WINTER SEVERITY INDEX WITH WINTER MAINTENANCE EXPENSES AND MATERIAL USAGE

FINAL REPORT

Research Administration
Reference Number: OR23-003

Prepared for
Michigan Department of Transportation
Division of Research
8885 Ricks Road
Lansing, MI 48917

Prepared by
Michigan State University
Department of Civil and Environmental Engineering
428 South Shaw Lane
East Lansing, MI 48824

July 2025

Technical Report Documentation Page

1. Report No. SPR-1755	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.**
4. Title and Subtitle Winter Severity Index with Winter Maintenance Expenses and Material Usage		**5. Report Date** July 2025 **6. Performing Organization Code** N/A
7. Author(s) Ali Zockaie, Ardeshir Fadaei, Farish Jazlan, Hamid Mozafari, Mehrnaz Ghamami, Timothy Gates, Peter Savolainen, Jeffrey Andresen.		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Michigan State University 428 S. Shaw Lane Department of Civil and Environmental Engineering 3546 Engineering Building East Lansing, MI 48824		**10. Work Unit No. (TRAIS)** N/A **11. Contract or Grant No.** Contract #2023-0155
12. Sponsoring Organization Name and Address Michigan Department of Transportation (MDOT) Research Administration 8885 Ricks Rd P.O. Box 30049 Lansing, MI 48909		**13. Type of Report and Period Covered** Final Report (02/06/2023 to 07/05/2025) **14. Sponsoring Agency Code** N/A

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Michigan Department of Transportation (MDOT) research reports are available at www.michigan.gov/mdotresearch.

16. Abstract

Effective winter road maintenance is crucial for safe travel and represents a substantial portion of the Michigan Department of Transportation's (MDOT) annual budget. A primary challenge in winter operations is resource allocation for different winter maintenance materials, due to the substantial variability in winter weather conditions across Michigan's diverse regions. MDOT currently employs a Weather Severity Index (WSI); however, this existing WSI does not explicitly account for regional differences in weather phenomena or directly translate weather severity into associated maintenance costs. To address this challenge, this study aimed to develop a more accurate and actionable index linking regional weather conditions directly to winter maintenance costs. Initially, a comprehensive literature review was conducted to identify best practices nationwide. This review revealed a variety of approaches among state Departments of Transportation agencies, emphasizing the benefits of region-specific weather indices that directly correlate to maintenance expenditures. To gain further insights, two targeted surveys were conducted. First, a statewide survey of Michigan's MDOT garages highlighted significant variability in local maintenance practices, driven primarily by localized weather phenomena such as lake-effect snow. Second, a nationwide DOT survey provided a broader perspective, confirming the value of integrating short-term forecasting and detailed weather data into severity indices to improve proactive resource management. Leveraging these insights, the research team developed the Material Cost-based Winter Severity Index (MC-WSI), explicitly designed to capture unique Michigan regional climates. The NOAA Climate Divisions were adopted as the regional framework, segmenting Michigan into 10 climatologically homogeneous regions. Due to limitations in operational cost data, standardized material unit costs derived from historical bid records were applied consistently across the state. Statistical analyses based on various weather factors correlated with material costs identified pavement temperature, hours of snowfall, and hours of freezing rain as the most significant predictors of monthly material usage. Robust linear regression models were developed and validated using five-fold cross-validation, confirming the high accuracy and reliability of the models. The MC-WSI depicts these predicted material costs into a standardized index ranging from 0 to 100, allowing decision-makers to directly interpret weather impacts and proactively adjust operational plans and budgets. Comparative assessments showed that the MC-WSI substantially outperforms the MDOT current index in correlating with actual material usage rates in different regions. Finally, strategic recommendations and future research opportunities were identified, including the adoption of MC-WSI into operational practice and developing an online tool for automated estimation and a short-term forecasting module integrated with an improved real-time data management system (weather features and maintenance costs). While specifically developed for Michigan, this research provides valuable methods and insights applicable to other states confronting similar winter maintenance challenges.

17. Keywords Winter Maintenance Operations, Winter Maintenance Budget Management, Weather Severity Index, Regression Models		**18. Distribution Statement** No restrictions. This document is available to the public through the Michigan Department of Transportation.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 137	**22. Price** $190,000.00

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

WINTER SEVERITY INDEX WITH WINTER MAINTENANCE EXPENSES AND MATERIAL USAGE

FINAL REPORT

July 2025

Principal Investigator
Ali Zockaie, Ph.D.
Associate Professor
Michigan State University

Authors
Ali Zockaie, Ardeshir Fadaei, Farish Jazlan, Hamid Mozafari, Mehrnaz Ghamami, Timothy Gates, Peter Savolainen, Jeffrey Andresen.

Sponsored by
Michigan Department of Transportation

A report from
Michigan State University
Department of Civil and Environmental Engineering
428 South Shaw Lane
East Lansing, MI 48824

PUBLICATION DISCLAIMER

This publication is disseminated in the interest of information exchange. The Michigan Department of Transportation (hereinafter referred to as MDOT) expressly disclaims any liability, of any kind or for any reason, which might otherwise arise out of any use of this publication or the information or data provided in the publication. MDOT further disclaims any responsibility for typographical errors or the accuracy of the information provided or contained within this information. MDOT makes no warranties or representations whatsoever regarding the quality, content, completeness, suitability, adequacy, sequence, accuracy, or timeliness of the information and data provided or that the contents represent standards, specifications, or regulations.

ACKNOWLEDGMENTS

The research team would like to acknowledge the Michigan Department of Transportation (MDOT) for sponsoring this research and the Federal Highway Administration for State Planning and Research (SPR) funds used for this project. The authors also acknowledge the contributions of the members of the MDOT Research Advisory Panel (RAP) for guidance and direction on project tasks, with special recognition to MDOT Project Manager, James Roath, and Research Manager, Andre Clover. The research team also expresses gratitude to all other MDOT RAP members: Melissa Longworth and John Paepke, who provided feedback on various stages of the project to ensure project objectives were met and to improve the quality of project deliverables and outcomes. In addition, we would like to thank Adam Chambers (DTN), John Mewes (DTN), Justin Dorste (MDOT), Jennett Dave (MDOT), and Sarah Plumer (TAMC) for their valuable support and contributions to the project. We also appreciate the staff from state DOTs across the country who participated in the nationwide surveys conducted as part of this research. Finally, Special thanks to the MDOT winter maintenance garage staff and the commissioned county garage staff for their participation in the statewide survey and for sharing insights that were critical to understanding on-the-ground practices and needs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Winter road maintenance in Michigan presents significant challenges due to the state's complex climate, geographic diversity, and extensive road network. The Michigan Department of Transportation (MDOT) annually invests substantial resources—particularly in salt, sand, and liquid deicers—to ensure safe travel conditions during winter months. Recently, MDOT has introduced a Weather Severity Index (WSI) to assess and compare winter severity over the years and link this metric to various activities and maintenance operations. However, this existing index has not fully captured the complexity and regional variability of Michigan's weather conditions. In addition, to incorporate this index for resource allocation and budget management, it is essential to correlate it with winter maintenance costs over the years to establish its merits for this particular application.

To address these limitations, this study developed and validated a Modified Weather Severity Index designed explicitly for Michigan. The project aimed to create a more accurate, reliable, and actionable proxy for estimating material costs associated with winter maintenance, thereby optimizing operational efficiency and financial planning.

Research Objectives

This study was undertaken to improve the MDOT's ability to allocate resources and manage winter maintenance budgets more effectively across the state. The primary objectives of the research were to:

- Develop a modified, regionally sensitive WSI that better reflects Michigan's diverse climatic conditions and maintenance needs.
- Link weather severity to actual material usage costs in a statistically robust and interpretable way.
- Provide actionable insights and tools to improve budget forecasting, material procurement, and operational planning.
- Enhance communication and coordination between MDOT-operated garages and contracted county service providers by promoting consistency in how winter severity is interpreted.

Research Approach

To achieve these objectives, the research followed a multi-stage plan incorporating both qualitative and quantitative methodologies:

- **Task 1:** Conduct a literature review of existing WSIs and winter maintenance practices nationally.
- **Task 2:** Analyze MDOT's current practices, including budgeting, material reporting, and garage-level operations.
- **Task 3:** Carry out a nationwide survey of state DOTs to understand best practices and emerging trends in winter severity measurement.
- **Task 4:** Survey local service providers and MDOT garages in Michigan to identify operational challenges and needs.
- **Task 5:** Develop a region-specific, Modified WSI tailored to Michigan's climate and operational data.
- **Task 6:** Validate and verify the new WSI through pilot testing and statistical analysis.
- **Task 7:** Provide final recommendations for operational integration, automation, and future improvements.

Regional Framework Selection

Initially, MDOT's administrative boundaries—comprised of seven regions coordinated by Transportation Service Centers—were examined. However, statewide garage surveys revealed that these administrative boundaries did not effectively capture local climatic variations, especially phenomena such as lake-effect snow and localized freezing rain. Results from a nationwide survey of other state DOTs also suggested that weather-centric frameworks significantly improve the precision and effectiveness of winter resource management. Therefore, the project team selected NOAA's Climate Divisions, dividing Michigan into 10 climate-based regions. This framework groups counties according to climatological similarity, capturing critical local weather phenomena and providing a better basis for region-specific modeling of winter maintenance needs. The numerical results and statistical analyses also confirmed that Region-specific models developed for the NOAA's Climate Divisions outperform models developed for MDOT administrative regions in terms of accuracy and validation metrics.

Standardized Material Costs Calculation

Accurately calculating winter maintenance costs ideally involves considering labor, equipment, operational expenses, and detailed materials data. However, such comprehensive data were not consistently available, prompting a focus on reliably accessible material-usage data. Since different garages incorporate different types of materials for their maintenance activities, there was a need to normalize the material-usage data to general material cost data. To this end, the team utilized standardized unit prices derived from publicly available historical bid records to consistently normalize material costs:

- Salt: $60 per ton
- Sand: $10 per ton
- Liquid Deicer: $0.50 per gallon

Monthly material usage from MDOT garages was converted to costs and aggregated at a regional level, normalized by total lane miles covered by each garage. This standardized “material cost per lane mile” provided a consistent basis for comparing regional expenditures and assessing weather impacts on maintenance operations.

Feature Selection and Data Preparation

A comprehensive evaluation of weather data sources identified MDOT’s Maintenance Decision Support System (MDSS) Weather and Maintenance Response Index (WMRI) as the most reliable and consistent data provider. Thirteen relevant weather variables were initially considered, including air temperature, pavement temperature, long-wave radiation, short-wave radiation, snowfall duration, freezing rain hours, snow accumulation, blowing snow duration, ice accumulation, strong wind hours, number of snow events, number of freezing rain events, and number of frost events.

To refine the list of variables, rigorous statistical methods—Pearson correlation analysis, Variance Inflation Factor (VIF) testing for multicollinearity, and Lasso regression—were employed. This meticulous feature selection process narrowed the predictive variables down to the three most significant and independent features:

- **Pavement temperature** (indicative of maintenance intensity, generally reducing material needs as temperature increases).

- **Hours of snowfall** (directly correlated with increased salt usage and plowing requirements).
- **Hours of freezing rain** (highly correlated with intensive use of deicing materials).

Model Development and Finalization

With refined regional divisions and optimized weather features, robust linear regression models were developed separately for each NOAA-based region. The robust regression method was specifically chosen because it effectively handles outliers, does not require normal distribution of residuals, and accommodates heteroscedasticity (changing variance in material costs with weather conditions). The resulting models were validated using a five-fold cross-validation approach, ensuring they were robust, reliable, and generalizable.

The final regression models exhibit consistent patterns across regions:

- **Intercept**: Represented baseline maintenance costs, capturing essential ongoing expenses independent of severe weather events.
- **Pavement Temperature**: Consistently negative coefficients across all regions, indicating cost reduction with warmer pavement conditions. Southeast Lower region (including Detroit) showed the highest sensitivity ($5.31 per one Fahrenheit degree decrease in temperature), indicating a significant cost increment with increasing temperatures.
- **Hours of Snowfall**: Positive coefficients indicated direct increases in material costs with longer snowfall events. The Southeast Lower region again demonstrated the highest sensitivity ($3.53 per hour of snow per lane mile).
- **Hours of Freezing Rain**: Positive coefficients signifying significant cost impact, particularly high in regions such as the Northwest Lower, indicating costly maintenance requirements during freezing rain events.

Notably, the Southeast Lower region—which includes large urban centers such as Detroit—exhibited the greatest sensitivity to changes in weather conditions, underscoring the significant operational challenges and associated costs faced by urbanized areas. Factors such as higher traffic volume, more complex infrastructure, and stringent maintenance standards explain the greater resource needs identified in these urban settings.

Validation and Comparative Performance

The MC-WSI was rigorously tested and validated against observed historical data. Results demonstrated significant improvements over MDOT's existing WSI system, with a very high coefficient of determination ($R^2 = 0.95$), reflecting strong predictive capability, and minimal prediction errors (RMSE = 8.36%). Comparative analyses confirmed the MC-WSI's superior ability to capture actual regional variations and associated cost impacts, enhancing MDOT's capability to allocate winter maintenance resources effectively.

Material Cost-based Winter Severity Index (MC-WSI) Rating Scheme

To facilitate straightforward interpretation and practical application of model results, estimated monthly material costs were normalized and scaled into a standardized cost-based index ranging from 0 (low severity) to 100 (extreme severity). This index, referred to as the MC-WSI, reflects the relative severity of winter conditions based on associated material costs.

The normalization is conducted using the maximum estimated material cost observed across all regions and months in the dataset. As such, MC-WSI values represent the proportional severity of a given region and month compared to the most severe condition historically observed.

This relative structure enables consistent comparison across regions and time periods, providing MDOT with a unified framework for evaluating winter maintenance needs. However, the index values are not intended to represent absolute thresholds of operational impact, and their interpretation should be made within the context of historical regional performance.

Recommendations

Based on the comprehensive modeling outcomes, several strategic recommendations and areas for future work have emerged:

- **Adoption of the MC-WSI:** Implement the MC-WSI framework in operational budget management and resource allocation practices to improve accuracy, efficiency, and resource planning across Michigan's diverse regions.
- **Training and Support for Implementation:** Conduct targeted training sessions for both MDOT-operated garages and contracted county agencies to support the understanding and application of the MC-WSI and associated tools. This will support consistent interpretation, data quality, and buy-in across all stakeholders.

- **Expand MDSS Access for Contracted County Garages:** Providing additional resources to ensure contracted county service providers have access to key MDSS functionalities, contributing consistent weather and operational data, and automated MC-WSI estimations.
- **Enhanced Data Collection and Management:** Strengthen current data collection practices, emphasizing the integration of more detailed operational costs, including labor and equipment usage, to enhance model accuracy in future refinements.
- **Ongoing Validation and Model Refinement:** Continuously validate and update regional models (in a 3–5-year time window), potentially incorporating additional operational or environmental variables as data becomes available, ensuring the MC-WSI maintains its predictive accuracy over time.
- **Enhancing Automation and Operational Efficiency:** Develop a state-of-the-art tool to automatically estimate MC-WSI for different garages, leveraging regional models to transform MDSS-generated weather data directly into monthly severity index values and cost estimates. By automating the data-cleaning and calculation processes, this tool would significantly reduce manual workload, minimize human error, and improve consistency in reporting. Additionally, integrating customizable dashboards for seamless data visualization, historical trend analysis, and data export capabilities would further enhance operational decision-making.
- **In-Season Budget Adjustment Capability:** Incorporate real-time budget recalibration methods within the automated tool by comparing current-season MC-WSI values to historical five-year averages. This feature would enable MDOT to proactively adjust financial allocations throughout the winter, allowing improved resource allocation and budgetary responsiveness to fluctuating seasonal conditions.
- **Expanding Forecasting Capabilities with Short-Term Probabilistic Forecasting:** Develop and integrate a predictive capability using 10-day probabilistic weather forecasts to generate short-term MC-WSI projections. This functionality would provide MDOT with early indications of upcoming weather severity, enabling proactive operational planning, timely adjustment of material orders, and ultimately achieving greater cost savings and operational efficiency.

Ultimately, the MC-WSI represents a substantial advancement in winter maintenance planning for MDOT, accurately reflecting regional weather complexities and their resource allocation implications. This study provides Michigan transportation authorities with an actionable, statistically robust tool that will facilitate a more cost-effective winter road management across the state.

CHAPTER 1 - INTRODUCTION

1.1 Statement of the Problem

State and local agencies nationwide allocate over $2.3 billion annually for snow and ice control operations, with winter maintenance accounting for approximately 20% of maintenance budgets for state Department of Transportation (DOT) (*1*, *2*). In Michigan, the challenge is especially severe due to the region's harsh winter conditions, highlighted by the use of over 411,001 tons of salt during the 2020–2021 winter season, which incurred a total winter maintenance cost of approximately $90 million. (*3*).

The core problem lies in the unpredictable nature of winter storms. Unforeseen storm events, especially those occurring early in the season, can lead to imbalanced resource allocation. This imbalance may result in excessive material use upfront and consequential shortages later in the season when demand is critical. Moreover, the current approaches to planning and budgeting, which rely on existing Weather Severity Indices (WSI), do not fully capture the dynamic relationship between weather variability, material consumption, and budget constraints.

The need for a more reliable and region-specific predictive tool is evident. An improved, modified WSI could serve as a surrogate measure that more accurately forecasts material usage and guides budget allocation, thereby ensuring a more consistent and effective winter maintenance operation across Michigan.

