeds?	0 (not sure), 1 (always prewet), 2 (often prewet), 3 (sometimes prewet), 4 (rarely change)

QueID	Variable Names	Category	Theme	Question	Choices
Q14 (15)		practice	adjustment (temperature)	How do you adjust your anti-/de-icing material application rates based on temperature trends?	0 (not sure, 1 (always less), 2 (often adjust), 3 (sometimes adjust), 4 (rarely adjust)
Q15 (16)	spinspeed_1	practice	spinner	How do you adjust your spinner speed when spreading materials?	0 (not sure), 1 (always the lowest), 2 (often the lowest), 3 (sometimes the lowest), 4 (rarely adjust)
Q16 (17)	drysalt_15F_1	practice	dry salt (pavement temperatures)	How do you decide whether to apply dry salt based on pavement temperatures?	0 (not sure), 1 (always avoid dry salt), 2 (often avoid), 3 (sometimes apply), 4 (usually apply)
Q17 (18)	materialswitch _15F_1	practice	material adjust (15F)	How do you adjust your choice of materials when pavement temperatures are below 15˚F?	0 (not sure), 1 (always switch), 2 (often), 3 (sometimes), 4 (rarely)
Q18 (19)	saltsandmix_1	practice	sand/salt mix	In which situations do you consider using a sand/salt mix, despite it generally not being advised?	not sure, freezing rain, instructed, never use
Q19 (20)	sand_1	practice	utilizing sand	How do you utilize sand in your snow and ice management practices?	0 (not sure), 1 (always use), 2 (often use), 3

QueID	Variable Names	Category	Theme	Question	Choices
					(sometimes use), 4 (never use)
Q20 (21)	saltstorage_1	practice	salts storage1	How do you manage the storage of road salts and other de-icing materials in your area of operation? (Select all that apply)	not sure, covered storage, uncovered storage, enclosed containers, other (specify)
Q20_4_TEXT (21)		practice	slats storage2	How do you manage the storage of road salts and other de-icing materials in your area of operation? (Select all that apply)	
Q58_1 (22)	soilsalinity_1	awareness (chloride impacts)	soil salinity	How aware are you that chlorides in road salts can increase soil salinity, leading to compaction and erosion?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_2 (23)	water_1	awareness (chloride impacts)	water	How aware are you that excess chlorides from road salt can soak into groundwater or run off to nearby bodies of water?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_3 (24)	aqualife_1	awareness (chloride impacts)	aquatic life1	How aware are you that chlorides in road salts can reduce oxygen levels in waterways, affecting aquatic life?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)

QueID	Variable Names	Category	Theme	Question	Choices
Q58_4 (25)	metals_1	awareness (chloride impacts)	metals	How aware are you that many de-icing materials might contain trace metals like cyanide, arsenic, lead, and mercury?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_5 (26)	aquaorganism_1	awareness (chloride impacts)	aquatic life2 (sand)	How aware are you that sand used for winter operations can smother fish eggs and other aquatic organisms if it washes into streams or lakes?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_6 (27)	aquasys_1	awareness (chloride impacts)	toxic to aquatic systems (calcium chloride)	How aware are you that calcium chloride is extremely toxic to aquatic systems and should not be used near open drains?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_7 (28)	persist_1	awareness (chloride impacts)	persistence	How aware are you that once chlorides enter waterways, they can persist for a long time due to the lack of biological removal processes?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_8 (29)	veget_1	awareness (chloride impacts)	vegetation	How aware are you that salt spray from road salts can damage roadside vegetation?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q58_9 (30)	corrosion_1	awareness (chloride impacts)	corrosion	How aware are you that road salts can corrode vehicles and bridges?	1 (not aware or not sure about this), 2 (somewhat aware),