1.2 Study Objectives

The overarching goal of this study is to enhance winter maintenance operations in Michigan through the development and implementation of a modified Weather Severity Index (WSI) that more accurately forecasts material usage and informs budgeting decisions. To achieve this, the study is designed around the following specific objectives:

- **Identify Current Uses of Winter Severity Indices Nationwide:**
  Investigate and synthesize the diverse applications of WSIs used by state DOTs across the country. This includes reviewing the methodologies, configurations, and rating schemes that have been employed to address winter maintenance challenges.
- **Define a WSI to Forecast Budget and Material Needs:**
  Configure a modified WSI tailored to Michigan’s unique climatic and operational conditions. The new index should integrate region-specific weather data and historical

material usage to provide a more accurate proxy for forecasting the necessary budget and materials for winter maintenance operations.

- **Improve Alignment and Consistency Between Service Providers:** Enhance the coordination between MDOT and local service providers by standardizing the use of a modified WSI. This objective aims to ensure that both state and local entities share a common understanding of winter severity and its impact on maintenance requirements, thereby reducing resource imbalances and operational inconsistencies.

These objectives collectively aim to bridge the gap between existing forecasting methods and the dynamic demands of winter maintenance, ensuring that Michigan is better equipped to manage its winter resources effectively.

1.3 Research Plan

The research plan is structured as a multi-stage process designed to ensure a comprehensive evaluation and development of a modified Weather Severity Index (WSI) tailored for Michigan's winter maintenance operations. The plan unfolds in the following sequential tasks:

- Task 1: Literature Review
- Task 2: Review of Michigan's Current Practices
- Task 3: Nationwide State DOTs Survey
- Task 4: Survey/Interview with Local Service Providers in Michigan
- Task 5: Develop Preliminary Modified WSI & Rating Scheme
- Task 6: Pilot Phase for Modified WSI Validation and Verification
- Task 7: Final Recommendation for WSI Improvements
- Task 8: Develop and Deliver Draft and Final Reports

These tasks and their relationships are illustrated in Figure 1-1.

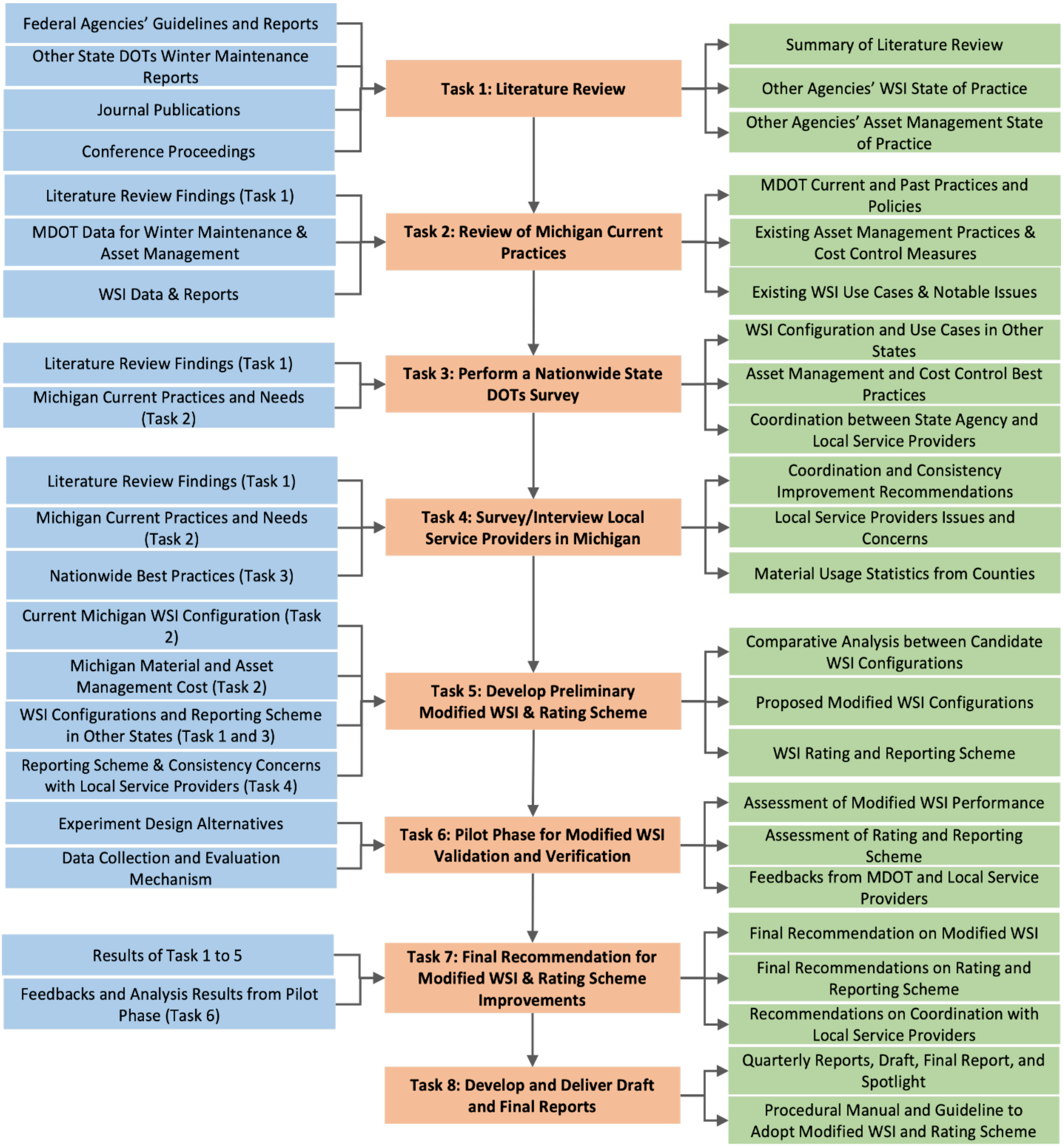


Figure 1-1: Project Research and Data Collection Plan Flowchart

1.4 Report Structure

The remainder of this report is structured as follows: Chapter 2 reviews the literature on winter maintenance operations, best practices, and previous studies, focusing on existing WSIs, state DOT investigations, and weather impacts on maintenance and safety. Chapter 3 provides a comprehensive review of MDOT's current practices and presents a survey of local service providers in Michigan, outlining the purpose, methodology, and insights gathered on material application, budgeting, and MDOT coordination. Chapter 4 details the nationwide survey of state DOTs, describing its design, administration, and key findings related to WSI configurations, material usage practices, and cost control strategies. Chapter 5 focuses on analyzing nationwide winter maintenance data from the Clear Roads annual survey to identify correlations between weather severity and winter maintenance costs across different U.S. climate regions. Chapter 6 describes the development of the modified WSI and its rating scheme, including region selection, material cost calculation, feature selection, model development, and a comparative analysis of various indices. Chapter 7 outlines the model validation and verification of the modified WSI developed in this study, implementing the 5-fold cross-validation approach, and highlighting the pilot study results. Finally, Chapter 8 summarizes the key findings and presents actionable recommendations for improving asset management and winter maintenance planning in Michigan.

CHAPTER 2 - LITERATURE REVIEW

This chapter provides a comprehensive overview of the existing knowledge and practices surrounding WSIs and their role in winter maintenance operations. It is organized into three main sections. Section 2.1 reviews prominent WSIs developed in past studies, including both standardized and customized approaches used across various states. Section 2.2 highlights the documented effects of winter weather on roadway maintenance needs and safety outcomes. Finally, Section 2.3 summarizes key takeaways from the literature and identifies existing gaps that the current study aims to address.

2.1 Review of Existing WSIs

2.1.1 Pre-defined Winter Severity Indexes

A number of pre-defined Winter Severity Indices have been developed over the past decades, each with its own methodological approach, advantages, and limitations. Four prominent indices are examined below.

Accumulated Winter Season Severity Index (AWSSI):

One of the earliest and most influential WSIs developed in the literature is the Accumulated Winter Season Severity Index (AWSSI), which compiles daily observations of temperature, snowfall, and snow depth into a cumulative score (equation 2-1). This index offers an objective, site-specific measure that facilitates historical comparisons and long-term climatological assessments. Its strength lies in its simplicity and ability to capture overall seasonal conditions. However, because it relies on daily cumulative data, AWSSI tends to smooth out the nuances of individual storm events, and its accuracy is highly dependent on the quality of snowfall measurements, which can be affected by issues such as gauge under catch and data gaps (*4*).

$$\text{AWSSI} = \sum_{i=1}^{N} [\underbrace{(\text{Min Temp Score}_i + \text{Max Temp Score}_i)}_{\text{Daily Temp Score}_i} + \underbrace{(\text{Snowfall Score}_i + \text{Snow Depth Score}_i)}_{\text{Daily Snow Score}_i}] \quad (2\text{-}1)$$

The daily total AWSSI point accumulation is determined based on maximum and minimum temperature, snowfall, and snow depth values, which are listed in Table 2-1.

Table 2-1: Point contributions to daily AWSSI as based on thresholds of daily maximum and minimum temperature, snowfall, and snow depth (*4*)

	Temperature (F)		Snow (in)	
Points	Max	Min	Fall	Depth
1	25–32	25–32	0.1–0.9	1
2	20–24	20–24	1.0–1.9	2
3	15–19	15–19	2.0–2.9	3
4	10–14	10–14	3.0–3.9	4–5
5	5–9	5–9	—	6–8
6	0–4	0–4	4.0–4.9	9–11
7	From -1 to -5	From -1 to -5	5.0–5.9	12–14
8	From -6 to -10	From -6 to -10	—	15–17
9	From -11 to -15	From -11 to -15	6.0–6.9	18–23
10	From -16 to -20	From -16 to -20	7.0–7.0	24–35
11	—	From -20 to -25	—	—
12	—	—	8.0–8.9	—
13	—	—	9.0–9.9	—
14	—	—	10.0–11.9	—
15	<-20	From -26 to -35	—	≥36
18	—	—	12.0–14.9	—
20	—	<-35	—	—
22	—	—	15.0–17.9	—
26	—	—	18.0–23.9	—
36	—	—	24.0–29.9	—
45	—	—	≥30	—

Road Accumulated Winter Season Severity Index (RAWSSI):

Building upon the AWSSI framework, the Road Accumulated Winter Season Severity Index (RAWSSI) was introduced to enhance operational relevance. By overlaying historical data and projecting current-season trends, RAWSSI provides additional context that can support more dynamic maintenance planning. Its ability to incorporate a wider network of observation stations improves spatial coverage, which is beneficial in regions with highly variable weather. Nevertheless, the increased complexity of RAWSSI demands robust, consistent data and sophisticated computational resources, which may challenge its reproducibility across different areas (*5*).

The Strategic Highway Research Program (SHRP) Index:

This index was developed with the goal of aiding resource allocation during winter weather events. It uses a simple linear combination of temperature, snowfall, and a frost-related parameter to create a score that has been widely correlated with maintenance costs over more than two decades of application. The SHRP Index is valued for its ease of implementation and clear relationship with operational expenditures. However, its generalized formulation does not account for local variability in weather patterns, which can limit its effectiveness in regions with distinct climatic characteristics (*6*).

Winter Storm Severity Index (WSSI):

The Winter Storm Severity Index (WSSI) is designed primarily as an operational forecasting tool. By integrating meteorological forecasts with non-meteorological data—such as land use, population, and climatological baselines—it produces a dynamic, impact-based graphical depiction of winter storm severity. This approach makes the WSSI particularly useful for real-time decision-making, as it conveys potential disruptions to transportation and society in a readily interpretable format. However, the complexity of its algorithm, which blends multiple data sources and impact modifiers, can reduce transparency and complicate long-term consistency and verification efforts (*7*).

Overall, while each index offers valuable insights, they share a common limitation: many fail to capture regionally nuanced weather features. For example, despite the significant operational challenges and costs associated with freezing rain—a phenomenon that can critically impact road maintenance—several of these indices do not explicitly incorporate it into their formulations. This omission can render some indices less suitable for regions where freezing rain is a major factor, highlighting the need for further refinement to ensure that regional weather characteristics are adequately represented in winter severity assessments.

2.1.2 State DOT Investigations on Winter Severity

Investigations into Winter Severity Indices by state DOTs reveal a diverse array of approaches, each reflecting regional priorities and climatic realities. In states such as Kansas and New Hampshire, research efforts have largely built on the SHRP Index (*2*, *6*, *8*). These states have refined the original formulation to incorporate local temperature extremes, snowfall, and frost conditions, resulting in an index that, while simple and cost-correlated, sometimes struggles to capture the finer nuances of regional weather phenomena (equation 2-2):

$$\mathrm{WSI_{SHRP}} = -25.58 \times \sqrt{\mathrm{T_{index}}} - 35.68 \times \ln\left(\frac{\mathrm{S_{daily}}}{10} + 1\right) - 99.5 \times \sqrt{\left(\frac{\mathrm{d_{freez}}}{\mathrm{T_{range}}} + 10\right)} + 50 \qquad (2\text{-}2)$$

Where:

- $\mathbf{T_{index}}$: is the temperature index (which is equal to 0 if the minimum air temperature is above 32 F; equal to 1 if the maximum air temperature is above 32 F while the minimum air temperature is below 32 F; and equal to 2, if the maximum air temperature is at or below 32 F)
- $\mathbf{S_{daily}}$: is the mean daily value of snowfall (millimeters)
- $\mathbf{d_{freez}}$: is the fraction of days within the analysis period that recorded minimum temperatures at or below32 F ($0 \leq \text{dfreez} \leq 1$)
- $\mathbf{T_{range}}$: is the mean monthly maximum air temperature minus the mean monthly minimum air temperature

Massachusetts has taken a slightly different route by adapting the SHRP-based index to directly compare its values with salt usage. This has allowed the Massachusetts DOT to monitor the effectiveness of its snow and ice control strategies in real-time (*8*). However, the documentation around its formulation remains somewhat sparse, limiting broader applicability without further calibration.

Wisconsin and Minnesota have pursued more detailed, state-specific indices (*2*, *9–11*). Wisconsin's approach integrates variables such as the number of snow events, freezing rain events, and storm duration (equation 2-3). This method, although providing a comprehensive seasonal picture, tends to be less responsive to individual storm events. In contrast, Minnesota divides the state into eight distinct districts and calculates WSIs for each region separately (equation 2-4) (*2*, *10*, *12*). This district-level approach enhances local relevance and allows for tailored resource allocation, but it requires robust data collection from multiple observation points.

$$\begin{aligned} \mathrm{WSI_{Wisconsin}} &= 0.16 \times \mathrm{D_{Snowevent}} + 0.28 \times \mathrm{D_{frrain}} + 0.03 \times \mathrm{D_{snowamount}} \\ &+0.01 \times \mathrm{D_{duration}} + 0.18 \times \mathrm{D_{incident}} \end{aligned} \tag{2-3}$$

Where:

- $\mathrm{D_{Snowevent}}$: is the number of snow events
- $\mathrm{D_{frrain}}$: is the number of freezing rain events
- $\mathrm{D_{snowamount}}$: is the snow amount in inches
- $\mathrm{D_{duration}}$: is the total storm duration in hours
- $\mathrm{D_{incident}}$: is the number of incidents (drifting snow, cleanup, and frost mitigation)

And

$$WSI_{\text{Minnesota}} = 0.18 \times D_{\text{Snowevent}} + 0.31 \times D_{\text{frrain}} + 0.08 \times D_{\text{snowamount}} + 0.32 \times D_{\text{duration}} \quad (2\text{-}4)$$

Where:

- $D_{Snowevent}$: is the number of snow events
- D_{frrain}: is the number of freezing rain events
- $D_{snowamount}$: is the snow amount in inches
- $D_{duration}$: is the total storm duration in hours
- $D_{incident}$: is the number of incidents (drifting snow, clean up, and frost mitigation)

Illinois and Pennsylvania have developed indices that are more closely tied to operational outcomes. Illinois uses a "salt day" metric based on days with measurable snowfall and temperature ranges indicated in equation (2-5) (*2*, *13*), while Pennsylvania's formulation incorporates a broader set of meteorological inputs—including snowfall intensities and frost days—to predict "premium hours" of maintenance effort expressed in equation (2-6) (*2*, *10*, *13*). Both indices show promise in linking weather conditions directly to maintenance activities, yet they face challenges in consistently representing diverse microclimates within the states.

$$WI_{\text{Illinois}} = D_{\text{Snow}} + D_{\text{cold}} \quad (2\text{-}5)$$

Where:

- D_{Snow}: is the number of days in which the daily snowfall accumulation is greater than or equal to 0.5 Inch
- D_{cold}: is the number of days where the mean daily temperature is between 15 and 30 F

$$SI_{\text{Penn}} = S_{\text{season}} + 2D_{\text{med}} + D_{\text{hvy}} + D_{\text{frost}} - \frac{D_{\text{freeze}}}{2} + H_{\text{si}} \quad (2\text{-}6)$$

Where:

- S_{season}: is the total inches of snowfall in the period
- D_{med}: is the number of days with snowfall between 1 and 6 in
- D_{hvy}: is the number of days with snowfall > 6 in
- D_{frost}: is the number of days with a maximum temperature above 32 F and a minimum temperature below 32 F
- D_{freeze}: is the number of days with temperature below 32 F

- H_{is}: is the total hours in the period when snow or ice occurs

Iowa stands out with its storm-based index, which is uniquely designed to capture pre-storm, in-storm, and post-storm conditions. By explicitly incorporating road surface temperature changes and wind conditions before and after an event, Iowa's index offers a more dynamic tool for operational decision-making, as shown in equation (2-7) (*2*, *14*). Nonetheless, its complexity can make it difficult to implement uniformly across different regions.

$$\boldsymbol{S}\mathrm{I}_{\mathrm{Iowa}} = \sqrt{\frac{1}{\mathrm{b}}\left[\left(\mathrm{E}_{\mathrm{storm}} \times \mathrm{T}_{\mathrm{roadduring}} \times \mathrm{W}_{\mathrm{during}}\right) + \mathrm{B}_{\mathrm{before}} + \mathrm{T}_{\mathrm{roadafter}} + \mathrm{W}_{\mathrm{after}} - \mathrm{a}\right]} \qquad (2\text{-}7)$$

Where:

- SI_{Iowa}: is the storm severity index
- E_{storm}: is the storm type (i.e., 1 = freezing rain, 2 = light snow, 3 = medium snow, 4 = heavy snow)
- $T_{roadduring}$: is the in-storm road surface temperature (cooling, consistent, or warming)
- W_{during}: is the in-storm wind condition
- B_{before}: is the early storm behavior (i.e., rain or no rain)
- $T_{roadafter}$: is the post-storm temperature (cooling, consistent, or warming)
- W_{after}: is the post-storm wind condition; a and b are parameters to normalize the index from 0 to 1

Colorado and Idaho have focused on pavement grip metrics, directly relating weather-induced reductions in friction to operational disruptions (*2*, *14*). As shown in equation (2-8), their index, which is event-based, captures the transient nature of winter storms more effectively than seasonal accumulative measures. Indiana, on the other hand, has developed a regionally segmented index that divides the state into four climate zones as shown in equation (2-9) (*9*). Although this method increases local specificity, it is computationally intensive and requires high-resolution data, which can be a limiting factor.

$$\mathrm{SI} = \text{Max Wind Speed (mph)} + \text{Max Layer Thickness (mm)} + \frac{300}{\text{Min Surface Temp(F)}} \qquad (2\text{-}8)$$

Where:

- $\textbf{Max Layer Thickness (mm)} = \textbf{max(}\ \textbf{Ice Layer},\ \textbf{Snow Layer},\ \textbf{Water Layer}\ )$

And,

$$WI_{Indiana} = a_1 \times D_{frost} + a_2 \times D_{frrain} + a_3 \times D_{drift} + a_4 \times D_{snowevent} + a_5 \times S_{depth} + a_6 \times H_{storm} + a_7 \times T_{avg} \quad (2\text{-}9)$$

Where:

- a_i: is the coefficient of respective variable
- D_{frost}: is the number of frost days (i.e., minimum temperature is at or below 32° F and minimum dew point is at or below 32° F)
- D_{frrain}: is the number of freezing-rain days (i.e., number of days with freezing rain and/or drizzle and a minimum temperature at or below 32 F)
- D_{drift}: is the number of drifting days (i.e., the number of days with wind speeds >15 mph and either snow on the ground or a snow event)
- $D_{snowevent}$: is the number of snow-event days, where a snow event day is defined as the number of days with minimum temperature at or below 32° F multiplied by the snowfall intensity and divided by the average temperature during the event
- S_{depth}:is the snow depth
- H_{storm}: is the duration of the event (hr)
- T_{avg}: is the average temperature

In the West, both California and Oregon have explored indices that estimate accident rates as a performance metric. California's formulation considers variables such as minimum and maximum temperatures along with snowfall days, whereas Oregon's index includes additional parameters such as average wind speed and snowfall frequency. These formulations aim to correlate directly with road safety outcomes, yet the variability in weather across different sub-regions sometimes complicates statewide generalizations, as shown in equations (2-10 and 2-11) (*2*, *10*).

$$AccRate_{California} = a_0 + a_1 \times Frost + a_2 \times T_{MIN} + a_3 \times N_{snow} + a_4 \times T_{MAX} \quad (2\text{-}10)$$

Where:

- a_i: is the coefficient of respective variable
- Frost: equals 1 if the maximum daily air temperature is >32 F and the minimum daily air temperature is <32 F and equals 0 otherwise
- T_{MIN}: is the minimum daily air temperature
- N_{snow}: is the number of days in a month with snowfall
- T_{MAX}: is the maximum daily air temperature

And

$$AccRate_{Oregon} = a_0 + a_1 \times T_{MIN} + a_2 \times WindSpd_{Avg} + a_3 \times Snow + a_4 \times Frost + a_5 \times SnowFreq + a_6 \times T_{MAX} + a_7 \times Temp_{low} \quad (2\text{-}11)$$

Where:

- a_i: is the coefficient of respective variable
- T_{MIN}: minimum daily air temperature
- $WindSpd_{Avg}$: average wind speed
- Snow: average rate of snowfall during the day
- Frost: equals 1 if the maximum daily air temperature is >32 F and the minimum daily air temperature is <32 F and equals 0 otherwise
- SnowFreq: frequency of snowfall during the day
- T_{MAX}: maximum daily air temperature
- $Temp_{low}$: is 1 if the temperature remains below the freezing point through the day

Montana's approach is similar to that of Oregon and California, focusing on how weather impacts accident rates, though with adjustments for dew point and rainfall as well as shown in equation (2-12) (*2*, *10*).

$$AccRate_{Montana} = a_0 + a_1 \times SnowFreq + a_2 \times Frost + a_3 \times T_{MAX} + a_4 \times DewPtTemp + a_5 \times Rain + a_6 \times Snow + a_7 \times WindSpd_{Avg} \quad (2\text{-}12)$$

Where:

- a_i: is the coefficient of respective variable
- SnowFreq: is the frequency of snowfall during the day
- Frost: equals 1 if the maximum daily air temperature is >32 F and the minimum daily air temperature is <32 F and equals 0 otherwise
- T_{MAX}: is the maximum daily air temperature
- DewPtTemp: is the average daily dew point temperature
- Rain: is the average rate of rainfall during the day
- Snow: is the average rate of snowfall during the day
- $WindSpd_{Avg}$: is the average wind speed
- $Temp_{low}$: is 1 if the temperature remains below the freezing point through the day

As shown in equation (2-13), New York's index combines mean land surface temperature, number of weeks with transitional surface temperature, snowfall accumulation, and freezing rain duration into a weighted severity score. This method aims to capture both the intensity and duration of winter events, making it a comprehensive tool for forecasting, though its multiple components may require ongoing recalibration as local conditions evolve (*15*). Lastly, Oklahoma's model splits its index into two components—one for non-precipitation and another for precipitation parameters—to better accommodate diverse forecast models such as the Weather Research and Forecasting model (WRF) or the Short-Range Ensemble and Forecast (SREF) model. This dual approach provides flexibility but adds to the complexity of the implementation (*16*).

$$S_w = 0.25 \times (W_1 + W_2 + W_3 + W_4) \tag{2-13}$$

Where:

- S_W: The weather severity score
- W_1: Average Wintertime Land Surface Temperature
- W_2: Number of Weeks with Transitional Surface Temperature
- W_3: Average Annual Snowfall Accumulation
- W_4: Average Annual Duration of freezing rains

State DOT investigations into winter severity indices have employed a wide range of approaches that reflect each state's climatic realities and operational priorities. In addition to the above-mentioned studies, recent research from Missouri and Nebraska provides valuable insights into refining WSI methodologies for operational planning.

Missouri's approach takes a comprehensive, data-driven stance by directly comparing winter maintenance, crash, and delay costs with the Weather Severity Index (*17*). This method correlates real-world operational expenditures—including the costs associated with maintenance, traffic crashes, and travel delays—with quantified measures of weather severity. By integrating these cost metrics with the WSI, Missouri's strategy provides a holistic assessment of winter weather impacts on transportation systems. This integrated analysis supports evidence-based decision-making, enabling the state to fine-tune its winter maintenance practices, optimize resource allocation, and enhance safety protocols. Moreover, by benchmarking these cost indicators against the WSI over time and across regions, the approach facilitates continuous improvement in both planning and operational performance during winter weather events.

Similarly, investigations by the Nebraska Department of Transportation have resulted in the development of the Nebraska Winter Severity Index (NEWINS) and its subsequent predictive variant, NEWINS-P (*18*, *19*). The Nebraska studies utilize a ten-year winter season database and an event-driven framework that categorizes individual winter storms based on key meteorological variables such as snow accumulation, precipitation type, and wind conditions. NEWINS-P, in particular, extends the index to provide a 72-hour predictive outlook by integrating quantitative precipitation forecasts, snow accumulation, ice accumulation, and surface wind speed. This predictive capability allows NDOT to more effectively plan for material procurement and operational response prior to the onset of winter storms

Overall, while state DOT investigations consistently demonstrate that Weather Severity Indices are valuable for forecasting and operational planning, recent studies indicate that many existing indices fall short when applied to regions with unique weather challenges. In particular, phenomena such as freezing rain—which can impose substantial maintenance challenges and escalate costs—are not explicitly accounted for in several WSIs, limiting their effectiveness in areas where such events are prevalent. The synthesis of these investigations reveals that a balance must be struck between maintaining simplicity and achieving operational specificity. Consequently, there is a clear need for regionally tailored WSIs that integrate comprehensive, high-quality meteorological data with localized operational realities. This approach will not only improve forecasting accuracy but also support more effective resource allocation and enhanced safety measures in winter maintenance operations.

2.2 Weather Impacts on Maintenance and Safety

A wealth of literature links winter weather conditions to both maintenance costs and road safety outcomes. Several studies have investigated how weather parameters such as temperature, snowfall, wind, and freezing rain influence the costs of winter road maintenance, while others have focused on the effects of adverse weather on surface friction and crash risks.

Research on maintenance costs frequently employs statistical and machine learning methods to establish quantitative relationships between meteorological data and operational expenditures. For instance, Carmichael et al. (2004) developed a winter weather index for Iowa by combining climate data with roadway treatment expenses, demonstrating that nonlinear approaches can outperform traditional linear regression models in predicting maintenance costs (*20*). Complementing this, the Clear Roads research brief detailed by Massachusetts DOT provided a cost analysis framework that connects weather severity directly with expenditures, emphasizing that consistent data collection is critical to understanding true maintenance costs (*21*). In Japan, Nakamae et al. proposed a cost management method for road snow removal that uses a linear regression of the “unit cost of snow removal” against cumulative snowfall, highlighting how regional differences in weather can lead to significant variations in maintenance expenses (*22*). Moreover, the study by Venäläinen and Kangas (2007) in Finland used climate data to estimate maintenance costs, underscoring the importance of precise meteorological inputs for cost prediction (*23*). More recent nonlinear modeling work from Illinois further demonstrates that incorporating nonlinear relationships between weather severity and expenditures yields a more accurate representation of maintenance cost behavior across different climatic zones (*24*).

Parallel to cost studies, numerous investigations have focused on safety metrics, particularly the relationship between weather and road surface friction—a key determinant of crash risk. Research employing machine learning techniques, such as the study using support vector regression and ensemble methods for road friction estimation, has shown that weather variables (including precipitation, temperature, and wind speed) critically affect surface conditions (*25*). Explainable AI methods, like SHAP analysis, have recently been applied to enhance the interpretability of these complex models, offering insight into which factors most strongly influence friction and, by extension, safety outcomes (*25*). Additionally, reports underscore that adverse weather—through mechanisms such as blowing snow and ice accumulation—directly reduces pavement friction and increases crash rates, with significant societal costs, as highlighted by national crash statistics (*26*)

Studies also emphasize the interconnectedness of cost and safety. For example, research from the University of Vermont Transportation Research Center quantifies the correlations between pavement conditions and snow and ice control costs, finding that degraded pavement quality not only drives up maintenance expenditures but also contributes to increased crash risks due to lower friction levels (*27*). Such analyses suggest that optimizing winter maintenance strategies can yield dual benefits by reducing both operational costs and accident rates.

In summary, weather plays a pivotal role in both the cost and safety dimensions of winter road maintenance. While advanced modeling techniques have improved the ability to predict maintenance expenditures and estimate road friction, limitations persist—particularly regarding regional specificity, data quality, and the integration of cost and safety outcomes. Continued efforts to refine these methodologies, ideally by combining the strengths of traditional and modern approaches, are essential to develop decision-support tools that enhance both economic efficiency and roadway safety.

2.3 Summary

Existing Winter Severity Indices—such as AWSSI, RAWSSI, the SHRP Index, and WSSI—provide valuable methods to quantify winter weather severity, yet each has inherent limitations. AWSSI's cumulative approach and RAWSSI's enhanced operational context offer useful historical insights but tend to smooth over the impact of individual storms. The SHRP Index is simple and correlates with maintenance costs but does not capture local variability, while the WSSI's dynamic, impact-based design is complex and can lack long-term consistency.

State DOT investigations across Kansas, New Hampshire, Massachusetts, Wisconsin, Minnesota, Illinois, Pennsylvania, Iowa, Colorado, Idaho, Indiana, California, Oregon, Montana, Maine, New York, and Oklahoma consistently reveal that while WSIs can guide maintenance planning and resource allocation, many do not account for regionally nuanced weather features—such as the critical impact of freezing rain.

Moreover, research linking weather conditions to maintenance costs and road safety demonstrates that adverse weather increases expenditures and crash risks. Although advanced modeling techniques have improved predictive accuracy, current indices often fall short in integrating cost and safety metrics in a regionally sensitive manner.

This project aims to address these gaps by developing a weather index that can forecast the budget and material needs for the winter season while improving the alignment and consistency among service providers. By leveraging high-quality meteorological data and integrating regional maintenance costs and safety outcomes, the proposed research will create a standardized yet adaptable WSI model. This new index is intended to overcome limitations in current WSIs—particularly their inability to capture local weather nuances—and provide a robust decision-support tool for both MDOT and local agencies.

CHAPTER 3 - CURRENT MDOT PRACTICES

This chapter provides a detailed overview of MDOT current winter maintenance operations and data practices. It is structured in three major sections. Section 3.1 presents the primary MDOT data sources, including regional structures, material usage reporting, budgeting and bidding strategies, and use of decision-support tools. Section 3.2 introduces complementary data sources relevant to Michigan's winter maintenance operations, such as AWSSI and NOAA records. Section 3.3 summarizes the statewide survey conducted with local service providers, describing their operational practices, budgeting methods, and coordination with MDOT. Together, these sections establish the foundational understanding necessary to develop a region-specific and cost-informed weather severity index.

3.1 MDOT Sources

3.1.1 MDOT Regions

Michigan Department of Transportation (MDOT) organizes its operations into seven distinct regional service areas—namely, Bay, Grand, Metro, North, Southwest, Superior, and University. These regions are determined based on geographic, climatic, and operational factors to enable more efficient management of state trunkline maintenance. Figure 3-1 illustrates how these regions are spatially clustered across Michigan.

MDOT's responsibility for trunkline winter maintenance is executed through a multi-tiered approach. In some counties, direct maintenance is performed by MDOT-run garages—often referred to as "direct forces"—that are dedicated exclusively to state highway operations (e.g., Mason Garage and Williamston Garage in Ingham County). In other counties, however, there are no MDOT facilities available; here, maintenance services are provided solely by county road commissions (e.g., Clinton County Road Commission). Additionally, certain counties employ a mixed model where both MDOT garages and contracted county road commissions share maintenance responsibilities, with each entity managing a specific portion of the road network (e.g., Wayne County Road Commission and Detroit Garage). This hybrid approach reflects local operational realities and funding structures, ensuring that even areas lacking direct MDOT presence receive adequate maintenance support.

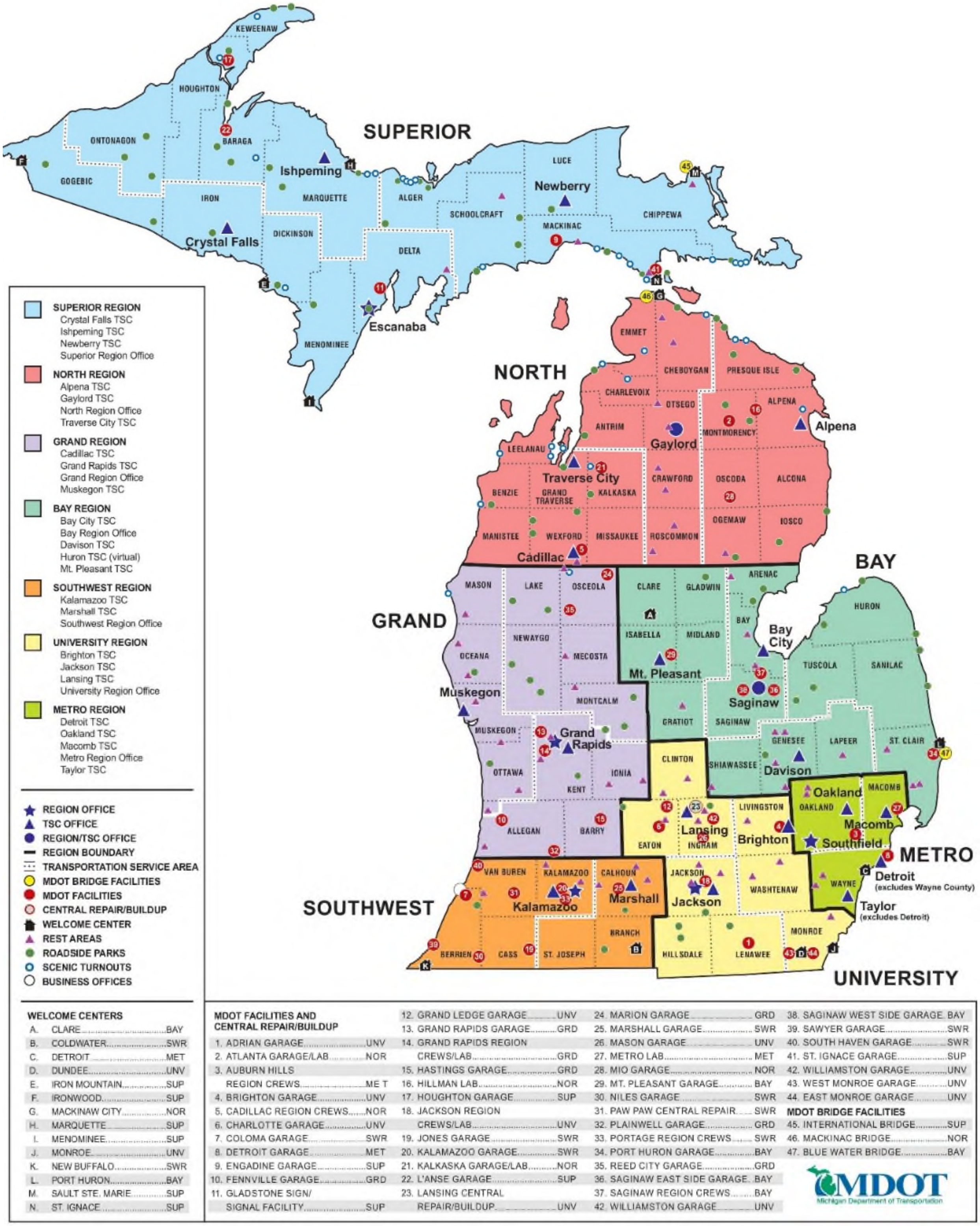


Figure 3-1: MDOT Regional Service Areas and Facilities (*28*)

Overall, these regional clusters and varied maintenance arrangements illustrate MDOT's strategic effort to align resources with local conditions. By segmenting the state into regions and tailoring maintenance practices—whether through direct MDOT operations, county road commissions, or a combination thereof—MDOT aims to optimize the allocation of resources, enhance responsiveness during adverse winter conditions, and maintain consistent road safety standards statewide.