QueID	Variable Names	Category	Theme	Question	Choices
					3 (aware), 4 (very aware)
Q58_10 (31)	drinkwater_1	awareness (chloride impacts)	drinking water	How aware are you that road salts can contaminate drinking water reservoirs and wells?	1 (not aware or not sure about this), 2 (somewhat aware), 3 (aware), 4 (very aware)
Q31 (32)	leftover_freq_1	leftover salt	frequency of finding	How often do you find yourself with leftover salt in your truck after completing a snow event?	0 (not sure), 1 (always), 2 (often), 3 (sometimes), 4 (rarely), 5 (never)
Q32 (33)	dowithleftover	leftover salt	what you do with residual salt1	What do you typically do with residual salt left in your truck after a snow event? - Selected Choice	not sure, return it to the stockpile, store it in the truck for the next event, spread it on the roads,
Q32_5_TEXT (33)		leftover salt	what you do with residual salt2	What do you typically do with residual salt left in your truck after a snow event? - Dispose of it in another way (please specify): __________ - Text	
Q33 (34)	return_freq_1	leftover salt	frequency of return	If you return residual salt to the stockpile, how frequently do you do so?	0 (not sure), 1 (always), 2 (often), 3 (sometimes), 4 (rarely), 5 (never)

QueID	Variable Names	Category	Theme	Question	Choices
Q34 (35)		leftover salt	storage1	When storing residual salt in the truck for the next event, how do you ensure it remains usable? (Select all that apply) - Selected Choice	cover it with a tarp, etc.
Q34_4_TEXT (35)		leftover salt	storage2	When storing residual salt in the truck for the next event, how do you ensure it remains usable? (Select all that apply) - Other (please specify): __________ - Text	
Q35 (36)	concern_excess_1	leftover salt	concern (excessive use)	How concerned are you about the potential for excessive salt use due to residual salts left in trucks?	1 (very concerned), 2 (concerned), 3 (somewhat), 4 (not concerned), 5 (not an issue),
Q36 (37)	guide_1	leftover salt	guidelines	Are there organizational guidelines on how to manage leftover salts after a snow event?	0 (not sure), 1 (Yes, detailed), 2 (Yes, vague), 3 (No)
Q37 (38)	guide_effective_1	leftover salt	guidelines (effectiveness)	In your opinion, how effective are these guidelines in managing residual salts?	0 (no guideline), 1 (very effective), 2 (effective), 3 (somewhat effective), 4 (not effective)
Q38 (39)		leftover salt	challenges1	What challenges do you face when dealing with leftover salts in your truck? (Select all that apply) - Selected Choice	

QueID	Variable Names	Category	Theme	Question	Choices
Q38_4_TEXT (39)		leftover salt	challenges2	What challenges do you face when dealing with leftover salts in your truck? (Select all that apply) - Other (please specify): _______________ - Text	
Q39 (40)		leftover salt	suggestions1	Do you have any suggestions for improving the management of residual salts to reduce excessive use? - Selected Choice	Yes, No
Q39_2_TEXT (40)		leftover salt	suggestions2	Do you have any suggestions for improving the management of residual salts to reduce excessive use? - Yes (please describe) - Text	
Q59_1 (41)	safetyvshard_2	agreement	transport safety outweighs hard infra	To what extent do you agree with the following statement? - The priority of applying de-icing materials to maintain road safety and traffic flow should outweigh the potential for corrosive damage to infrastructure, including bridges, roads, vehicles, and underground utilities.	1 (strongly agree), 2 (agree), 3 (neither), 4 (disagree), 5 (strongly agree)
Q59_2 (42)	safetyvsnatural_2	agreement	transport safety outweighs natural env	To what extent do you agree with the following statement? - The use of anti-/de-icing materials on roads is essential for maintaining traffic flow and safety during winter weather	1 (strongly agree), 2 (agree), 3 (neither), 4 (disagree), 5 (strongly agree)

QueID	Variable Names	Category	Theme	Question	Choices
				events, despite the potential negative impacts on the natural environment.	
Q46_1 (43)	sustprac_1	Perception	ASSHTO guidelines1 (sustprac)	Based on your perception, is your organization exercising the practices listed below for its winter maintenance program? (Choose one for each). Note that the following winter maintenance practices have been determined to be some of the most important necessary for a world-class winter maintenance program according to the AASHTO guidelines. Using sustainable winter maintenance practices	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_2 (44)	wethfore_1	Perception	ASSHTO guidelines2 (wethfore)	Utilization of accurate and timely weather forecasts	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_3 (45)	routeopt_1	Perception	ASSHTO guidelines3 (routeopt)	Optimal route planning or route optimization programs	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)

QueID	Variable Names	Category	Theme	Question	Choices
Q46_4 (46)	equipcalib_1	Perception	ASSHTO guidelines4 (equipcalib)	Reliable equipment and equipment calibration programs	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_5 (47)	equipmaint_1	Perception	ASSHTO guidelines5 (equipmaint)	Equipment maintenance program (preventative and routine)	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_6 (48)	effopr_1	Perception	ASSHTO guidelines6 (effopr)	Efficiency in operations - intelligent use of resources	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_7 (49)	comm_1	Perception	ASSHTO guidelines7 (comm)	Communication between operation controllers and drivers	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_8 (50)	snowplans_1	Perception	ASSHTO guidelines8 (snowplans)	Snow plans (Include operational evaluation/continuous improvement)	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q46_9 (51)	perfstand_1	Perception	ASSHTO guidelines9 (perfstand)	Performance standards for winter-service are in place	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at

QueID	Variable Names	Category	Theme	Question	Choices
					all), 4 (being searched)
Q46_10 (52)	levelserv_1	Perception	ASSHTO guidelines10 (levelserv)	Defined levels of service	0 (not sure), 1 (fully implemented), 2 (partially), 3 (not at all), 4 (being searched)
Q60_1		MCA	cost	Relative importance of different criteria for selecting which de-icing materials to use. As part of our efforts to improve winter road maintenance, we are evaluating the criteria for choosing the best de-icing materials. We value your experience and judgment in this area. Please rank the following eight criteria in order of importance, from most important (1) to least important (8), based on your experience in winter operations. Your input will help us make informed decisions. Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Cost** (Direct cost of material)	

QueID	Variable Names	Category	Theme	Question	Choices
Q60_2		MCA	Availability	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Availability** (Consistency of supply and ease of procurement)	
Q60_3		MCA	Melting Capacity	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Melting Capacity** (Ability of material to melt ice at different temperatures)	
Q60_4		MCA	Residual Effectiveness	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Residual Effectiveness** (How long the material remains effective after application)	
Q60_5		MCA	Environmental Impact	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) –	

QueID	Variable Names	Category	Theme	Question	Choices
				Environmental Impact (Impact on flora / fauna, biodegradability, and waterways and aquatic life)	
Q60_6		MCA	Corrosiveness	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Corrosiveness** (Potential for causing damage to roads, bridges, and vehicles)	
Q60_7		MCA	Safety	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Safety** (Impact on traction and road condition for drivers)	
Q60_8		MCA	Ease of Application	Please provide your ranking of each criteria by dragging each option to its appropriate location (top is the highest rank and bottom is the lowest rank) - **Ease of Application** (Simplicity and speed for applying the material)	

Appendix I. A Sample of Past Related JTRP Studies Related to Road Deicing

Aspect: Salting and snow-removal management and operations

- Wright (1988)
- McClellan et al. (2009)
- McCullouch et al. (2013)
- Desai et al. (2020)
- Mahlberg et al. (2021)
- Iyer et al. (2021)
- Iyer et al. (2022)
- Mahlberg et al. (2023)
- Zhang et al. (2024).

Aspect: Measurement and mitigation of environmental damage posed by salt applications

- Wilcox (1982)
- Alleman et al. (2004)
- Corson (2004)
- Hashad et al. (2006)
- Garner and Royer (2010)
- Ji et al. (2020).