3.1.2 MDOT Winter Material Usage Reporting

To monitor winter maintenance activities, MDOT compiles material usage data in a series of **nine** Excel-based reports spanning November 1 to May 15. These reports are generated **twice a month** (e.g., "Report 1" covers November 1–15, "Report 2" covers November 16–30, etc.) and track **three primary materials**—salt, liquid (brine or additives), and sand—across different organizational levels:

1. **Statewide Summary**

   The first sheet in the workbook provides a **statewide snapshot** of material usage by region (Superior, North, Grand, Bay, Southwest, University, and Metro). It lists usage totals (in tons) for each material in each two-week reporting period, culminating in a year-to-date (YTD) total.

2. **Regional Material Usage**

   Each subsequent sheet focuses on **one MDOT region**, detailing county-by-county or garage-by-garage usage for every two-week interval. This structure allows local offices to see how their material usage compares with that of neighboring counties and garages within the same region.

3. **Lane-Mile Coverage and Per-Lane-Mile Usage**

   The final sheet compiles **lane-mile coverage** data for each region and then calculates the **per-lane-mile usage** of salt, liquid, and sand. By normalizing total usage by lane miles, MDOT can compare operational efficiency across counties or garages of different sizes.

3.1.3 MDOT Budgeting and Bidding for Winter Maintenance Materials

Michigan's approach to winter maintenance budgeting relies on five-year historical averages to project maintenance expenses and funding needs for the upcoming fiscal year. This long-range perspective stabilizes maintenance costs and provides a baseline for material procurement. At the beginning of each season, MDOT garages estimates the needed materials based on current inventories and these historical consumption trends.

Salt Procurement and Bidding Process

- Salt is procured annually through a competitive bidding process involving three primary vendors.
- For each region or county, the contract is awarded to the lowest bidder, which can vary from year to year, resulting in different vendors across neighboring counties.

Managing Shortages and Surpluses

- In the event of a salt shortage during an ongoing winter, emergency measures are promptly taken to obtain additional salt.
- In such cases, the timely delivery of materials takes precedence over budget constraints to ensure safe road conditions.
- Surplus salt is usually stored in dedicated salt sheds. If one region or county has excess supply, it may be redistributed to another region in need of additional stock or storage capacity.

This framework ensures MDOT's readiness for adverse weather events while providing the flexibility to handle unexpected demands for maintenance materials. By coupling five-year historical averages with competitive bidding and region-to-region resource sharing, Michigan can maintain consistent service levels and mitigate the risks of material shortages during severe winter conditions.

Complementing these practices, MDOT maintains a dynamic Winter Material Dashboard that produces graphical reports at any time. This dashboard is available both regionally and statewide and includes several key components:

- **Lane Mile Coverage:** It reports the total lane miles for each region.
- **Material Usage per Lane Mile:** It displays year-to-date (YTD) material usage for salt, liquid, and sand.
- **Regional Maps:** It offers maps of each MDOT region showing YTD material usage for each county or garage.
- **Comparative Trends:** The dashboard presents cumulative YTD salt usage alongside a five-year average, allowing users to compare current trends against historical performance.

- **Deviation Analysis:** A dedicated figure shows the percentage by which current usage is higher or lower than the five-year average.
- **Detailed Regional Breakdown:** Additional charts compare each county or region's material usage with their five-year history, providing granular insight into regional variations.

This integrated dashboard not only supports real-time monitoring and decision-making but also serves as a valuable tool for benchmarking performance and optimizing resource allocation across Michigan's diverse roadway network.

3.1.4 MDOT Maintenance Decision Support System (MDSS)

Michigan's MDSS is a tool that enhances winter maintenance by providing real-time and historical weather data. It informs decision-making on major highways by combining road weather observations with forecasting models to deliver actionable recommendations to maintenance supervisors (*29*). MDSS aggregates a wide range of information, including RWIS data, live camera feeds, truck tracking, thunderstorm outlooks, and forecasted road conditions and routes for up to 72 hours. In addition, it offers a DTN 10-day forecast feature, which further enhances its predictive capabilities. Figure 3-2 displays the interface of Michigan's MDSS dashboard.

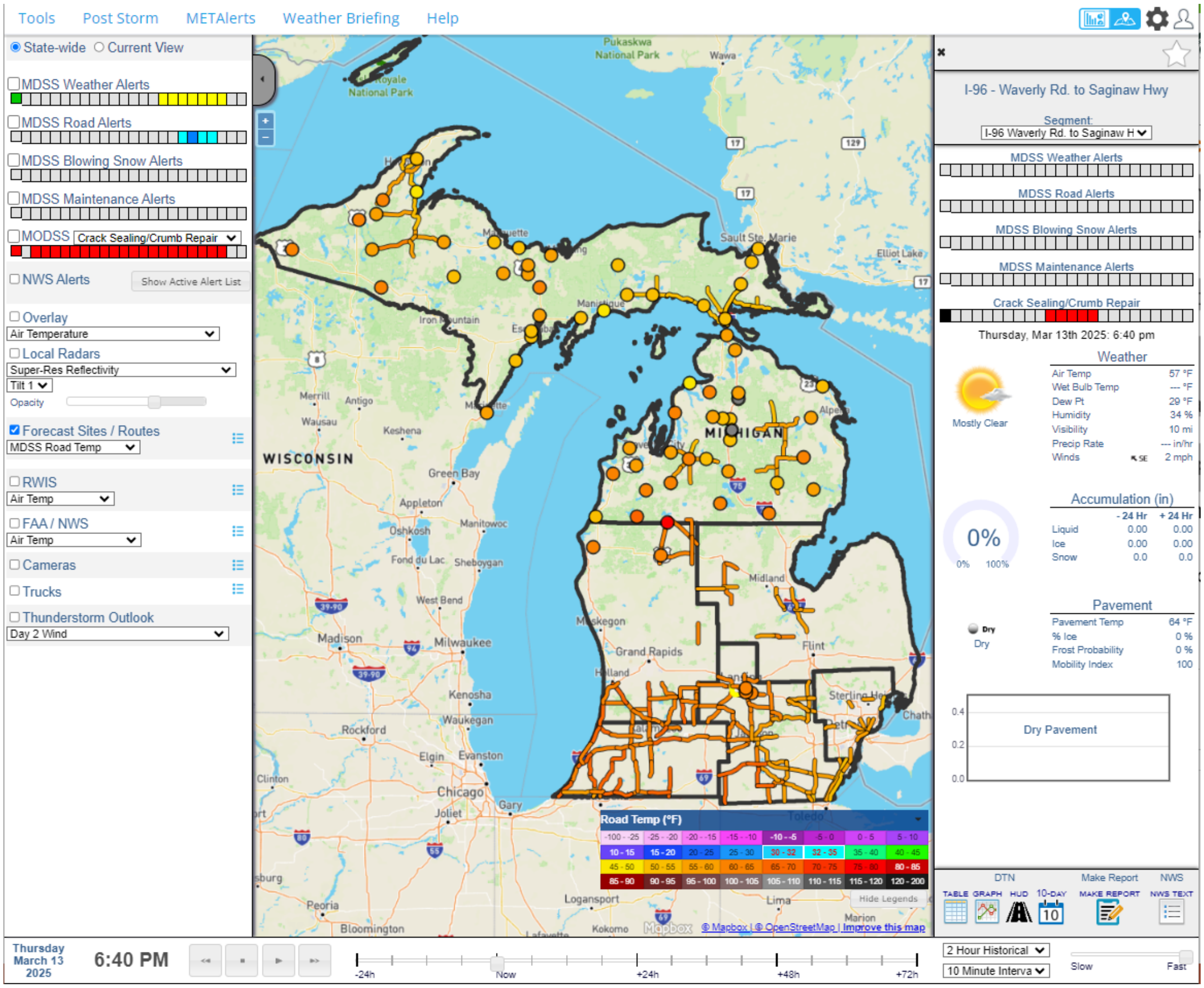


Figure 3-2: Michigan MDSS Interface

Beyond its real-time functionality, MDSS includes a post-storm dashboard known as the WMRI tool. This tool enables users to generate detailed reports for any desired time interval, making it possible to analyze weather elements and maintenance responses. The WMRI tool supports various formats for reporting—either as CSV files or as maps embedded within the system—and can display numerous weather elements for any specified location. However, it is important to note that historical data in this tool is only available from December 2014 onward.

Although MDSS has been instrumental in reducing costs and improving maintenance services on trunklines, it does not capture the full spectrum of winter maintenance costs across Michigan's diverse road network. There are some limitations to the system. Data probes within MDSS are relatively sparse as not all counties have installed them—often due to budget constraints or reliance on data from surrounding areas. Additionally, not every roadway is represented on the MDSS map. This is partly because the system consolidates data from both contract counties and direct MDOT forces; contract counties, in particular, may not have visible routes on the MDSS due to a lack of funding. The node data used for each county is derived from averaged data obtained from MDOT or the National Weather Service and is strategically placed to best represent overall local conditions.

Together, these features and limitations shape the MDSS as a vital, albeit imperfect, tool for guiding winter maintenance decisions across Michigan's diverse roadway network.

3.1.5 MDOT Current WSI

Michigan has developed its own Winter Severity Index (WSI) to better reflect local weather conditions and maintenance challenges. As outlined in the 2015 Michigan Winter Severity Index report (*30*), Michigan's approach integrates observed weather data from the Maintenance Decision Support System (MDSS)—covering key parameters such as the number of snow events, freezing rain events, total snowfall, cold precipitation hours, and blowing snow duration—into a unified 100-point scale (equation 3-1). This index assesses the impact of snow events, freezing rain events, total snowfall, cold precipitation duration, and blowing snow duration on WSI, with respective contributions of 30%, 15%, 20%, 20%, and 15%.

$$WSI = (30 * \frac{\#\ snow\ events}{Max\ \#\ of\ snow\ events} + 15 * \frac{\#\ freeze\ rain\ events}{Max\ \#\ of\ freeze\ rain\ events} + 20 * \frac{snow\ total\ (in)}{Max\ inches\ of snow\ total} + 20 * \frac{event\ duration\ (hr)}{Max\ hours\ of\ event\ duration} + 15 * \frac{blowing\ snow\ duration\ (hr)}{Max\ \ hours\ of\ blowing\ snow\ duration}) \tag{3-1}$$

This custom WSI is designed to capture the seasonal variability of winter weather across the state by using both direct MDSS data and surrogate routes established in counties that lack full MDSS coverage. The methodology includes annual recalibration of maximum recorded values to ensure that the index remains comparable year over year.

Figure 3-3 shows the map for FY 2019 developed by MDOT that overlays WSI with salt usage per lane mile, distinguishing counties by color from red (indicating higher WSI values between 60 and 70, hence harsher winter conditions) to light green (lower WSI values between 23 and 35, indicating milder conditions). This visualization is intended to illustrate the relationship between the assigned WSI and the corresponding salt usage across county road commissions and MDOT garages.

However, this map reveals some levels of inconsistencies. For example, Chippewa County, marked in red with a WSI range of 60–70, records a salt usage of 24.3 tons per lane mile. In contrast, Dickinson County, depicted in blue with a WSI range of 40–45, shows a similar salt usage of 24.7 tons per lane mile. This near equivalence in salt application despite a marked difference in WSI suggests that the current index may not fully capture the intensity of winter weather conditions in terms of material usage.

Furthermore, when comparing Marquette County (red WSI, range 60–70) to Menominee County (green WSI, range 35–40), both counties are located in the same region where weather patterns are expected to be relatively homogeneous. Yet, the index assigns significantly different severity values, even though both counties show nearly identical salt usage per lane mile (31.5 tons for Marquette County and 29.6 tons for Dickinson County). Such disparities indicate that the current WSI does not accurately reflect local weather nuances and the resultant operational responses, as counties within the same region should display more similar indices.

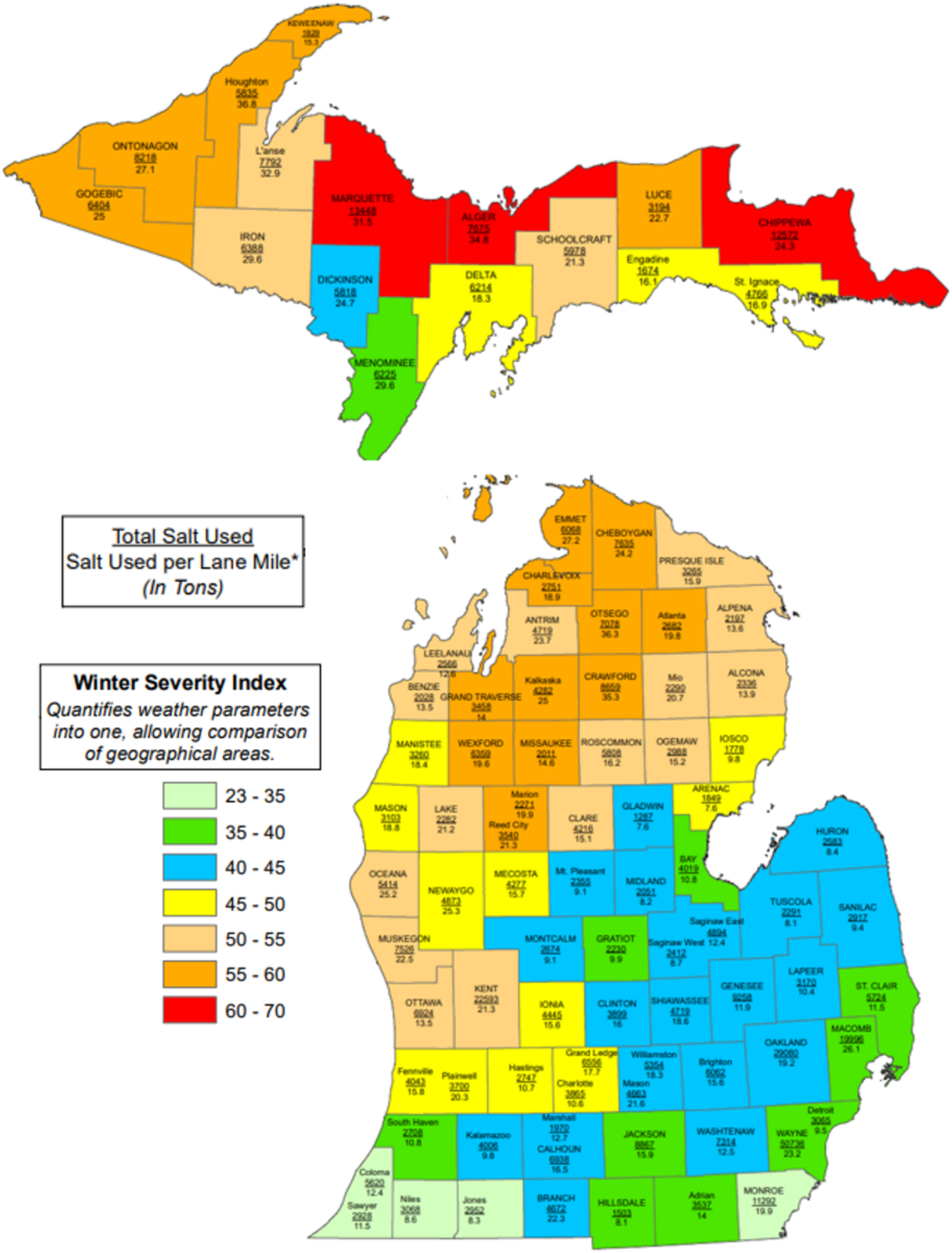


Figure 3-3: Salt Usage FY 2019 with Winter Severity Index, County Road Commission and MDOT Garages

These discrepancies serve as clear evidence that the existing WSI, while useful as a general guide, may not be the best predictor of material usage. The index appears to lack the sensitivity to capture local variations in weather conditions that directly impact salt application rates. This calls for further refinement and calibration of the WSI to ensure that it more closely correlates with observed maintenance practices and material consumption, ultimately leading to more effective and data-driven winter maintenance planning.