Aspect: Infrastructure damage caused by deicing salts

- Frosch et al. (2014)
- Labi et al (2014)
- Suraneni et al. (2016)
- Tokpatayeva et al. (2025)
- Cope et al. (2011)

References

Alaska Department of Transportation. (2014). *Alaska highway maintenance and operations handbook*. https://dot.alaska.gov/stwddes/research/assets/pdf/ak_maint-ops_hb.pdf

Brown County Public Works Department. (2020). *Winter highway maintenance manual*. https://www.browncountywi.gov/i/f/files/Public-Works/Brown%20County%20Winter%20Highway%20Maintenance%20Manual_2020-21edition.pdf

Casey, P. C., Alwan, C. W., Kline, C. F., Landgraf, G. K., & Lonsenmayer, K. R. (2014). *Impacts of using salt and salt brine for roadway deicing* (Idaho Transportation Department Report No. FHWA-ID-14-231). https://apps.itd.idaho.gov/apps/research/Completed/RP231.pdf

Cope, A., Bai, Q., Samdariya, A., & Labi, S. (2011). Assessing the efficacy of stainless steel for bridge deck reinforcement under uncertainty using Monte Carlo simulation. *Structure and Infrastructure Engineering*, *9*(7), 634–647. https://doi.org/10.1080/15732479.2011.602418

Corson, L. A. (2004). *Development of a strategy for preparing an INDOT storm water quality management plan* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2004/18). Purdue University. https://doi.org/10.5703/1288284313189

Desai, J., Mathew, J. K., Kim, W., Liu, M., Li, H., Brooks, J. D., & Bullock, D. M. (2020). *Dashboards for real-time monitoring of winter operations activities and after-action assessment* (JTRP Affiliated Reports Paper 33). Purdue University. https://doi.org/10.5703/1288284317252

Frosch, R. J., Labi, S., & Sim, C. (2014). *Increasing bridge deck service life: Volume I—Technical evaluation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/16). Purdue University. https://doi.org/10.5703/1288284315516

Gardner, K. M., & Royer, T. V. (2010). Effect of road salt application on seasonal chloride concentrations and toxicity in south-central Indiana streams. *Journal of Environmental Quality*, *39*(3), 1036–1042. https://doi.org/10.2134/jeq2009.0402

Hashad, M. F., Sharma, S., Nies, L. F. & Alleman, J. E. (2006). *Study of salt wash water toxicity on wastewater treatment* (Joint Transportation Research Program Publication FHWA/IN/JTRP-2005/21). Purdue University. https://doi.org/10.5703/1288284313386

Iyer, A. V., Dunlop, S. R., Senicheva, O., Thakkar, D. J., Yan, R., Subramanian, K., Vasu, S., Siddharthan, G., Vasandani, J., & Saurabh, S. (2021). *Improve and gain efficiency in winter* *operations* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/11). Purdue University. https://doi.org/10.5703/1288284317312

Iyer, A. V., Labi, S., Dunlop, S. R., Thakkar, D. J., Mishra, S., Kumar, L. K., Du, R., Gala, M., Banerjee, A., & Siddharthan, G. (2022). *Heavy fleet and facilities optimization* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2022/03). Purdue University. https://doi.org/10.5703/1288284317365

Ji, Y., McCullouch, B., & Zhou, Z. (2020). *Evaluation of anti-icing/de-icing products under controlled environmental conditions* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2020/22). Purdue University. https://doi.org/10.5703/1288284317253

Labi, S., Frosch, R. J., Samdariya, A., & Qing, Y. (2014). *Increasing bridge deck service life: Volume II—Economic evaluation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/17). Purdue University. https://doi.org/10.5703/1288284315517

Mahlberg, J. A., Manish R., Koshan, Y., Joseph, M., Liu, J., Malackowski, H. A., DeLoach, Z., Wells, T., McGuffey, J., Habib, A., & Bullock, D. M. (2023). *Salt monitoring and reporting technology (SMART) for salt stockpile inventory reporting* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/19). Purdue University. https://doi.org/10.5703/1288284317650