3.2 Michigan's Other Sources

3.2.1 Michigan's Accumulated Winter Season Severity Index (AWSSI)

As mentioned in section 2-1-1, AWSSI is a climatologically based tool that quantifies winter weather severity by accumulating daily weather data—such as snowfall, air temperature, and snow depth—over an entire winter season. This cumulative score provides a measure of how severe a winter has been: higher scores indicate harsher conditions, while lower scores represent milder winters.

In Michigan, AWSSI data is available for 17 cities, including Alpena, Ann Arbor, Cheboygan, Detroit, Flint, Gaylord, Grand Rapids, Herman, Houghton Lake, Iron Mountain, Ironwood, Lansing, Marquette, Muskegon, Port Huron, Saginaw, and Sault Ste. Marie. A useful visualization of these trends is provided by the MRCC's online AWSSI chart, which displays the current year's trend alongside historical data dating back to 1950. Figure 3-4 shows the AWSSI trend for Detroit, MI, over the current year and the past five years. This chart uses different ranges or color thresholds to illustrate various levels of winter severity; however, data gaps exist in some years for certain cities.

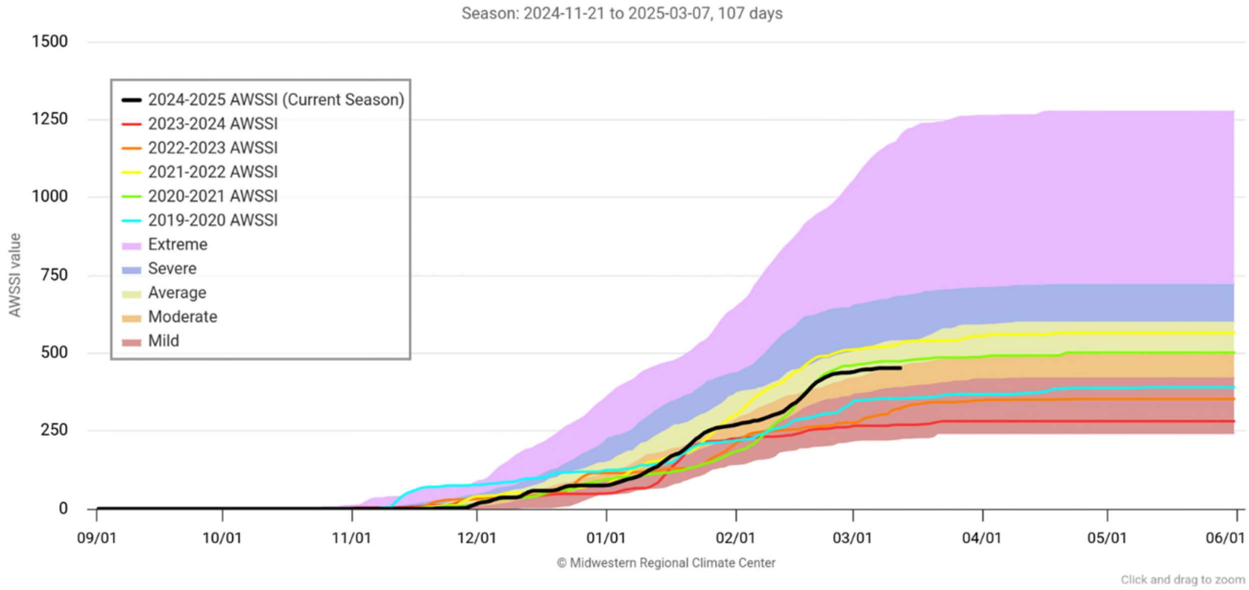


Figure 3-4: 2024-2025 AWSSI: MI – Detroit (*31*)

Despite its utility in providing a broad, seasonal picture of winter severity, AWSSI has important limitations. It cannot capture the regional nuances inherent in Michigan's diverse climate. In particular, it does not account for critical weather variables such as blowing snow, freezing rain, or other locally significant weather phenomena that can have a substantial impact on road conditions and maintenance practices. This shortfall underscores the need for additional, regionally tailored indices or supplementary tools to fully inform winter maintenance planning and budgeting across Michigan's varied regions.

3.2.2 National Oceanic and Atmospheric Administration (NOAA) Data for Michigan

NOAA offers a comprehensive array of data and forecasting tools essential for understanding and managing Michigan's winter weather. For example, the National Weather Service (NWS) provides real-time observations from Automated Surface Observing Systems (ASOS) and Automated Weather Observing Systems (AWOS) across Michigan, delivering hourly updates on temperature, wind speed, precipitation type, snowfall amounts, and other vital parameters—which are also integrated into MDOT's MDSS. Historical climate records are maintained by NOAA's National Centers for Environmental Information (NCEI), which allow users to access decades of weather data—critical for trend analysis and index development.

In addition, NOAA's Local Climatological Data (LCD) provides comprehensive historical climate summaries for individual stations—52 across Michigan—with records dating back to approximately 1950. The LCD summaries compile hourly, daily, and monthly observations of key climatic variables such as temperature, dew point, humidity, wind speed and direction, sky conditions, weather type, and atmospheric pressure. These summaries, derived from both manual and automated observations from NCEI's Integrated Surface Data, are essential for trend analysis and for developing robust weather indices. However, several datasets downloaded for specific stations from LCD were incomplete and could not be used for analysis.

Additionally, the National Digital Forecast Database (NDFD) offers high-resolution forecast data, including detailed maps of snowfall accumulations, temperature forecasts, and severe weather outlooks for up to 72 hours—with ensemble forecasts extending to 10 days—features that are similar to those available through MDOT's MDSS and DTN.

An important aspect of NOAA's approach to climate monitoring is its standardized division of the United States into climate regions. Specifically, NOAA/NCEI has divided Michigan into 10 distinct climate divisions. This division—grounded in decades of research by U.S. climatologists and refined by key modern studies (*32*, *33*)—reflects Michigan's unique geographic and climatic influences. The 10-region scheme accounts for the moderating impact of the Great Lakes and distinguishes the contrasting climatic conditions between the Upper and Lower Peninsulas, ensuring that each division is as climatologically homogeneous as possible. Collectively, these NOAA products deliver a comprehensive perspective on both current conditions and historical trends in Michigan's winter weather, thereby supporting a range of applications for winter maintenance.

3.2.3 Michigan's Transportation Asset Management Council (TAMC)

The Transportation Asset Management Console (TAMC) goes beyond MDOT's traditional focus on trunkline maintenance by offering a comprehensive perspective on roadway upkeep across Michigan. TAMC gathers detailed cost data—including material usage, labor, and equipment expenses—from both local and state sources, which allows local agencies to benchmark their performance and fine-tune their maintenance strategies based on actual expenditure trends (*34*).

Maintenance data in TAMC covers two broad categories. The first encompasses routine or preventive maintenance of roads and bridges—activities such as roadside mowing, patching, and sign management. It also includes reactive repairs necessitated by events like crashes or severe weather (for example, fixing washouts, removing fallen trees, or repairing damaged guardrails). These costs are reported annually in ACT 51 financial reports. The second category specifically addresses snow and ice control, with separate reporting for expenditures on plowing, salting, and other winter weather response activities. Figure 3-5 illustrates the TAMC's winter maintenance costs for primary and local roads in Ingham County.

A key element of TAMC's approach is the use of lane-mile metrics to standardize maintenance expenditure data. Lane miles are calculated as centerline miles multiplied by two, although efforts are underway—using Pavement Surface Evaluation and Rating (PASER) road condition data—to improve accuracy, particularly for urban counties like Monroe and Wayne. It is important to note that the financial reports filed by Cities and Villages differ from those of County Road agencies, so current maintenance dashboards are focused on county-level data.

This integrated system provides a rich, data-driven foundation for managing and optimizing primary and local roadway maintenance throughout Michigan.

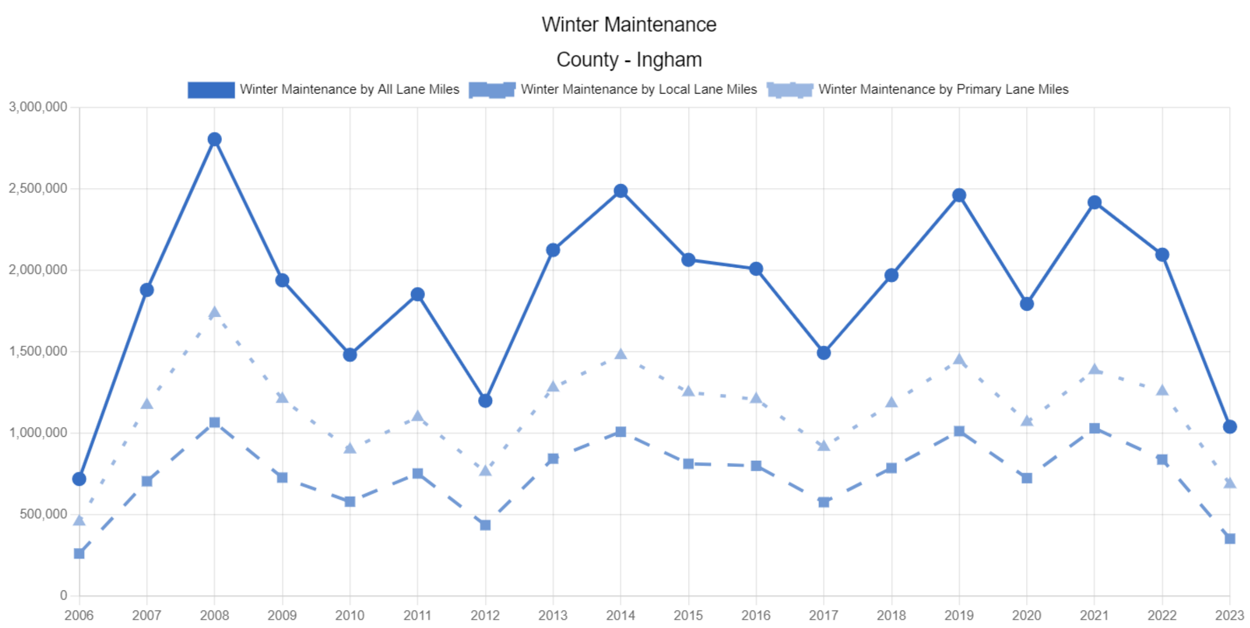


Figure 3-5: Winter maintenance cost for primary and local roadways, Ingham, MI (*34*)

3.3 Survey of Local Service Providers in Michigan

3.3.1 Purpose

Effective winter maintenance depends critically on how well garages understand and respond to the challenges they face—from their perception of weather conditions to their selection of materials and operational practices. Garages adopt various approaches to maintain roads, and their preparedness, decision-making, and material usage play a pivotal role in overall winter road safety and efficiency. The purpose of this chapter is to survey local service providers in Michigan in order to:

- **Identify the current state of practice in Michigan:** Capture how local service providers conduct their winter maintenance operations, including the practices they follow and the challenges they encounter.
- **Gather county-level data:** Obtain detailed information on material usage rates and winter maintenance costs at the county/garage level.
- **Examine estimation and budgeting practices:** Understand how local service providers estimate the amount of materials needed and plan their budgets.
- **Assess alignment issues:** Uncover notable alignment and consistency issues between MDOT and local service providers in conducting winter maintenance operations.
- **Evaluate perceptions of data availability:** Explore the perceptions of local service providers regarding the availability and usefulness of existing data systems such as WSI and MDSS.
- **Collect improvement recommendations:** Solicit recommendations on how to enhance the alignment and consistency of information sharing between MDOT and local service providers.

This survey is designed to ensure that the questions and topics addressed are directly relevant to the operational realities and needs of Michigan local service providers. The outcomes provide key insights on developing a region-specific WSI for Michigan and facilitate its application for local service garages.

3.3.2 Survey Design and Administration

The MSU research team developed a survey questionnaire to investigate the state-of-the-practice for winter maintenance operations across the state of Michigan. The topics and questions included were developed based on the literature review and were revised based on MDOT RAP members' feedback. The survey was designed and implemented in a web-based format through the Qualtrics platform and consisted of four sections that sought the following information:

- Section 1: Respondent Details
- Section 2: Material & Resource Management
- Section 3: Winter Maintenance Tools and Practices
- Section 4: Collaboration & Information Sharing

MDOT Research Advisory Panel (RAP) members provided the research team with a pool of contacts from Michigan garages and contract counties in charge of winter maintenance operations. The survey was first distributed on October 11, 2024, with a survey deadline of December 1st, providing approximately two months of survey response period. In between, several rounds of reminders were sent out to survey invitees, namely on November 15. After the survey response collection had ended, the research team analyzed response previews and conducted a follow-up survey from December 1st through January 1st to ramp up the complete response rate. The survey officially closed on January 1st, with a total running duration of three months. The list of survey questions is provided in Appendix A of this report.

3.3.3 Summary of Results

3.3.3.1 Overview of the responses

The survey achieved a solid response rate with the following highlights:

A total of 92 MDOT and county garages across Michigan were contacted. The survey received 51 valid responses, which corresponds to an approximate response rate of 55%:

- Among the respondents, 20 were from the 31 directly managed MDOT forces.
- The remaining 31 responses came from the 61 contract counties.

The responses ensured comprehensive regional coverage with secured representations from all MDOT regions, including Bay, Grand, Metro, North, Southwest, Superior, and University Regions. Figure 3-6 illustrates the distribution of counties whose corresponding garages provided a response to the survey. Additionally, the detailed list of garages that responded and those that did not is attached in Appendix B.

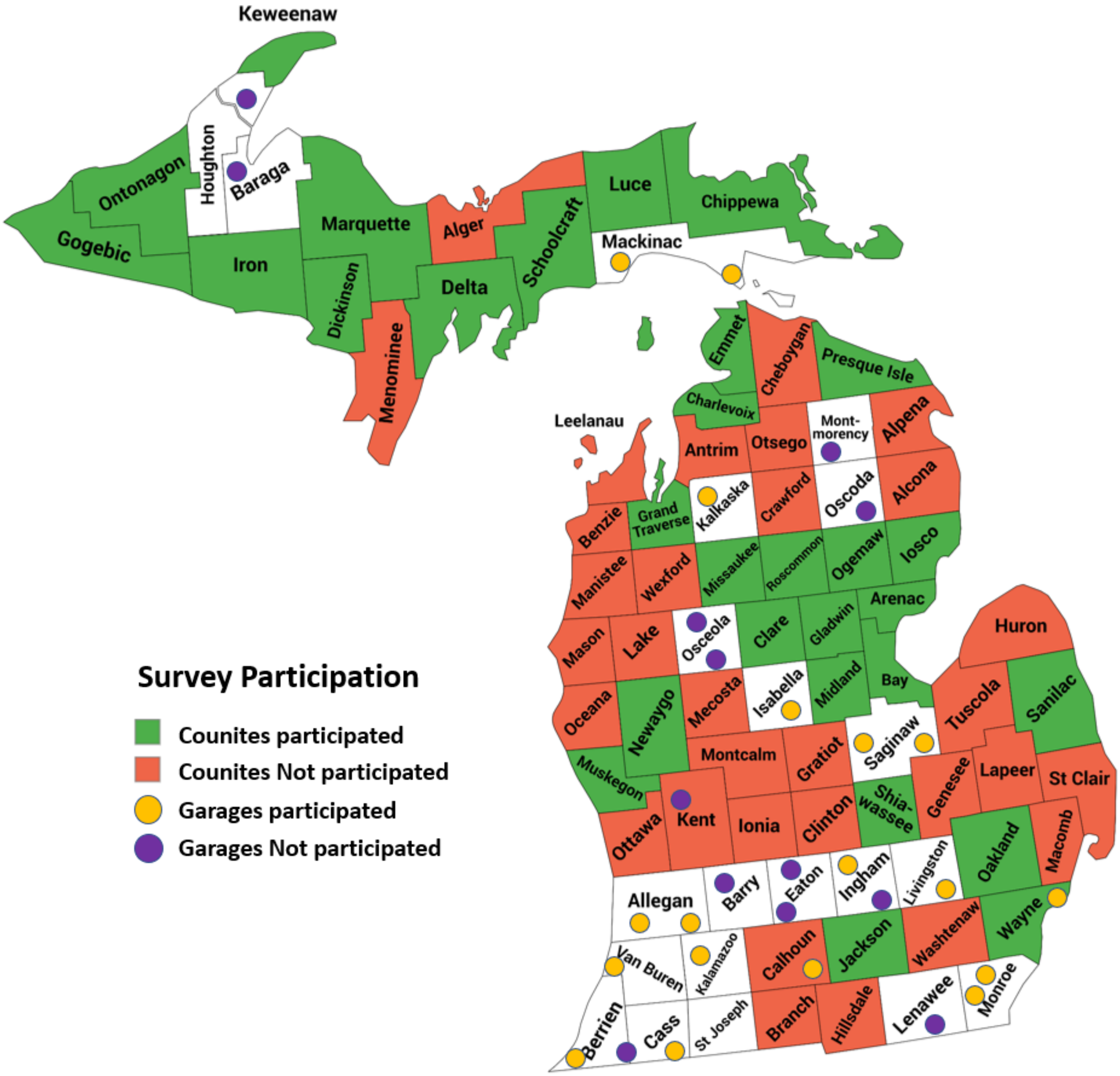


Figure 3-6: Statewide survey response overview by garage location

3.3.3.2 Survey Analysis & Insights

Section 2: Material & Resource Management

The garages were asked to describe how they determined their material application rates. Respondents could select multiple options. The analysis shows that while many garages adhere to MDOT-enforced rates, most also incorporate on-the-ground judgment of drivers or foremen. Specifically, out of 29 garages that reported using MDOT-enforced rates, 24 also relied on practical judgment, highlighting the importance of real-time, localized decision-making in their operations. (Figure 3-7).

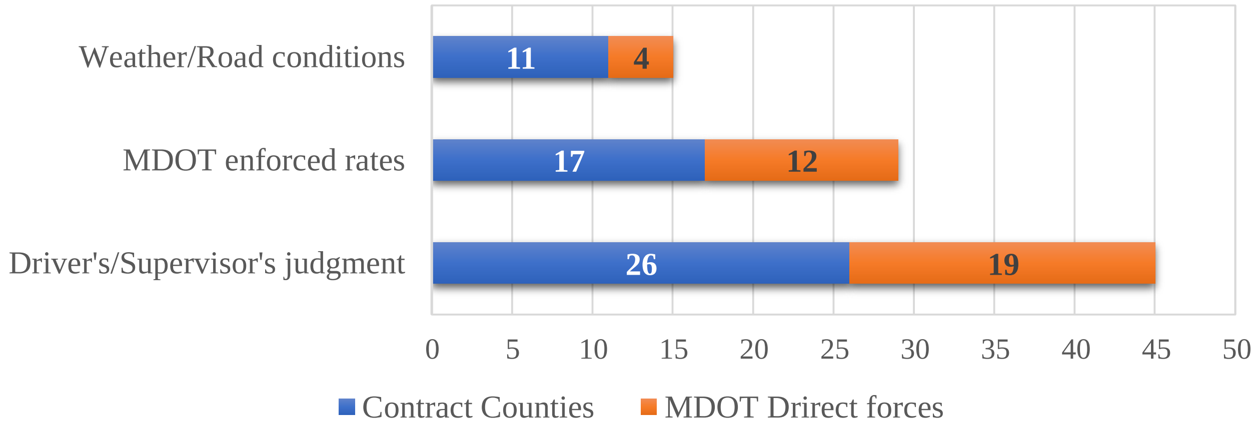


Figure 3-7: Approaches to determine material application rates

When asked to provide their average salt application rates (in pounds per lane mile), the majority of garages reported applying between 200 and 350 lbs, as depicted in Figure 3-8. The regional distribution in Table 3-1 illustrates variations across Michigan regions, suggesting that local weather patterns and roadway characteristics may play a significant role in determining salt usage rate.

For sand and liquid materials, the survey responses indicate:

- **Sand:** Garages generally use sand less frequently than salt, indicating it is a secondary material for winter maintenance. (Figure 3-9)
- **Liquid (Brine):** Most respondents reported applying less than 10 gallons of liquid brine per lane mile, which reflects a conservative approach to using liquid deicers. (Figure 3-10)

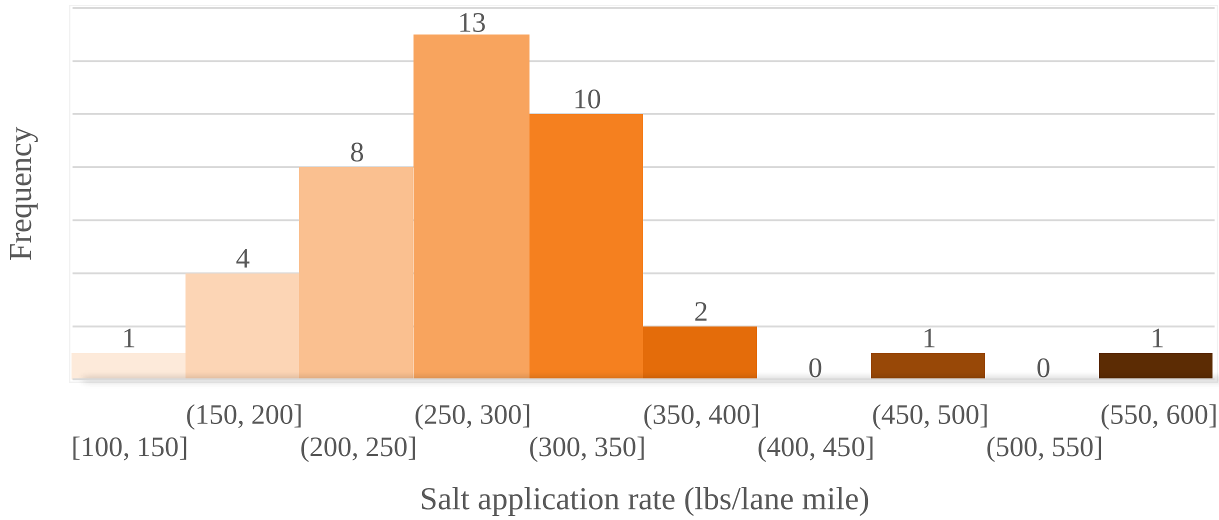


Figure 3-8: Salt application rate distribution

Table 3-1: Salt application rates distribution by region

Application Rate Range (lb/lane mile)	West Upper	East Upper	Northwest Lower	Northeast Lower	West Central Lower	Central Lower	East Central Lower	Southwest Lower	South Central Lower	Southeast Lower
100-150							1			
150-200	1		1					1		1
200-250			1		1	1	2	2	1	
250-300	1		1		1	3	1	2	2	
300-350		2	1	2		1	1		1	2
350-400		1		2						1
450-500	1									
550-600		1								

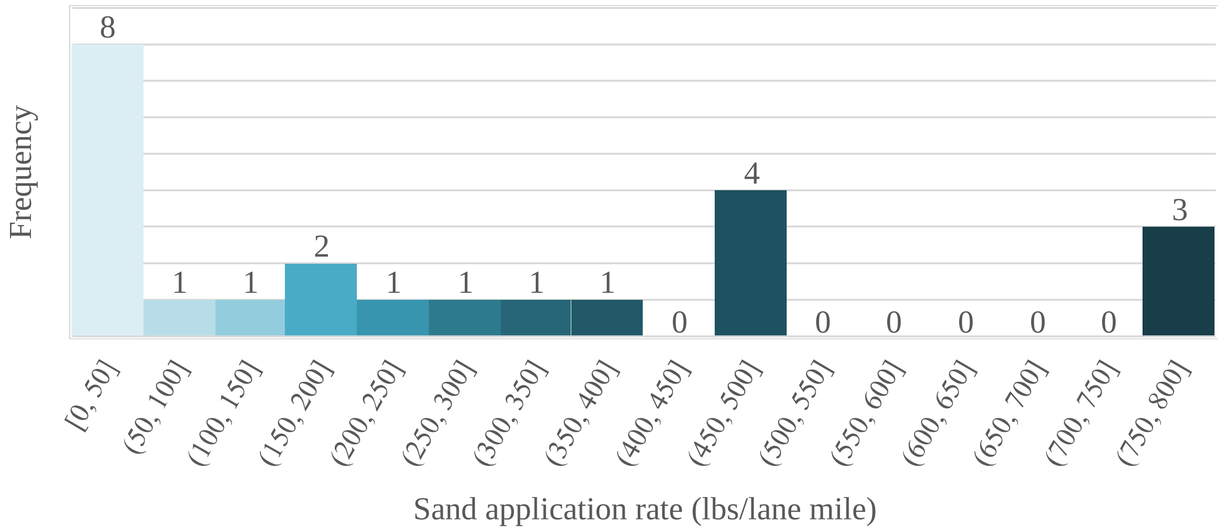


Figure 3-9: Sand application rates distribution

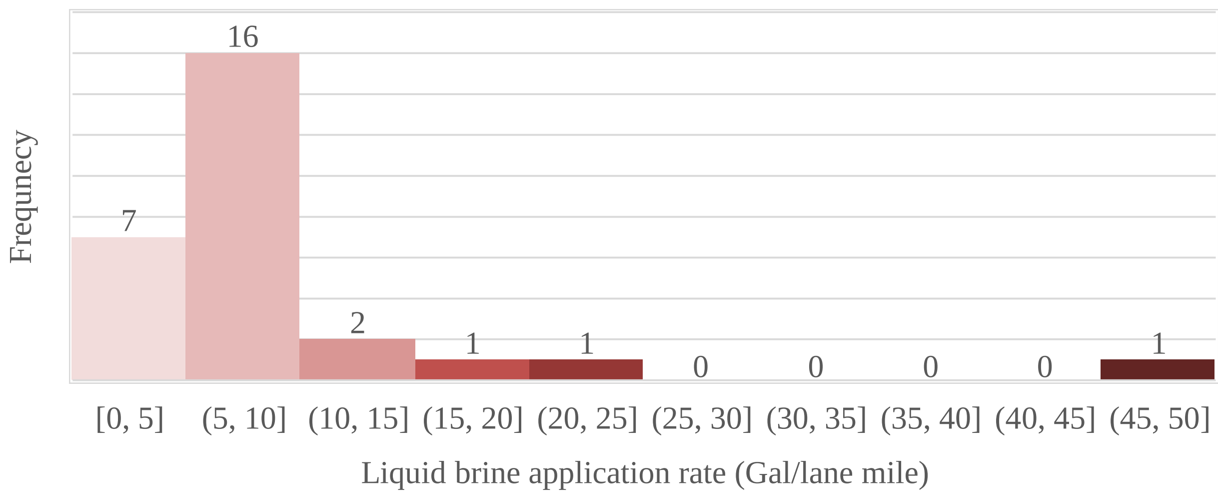


Figure 3-10: Liquid brine application rates distribution

Respondents were also asked to list any additional materials used in their operations:

- Several garages employ a 50/50 mix of salt and sand, notably in counties such as Grand Traverse, Jackson, Kalkaska, Leelanau, Muskegon, and Roscommon.
- Specific products, such as Beet Heet (approximately 10 gallons per ton of salt), were mentioned by garages in Charlevoix County and Marshall Garage.
- Other specialized materials, including CS 26, CS 49, Freeze Free S30-T, and CMA, were mentioned by a few respondents, underscoring the diversity of material choices based on regional and operational needs.

The survey also asked garages how they determine the need to order more materials (Figure 3-11). Responses indicated that the majority of garages use specific inventory thresholds (for example, when stock reaches 300 tons, 40% capacity, or when storage sheds are half full) as triggers for reordering. Some garages also rely on historical data from previous years to forecast their material needs. In response to situations when material inventories fall below required levels (such as during unexpected winter storms), the garages were asked about their strategies for managing these shortages (Figure 3-12). The survey results reveal that:

- The predominant strategy is to reorder supplies immediately once inventory drops below the defined thresholds.
- Relying on neighboring garages for additional resources or substituting materials is much less common.

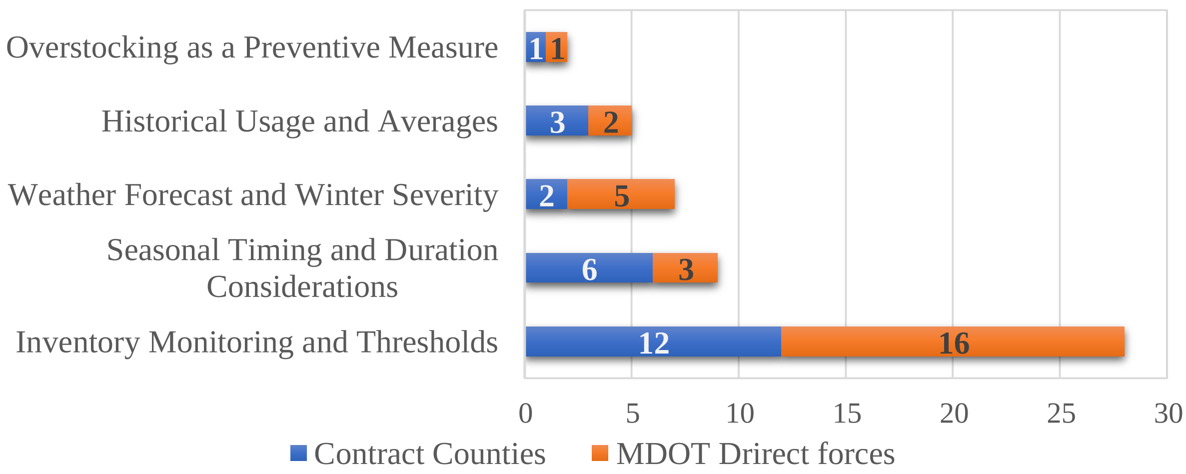


Figure 3-11: Criteria and/or thresholds that prompt to order more material

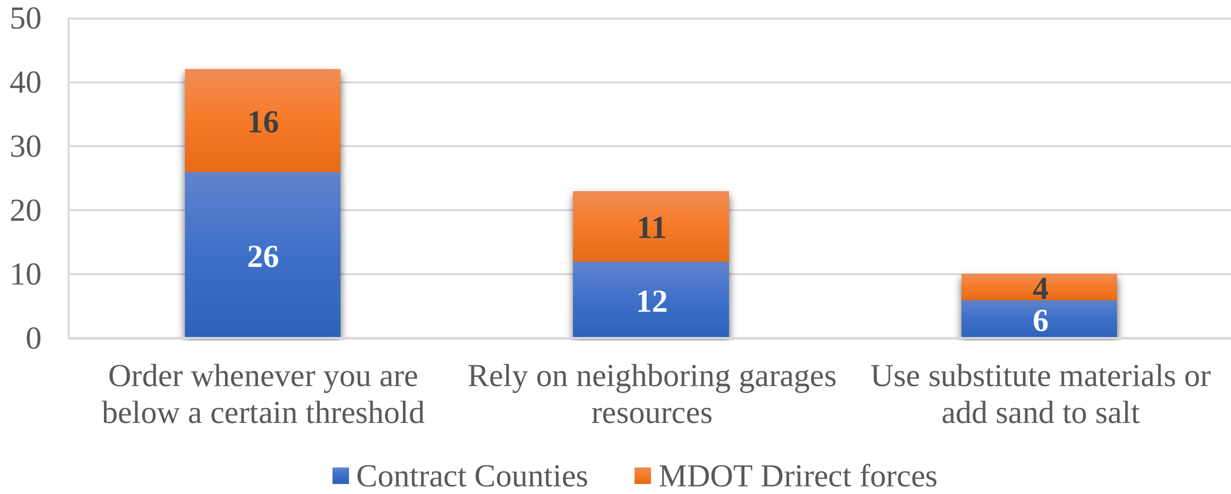


Figure 3-12: Various approaches for handling material shortage

Finally, regarding the integration of the Winter Severity Index (WSI) in their planning, approximately 23% of the garages indicated that they currently use MDOT's WSI (Figure 3-13).

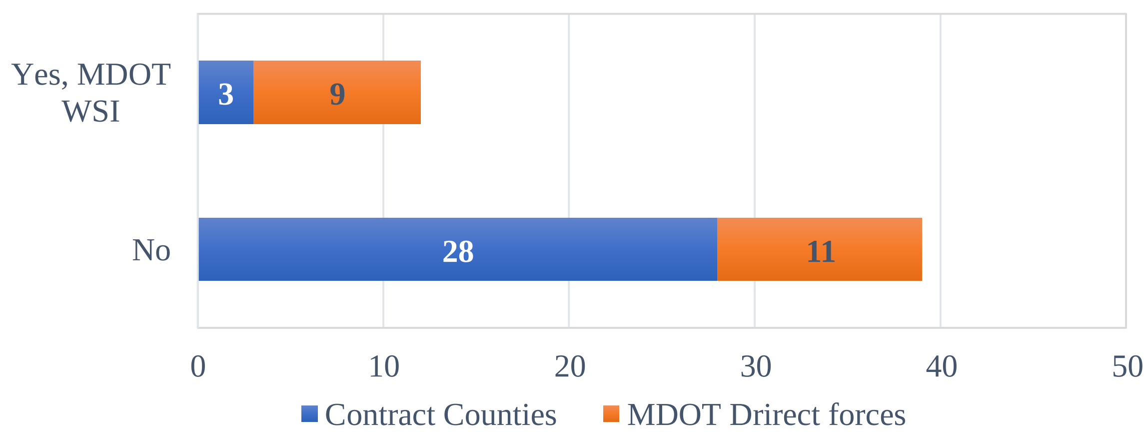


Figure 3-13: Incorporating the current MDOT Weather Severity Index (WSI) by local garages

Section 3: Winter Maintenance Tools and Practices

The garages were asked to provide feedback on MDSS applications as part of their maintenance operations. Out of the 51 respondents, 24 (all from contract counties) indicated that they do not use MDSS. The reasons for not adopting MDSS are shown in Figure 3-14. The survey also inquired regarding the main reasons garages use the MDSS. The results show that MDSS is primarily used for weather observations and operational planning among garages. Figure 3-15 summarizes these responses. Garages were also asked about the challenges encountered when using MDSS. While many users (15 out of 27) reported no significant issues, some garages mentioned a couple of challenges with MDSS that are listed in Figure 3-16.