Mahlberg, J., Zhang, Y., Jha, S., Mathew, J. K., Li, H., Desai, J., Kim, W., McGuffey, J., Wells, T., Krogmeier, J. V., & Bullock, D. M. (2021). *Development of an intelligent snowplow truck that integrates telematics technology, roadway sensors, and connected vehicle* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/27). Purdue University. https://doi.org/10.5703/1288284317355

McClellan, T., Coleman, M., Boone, P., & Carpenter, K. (2009). Implementing a winter maintenance decision support system: Indiana Department of Transportation's process, success, and savings. *TR News*, *265*, 35–37. https://onlinepubs.trb.org/onlinepubs/trnews/trnews265rpo.pdf

McCullouch, B., Partridge B., & Noureldin S. (2013). *Snow and ice performance standards* (Joint Transportation Research Program Publication FHWA/IN/JTRP-2013/21). Purdue University. https://doi.org/10.5703/1288284315223

Michigan Department of Transportation. (2013). *Michigan winter maintenance manual – Promoting safe roads and clean water*. Retrieved from https://miwintermaintenance.weebly.com/uploads/1/7/1/6/17161926/mi_winter_maintenance_manual_2013.pdf

Minnesota Department of Transportation. (2022). *Minnesota snow and ice control handbook for snowplow operators* (2022RIC01). https://mdl.mndot.gov/items/2022RIC01

South Dakota Department of Transportation. (2023). *2022-2023 South Dakota Department of Transportation winter highway maintenance plan*. https://boardsandcommissions.sd.gov/bcuploads/Attach%204%20-%20Consideration%20of%20Winter%20Highway%20Maintenance%20Plan%202022%20-%2023.pdf

Suraneni, P., Monical, J., Unal, E., Farnam, Y., Villani, C., Barrett, T. J., & Weiss, W. J. (2016). *Performance of concrete pavement in the presence of deicing salts and deicing salt cocktails* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/25). Purdue University. https://doi.org/10.5703/1288284316350

Tokpatayeva, R., Castillo, A., & Olek, J. (2025). *Interaction of cementitious systems containing nontraditional and natural pozzolans (NNPs) with chloride-based deicers* [Conference session]. Eighth International Conference on Durability of Concrete Structures, Heriot-Watt University, Edinburgh, United Kingdom. https://doi.org/10.5703/1288284318138

Town of Greenville Department of Public Works. (2015). *Snow and ice control manual*. https://cms3.revize.com/revize/greenvillewi/Snow%20Manual%20-%202019%20WEBSITE.pdf

Vermont Agency of Transportation. [VTrans]. (2015, March 24). *Vermont's snow and ice control plan* [Video]. YouTube. https://www.youtube.com/watch?v=rmnYab85DBc

Walworth County. (2022). *Winter maintenance manual*. https://www.co.walworth.wi.us/DocumentCenter/View/10156/Walworth-County-Winter-Maintenance-Manual-PDF?bidId=

Wilcox, D. A. (1982). *The effects of deicing salts on water chemistry and vegetation in Pinhook Bog, Indiana* [Doctoral dissertation, Purdue University]. https://docs.lib.purdue.edu/dissertations/AAI8300976/

Wright, J. R. (1988). Development of a prototype system for snow route design and management (Joint Highway Research Project Publication FHWA/IN/JHRP-88/17). Purdue University. https://doi.org/10.5703/1288284314156

Zhang, Y., Ault, A., Krogmeier, J. V. (2024). Automated record keeping for statewide winter road maintenance using telematics tracks [Conference session]. 2024 IEEE 99th Vehicular Technology Conference, Singapore. https://doi.org/10.1109/VTC2024-Spring62846.2024.10683171

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at https://docs.lib.purdue.edu/jtrp/.

Further information about JTRP and its current research program is available at https://engineering.purdue.edu/JTRP.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

John, A. P., Shin, H. C., Mwamba, I. C., Yu, D. J., Shah, A., & Labi, S. (2025). *Reducing the dependency on chlorides and impacts* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2025/15). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317879