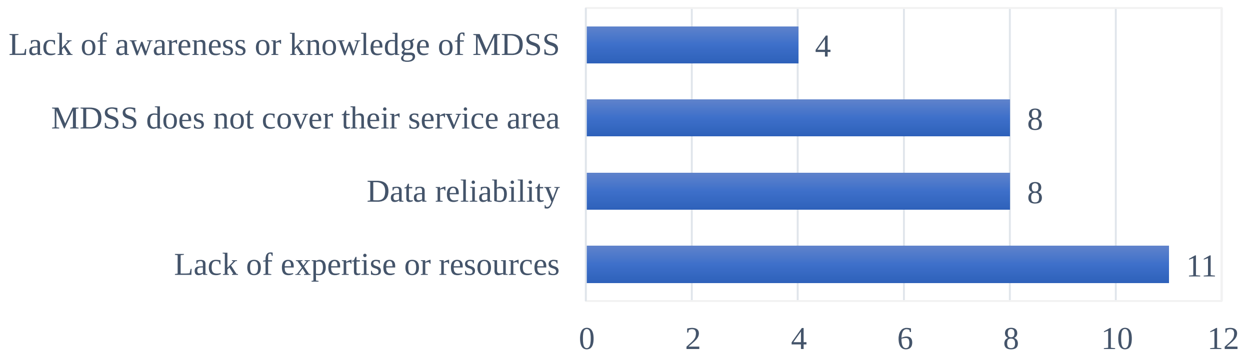


Figure 3-14: Reasons provided by local garages that do not utilize MDSS

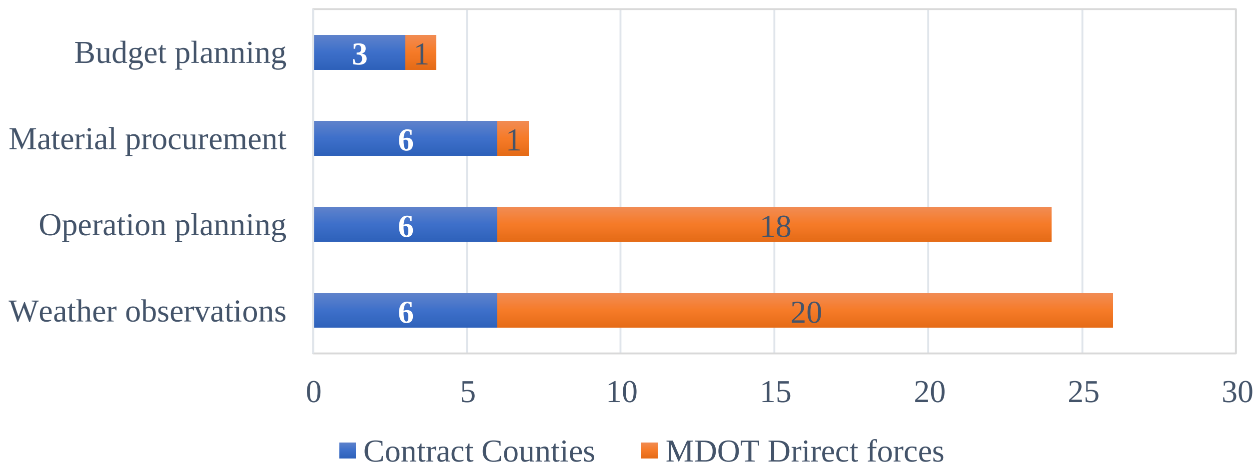


Figure 3-15: Different applications of MDSS for local garages

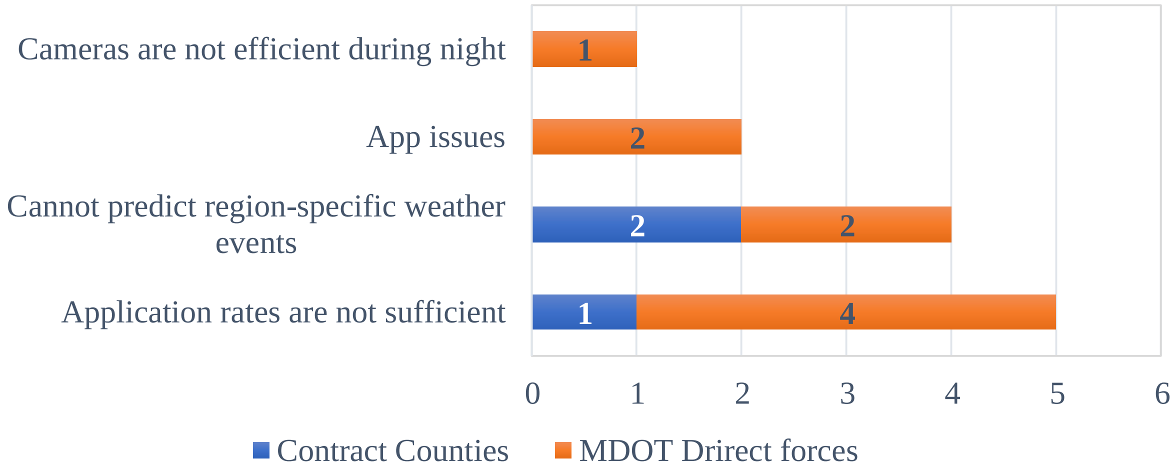


Figure 3-16: Challenges encountered when using MDSS by local garages

The survey also inquired about other weather tools or systems used alongside or instead of MDSS. Respondents mentioned several systems, as shown in Figure 3-17.

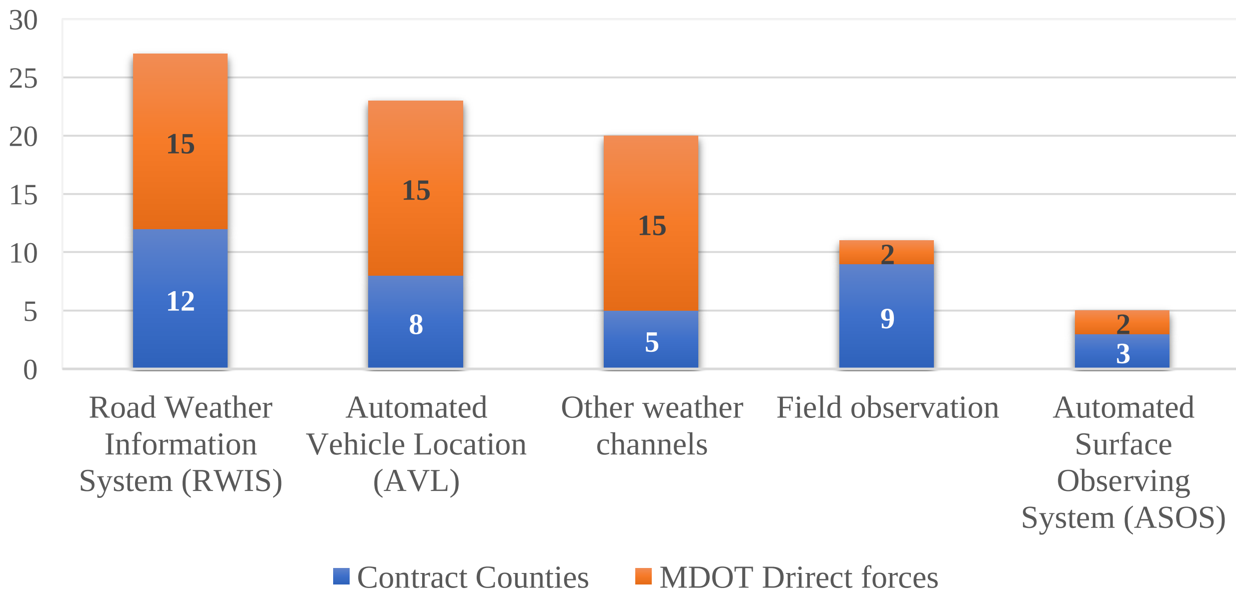


Figure 3-17: Other weather tools/software/data that local garages rely upon

Garages were also asked to identify the key thresholds that trigger their winter maintenance operations (Figure 3-18).

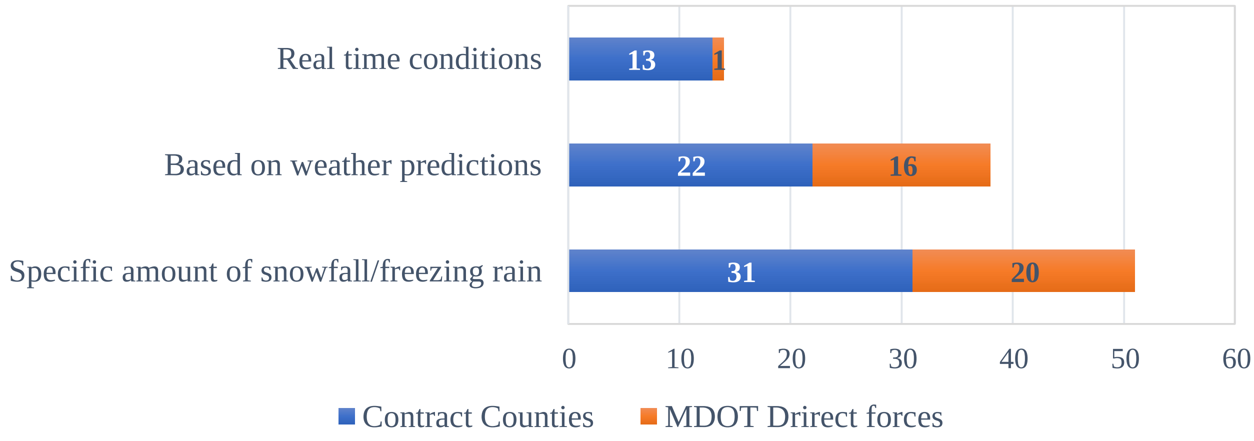


Figure 3-18: Key thresholds that trigger winter maintenance operations for local garages

In response to which weather elements are critical for their operations, garages indicated the listed factors in Figure 3-19. Although not initially included in the survey options, respondents identified lake effect, rush hour traffic, prior material applications, and sunlight as significant factors. When asked about unique challenges specific to their regions, respondents highlighted some other factors, as shown in Figure 3-20. Examples of infrastructure and terrain challenges and operational and staffing issues are as follows:

- Urban-rural mix (e.g., freeways vs. open farmland) leading to different maintenance needs
- Different pavement materials (concrete vs. asphalt) require tailored treatments
- No around-the-clock shift work limits responsiveness
- Scheduling crews during off-hours

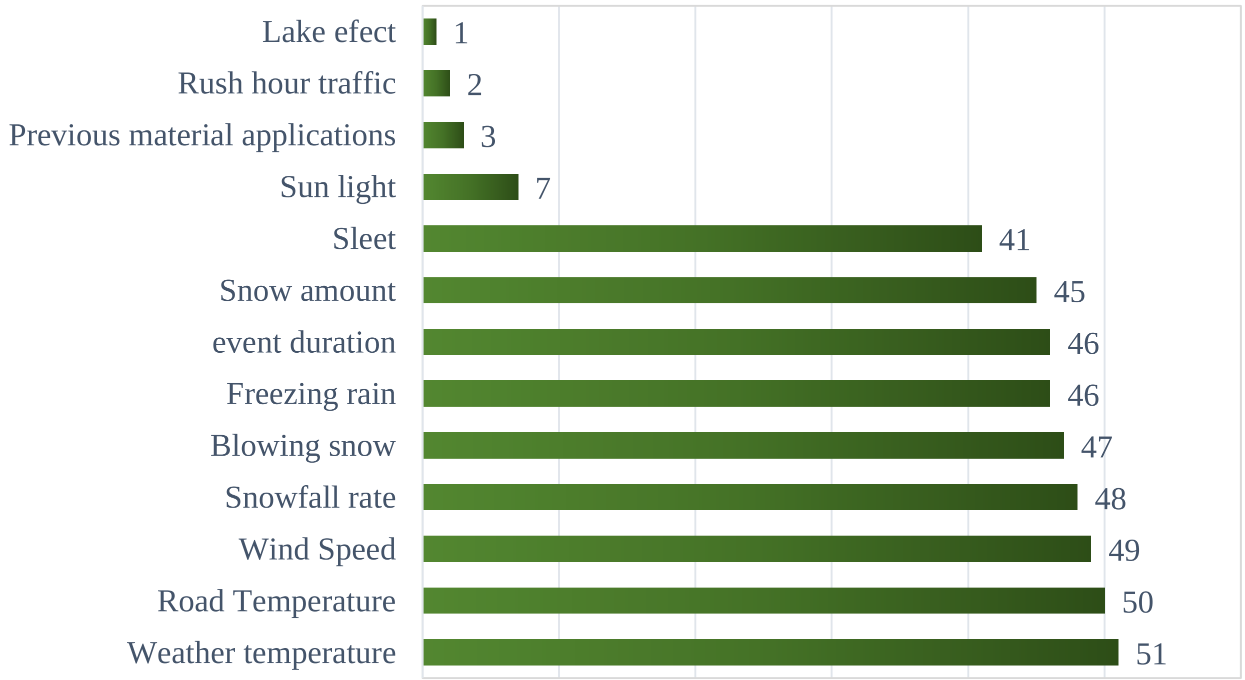


Figure 3-19: Key weather variables over the service area of local garages

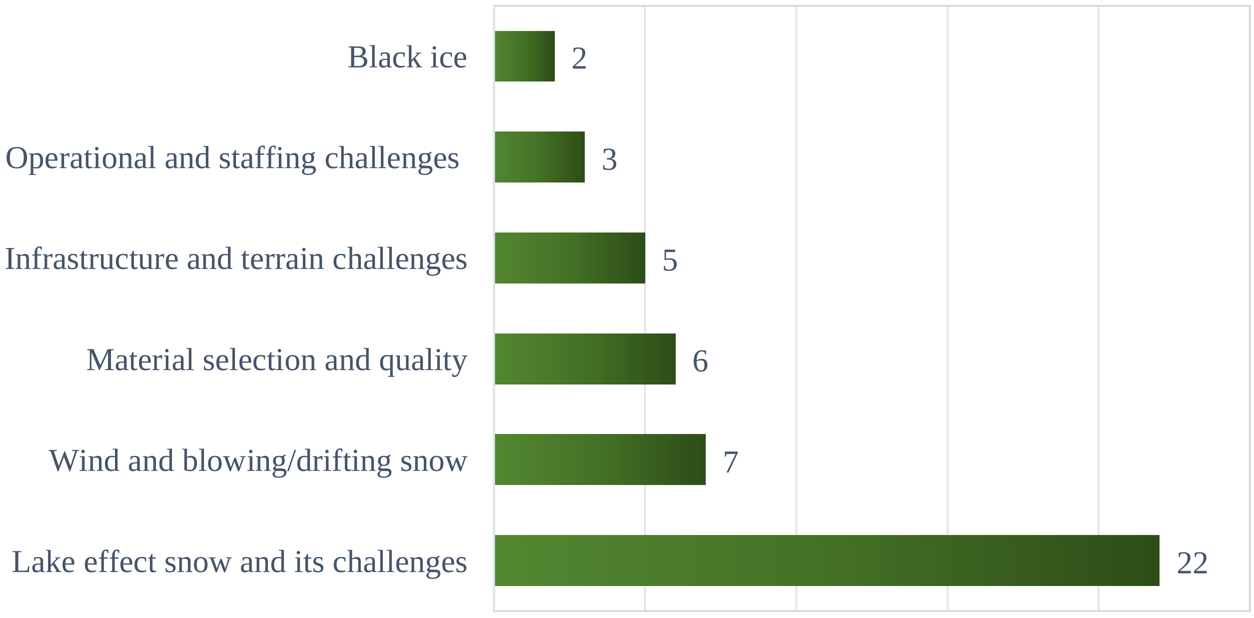


Figure 3-20: Unique challenges or considerations specific to the service areas of local garages

Finally, garages were invited to share any additional comments or observations. Common themes from these responses included:

- A strong belief that “experience is the best resource for decision-making”.
- The need for material application strategies that are customized to local conditions.
- Consideration of factors not pre-listed in the survey, such as rush hour traffic, previous material applications, and sunlight effects.
- Suggestions for post-storm cleanup strategies and a desire for enhanced technology integration for real-time monitoring.

Section 4: Collaboration & Information Sharing

Respondents were asked to evaluate their current communication and information sharing with MDOT. Out of the 51 garages, 34 reported having effective communication with MDOT. However, several respondents suggested potential approaches to enhance this coordination (Figure 3-21). Garages were also asked about their willingness to participate in a pilot test for the developed WSI in this project that is tailored to their regional specifications (Figure 3-22). 20 garages that chose “Maybe” indicated they would like more information before committing to a pilot program. Among the 11 garages that chose “No”:

- 5 garages indicated that current methods have been effective and do not see the need for additional systems.
- Two garages expressed concerns about over-reliance on an index, which could lead to inaccurate decisions and potentially unsafe conditions.
- Two other garages expressed concerns about practical challenges.

The garage representatives were also asked about the proposed WSI applications and what aspects of operations and planning are intended to be facilitated (Figure 3-23).

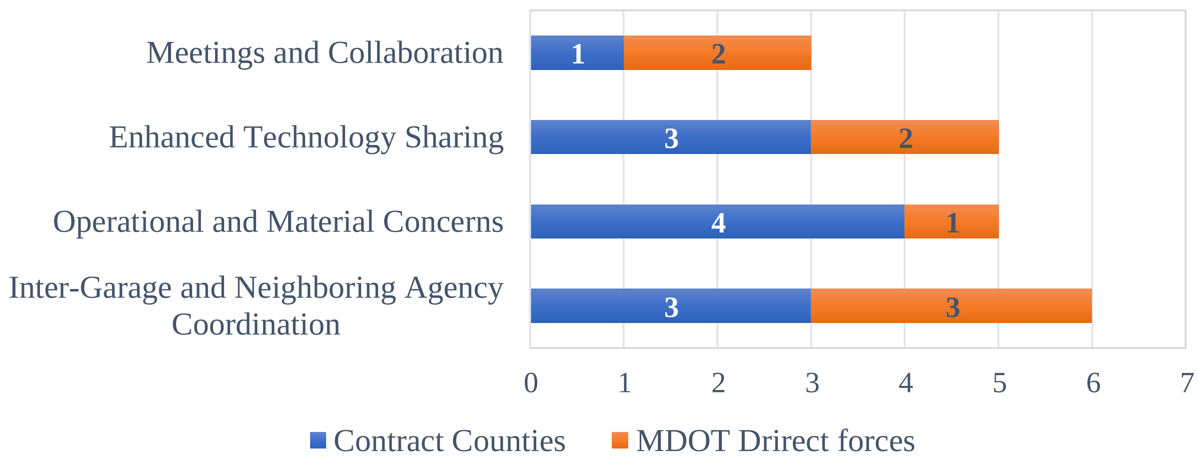


Figure 3-21: Approaches to enhance communication and coordination between MDOT and local garages

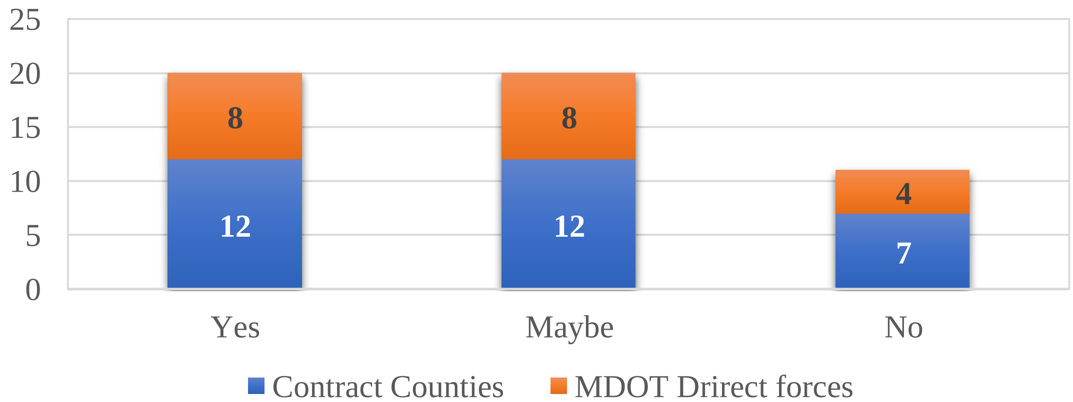


Figure 3-22: Willingness to use WSI

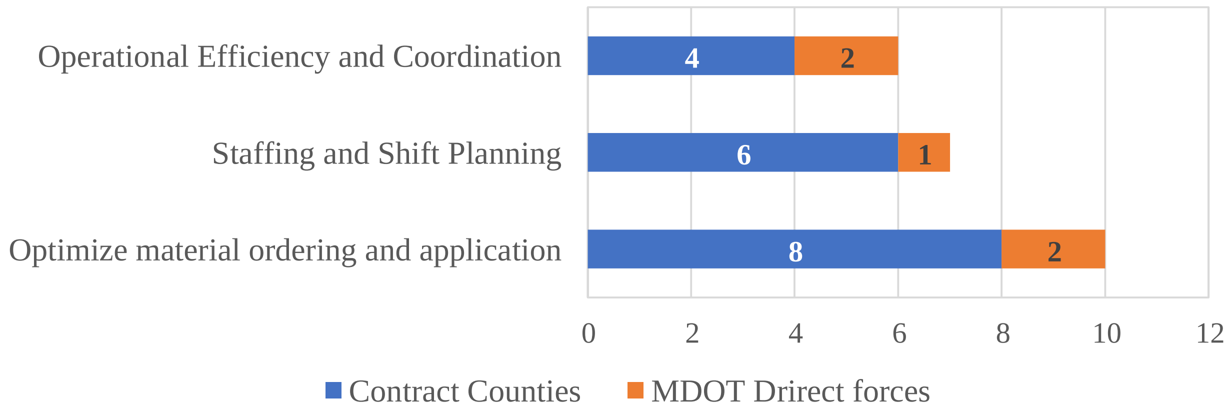


Figure 3-23: Expectations from the proposed WSI

In addition to these responses, 14 garages indicated that the WSI is expected to improve weather forecasting—particularly for region-specific factors like the lake effect—even though this expectation may not align with WSI's intended purpose.

Respondents were also asked about the types of support they need from MDOT (Figure 3-24). The top priority for garages is better access to advanced technology and equipment. Additional funding and more accurate weather and road condition data are also key areas for MDOT support.

The survey inquired about current collaborative efforts with other roadway maintenance agencies. Out of 51 garages, 34 reported that they are engaged in some form of collaboration (Figure 3-25). The types of collaborative efforts mentioned include joint equipment, sharing programs, coordinated snow removal operations, and shared material inventories (Figure 3-26). Finally, garages were asked to describe the benefits they experience from collaborating with other agencies (Figure 3-27).

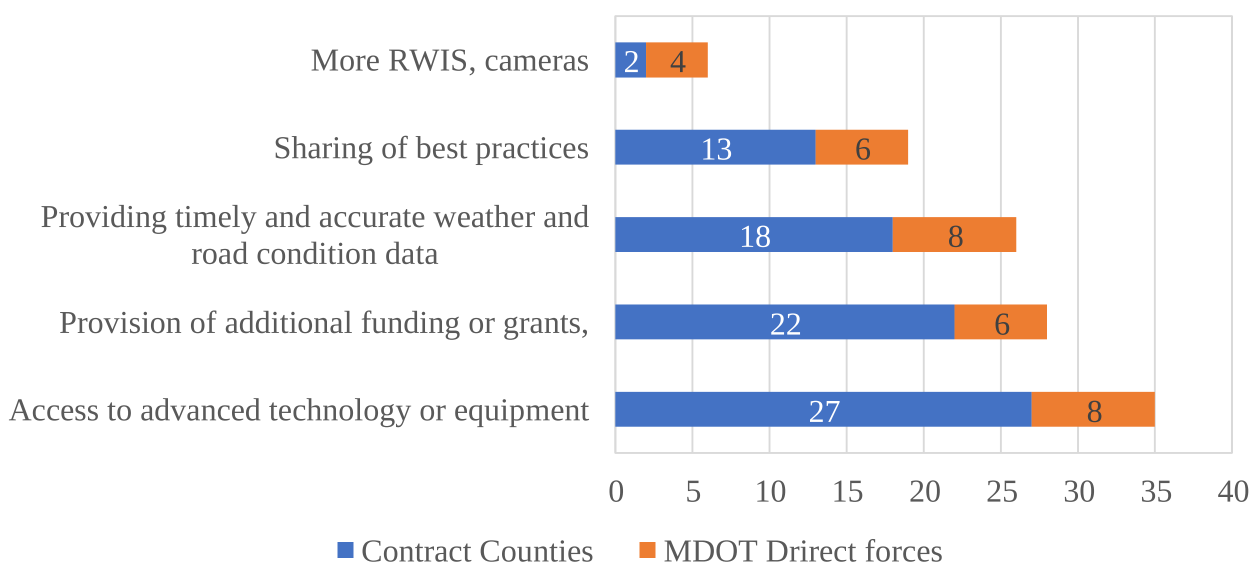


Figure 3-24: Areas where MDOT could provide additional support for local garages

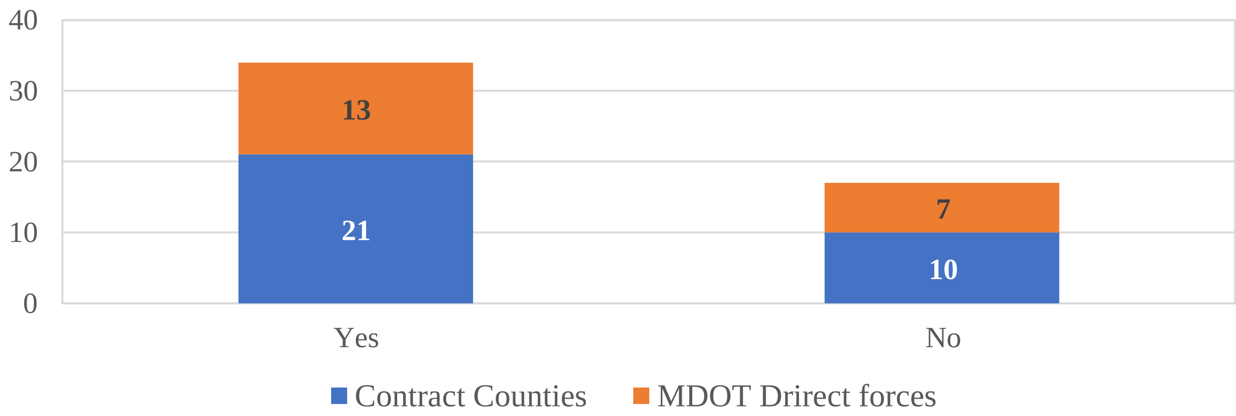


Figure 3-25: Cooperative efforts or collaborations with other roadway maintenance agencies

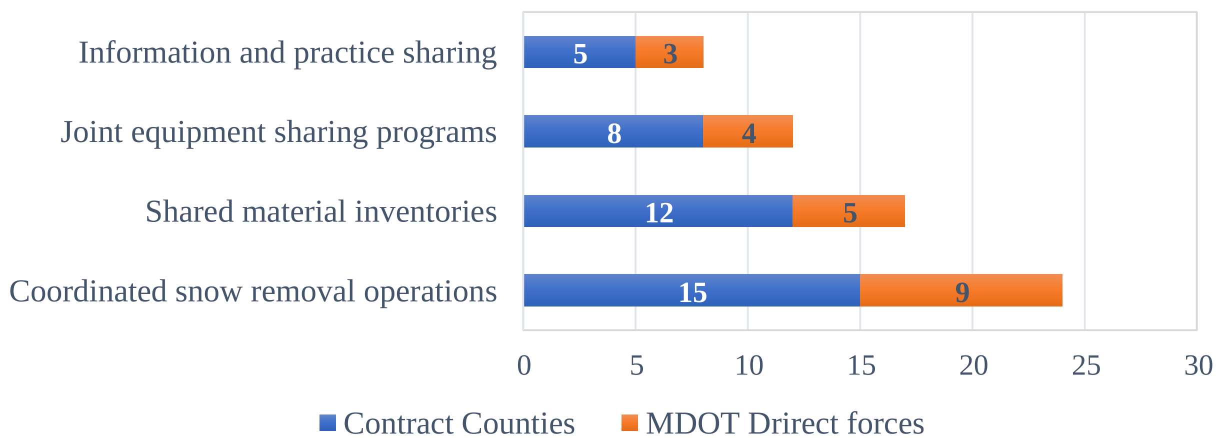


Figure 3-26: Specific types of collaborative efforts with neighboring agencies

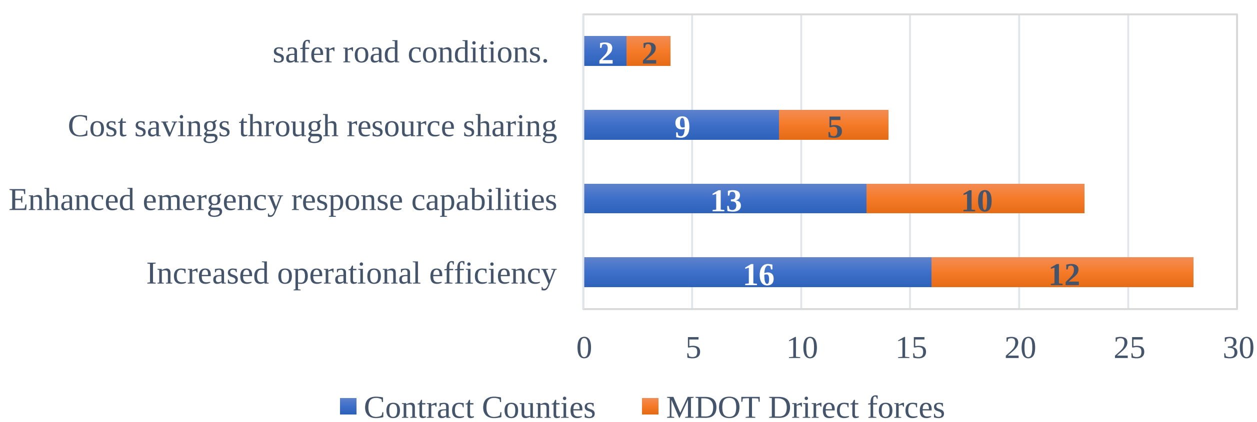


Figure 3-27: The benefits of collaborative efforts with neighboring garages

3.3.4 Summary of Findings

Together, these insights demonstrate that while effective communication with MDOT is generally in place, there is room for improvement, particularly in the areas of real-time data exchange and clarity of information. Moreover, the conditional willingness to adopt a tailored WSI, coupled with a clear vision of its benefits, highlights the potential for a more integrated approach to winter maintenance planning. Enhanced MDOT support and continued collaboration with other agencies further promise to boost overall operational efficiency and cost-effectiveness.

The survey of local service providers in Michigan provides a comprehensive insight into current winter maintenance practices at the local level. A total of 51 valid responses were collected from 92 contacted garages, with responses coming from both directly managed MDOT forces and contract counties, ensuring broad regional representation. The survey reveals that while many garages adhere to the standard MDOT-enforced material application rates, a significant number also rely on the practical judgment of drivers and foremen, highlighting the critical role of real-time, localized decision-making. Data on salt usage indicated that most providers apply between 200 and 350 lbs per lane mile, with notable regional variations reflecting local weather conditions and roadway characteristics. In terms of budgeting and resource estimation, the responses demonstrate that local service providers use a combination of historical data and current observations to determine material reordering thresholds, underscoring a focus on maintaining efficiency and safety. Additionally, the survey highlights challenges and opportunities in coordination and data sharing between MDOT and local agencies, with respondents indicating a need for improved alignment through enhanced communication and technological integration, such as with the MDSS. Overall, these findings emphasize that while MDOT's baseline protocols provide a framework for winter maintenance, local adaptations are essential, and there remains significant potential for refining decision-support tools like the modified WSI developed as part of this project to capture regional nuances more effectively and support more informed resource allocation.

CHAPTER 4 - NATIONWIDE SURVEY OF STATE DEPARTMENT OF TRANSPORTATION

This chapter presents findings from a nationwide survey of state DOTs regarding their use of WSIs and related winter maintenance practices. The chapter is organized into three main sections. The first section outlines the objectives of the survey and its relevance to the study. The second section describes the survey's design, administration, and methodology, including how participants were selected and how data were collected. The last section summarizes the key findings, including how WSIs are configured, the variables commonly used, their operational purposes, and insights into budgeting, coordination, and data integration across states.

4.1 Purpose

Effective planning for winter maintenance relies on accurately estimating and forecasting how adverse weather affects road conditions and maintenance costs. Given that state DOTs across the nation employ Winter Severity Indices (WSI) to gauge winter weather conditions and inform their budgeting and resource allocation decisions, this survey was designed to explore current practices nationwide. The goal is to learn how different agencies configure, apply, and utilize WSIs for both operational planning and fiscal forecasting so that best practices and innovative approaches can be identified and compared.

This survey aims to:

- Determine the extent and manner in which state DOTs use WSIs for material procurement, maintenance cost estimation, and resource allocation.
- Identify the specific weather variables and data sources incorporated into existing WSI formulations.
- Understand the reporting structures, rating schemes, and coordination practices in place, particularly how WSIs are integrated with local service provider operations.
- Provide context for Michigan's own efforts to refine its WSI by comparing these practices against those of other states.

By gathering detailed responses from state DOTs nationwide, the survey will provide useful insights for the development of a modified, regionally sensitive WSI that not only reflects local weather patterns but also enhances material usage planning and cost control for Michigan.

4.2 Survey Design and Administration

The MSU research team developed a survey questionnaire to investigate the state-of-the-practice for winter maintenance operations across the nation. The topics and questions included were developed based on the literature review and were revised based on MDOT RAP members' feedback. The survey was designed and implemented in a web-based format through the Qualtrics platform and consisted of five sections that sought the following information:

- Section 1: Respondent Details
- Section 2: WSI Utility
- Section 3: Weather Index Configuration
- Section 4: Asset Management
- Section 5: Coordination and Communication

Through an exhaustive search of publicly available records and the assistance of RAP members, the research team gathered a pool of contacts from state DOTs nationwide in charge of winter maintenance operations. The survey was first distributed on October 9th, 2023, with a survey deadline of December 1st. During this period, several rounds of reminders were sent out to survey invitees. After the survey response collection had ended, the research team analyzed response previews and conducted a follow-up survey from December 1st through January 1st, 2024, to ramp up the complete response rate. The survey officially closed on January 1st, with a total running duration of three months. Several respondents also provided the research team with supplemental documentation and information, and the provided data was manually input into their survey responses. The list of survey questions is provided in Appendix C of this report.

4.3 Summary of Results

4.3.1 Overview of the Responses

The nationwide survey was designed to capture state DOTs' practices regarding the application and configuration of Winter Severity Indices (WSI) for winter maintenance operations. In total, the survey was distributed to agencies nationwide, and it achieved robust participation, with responses from 41 states. This broad representation provided diverse insights into state practices regarding the use of WSIs for operational planning and maintenance management. Here is the list of the state DOTs, which did not participate in the survey:

- **No Response:** Nine states did not respond to the survey. These states include Hawaii, California, Colorado, Arkansas, Kentucky, Delaware, Maryland, Florida, South Carolina, and the District of Columbia.
- **Incomplete Responses:** Two states – New York and Connecticut – submitted incomplete responses.

Figure 4-1 illustrates the distribution of survey responses received by state.

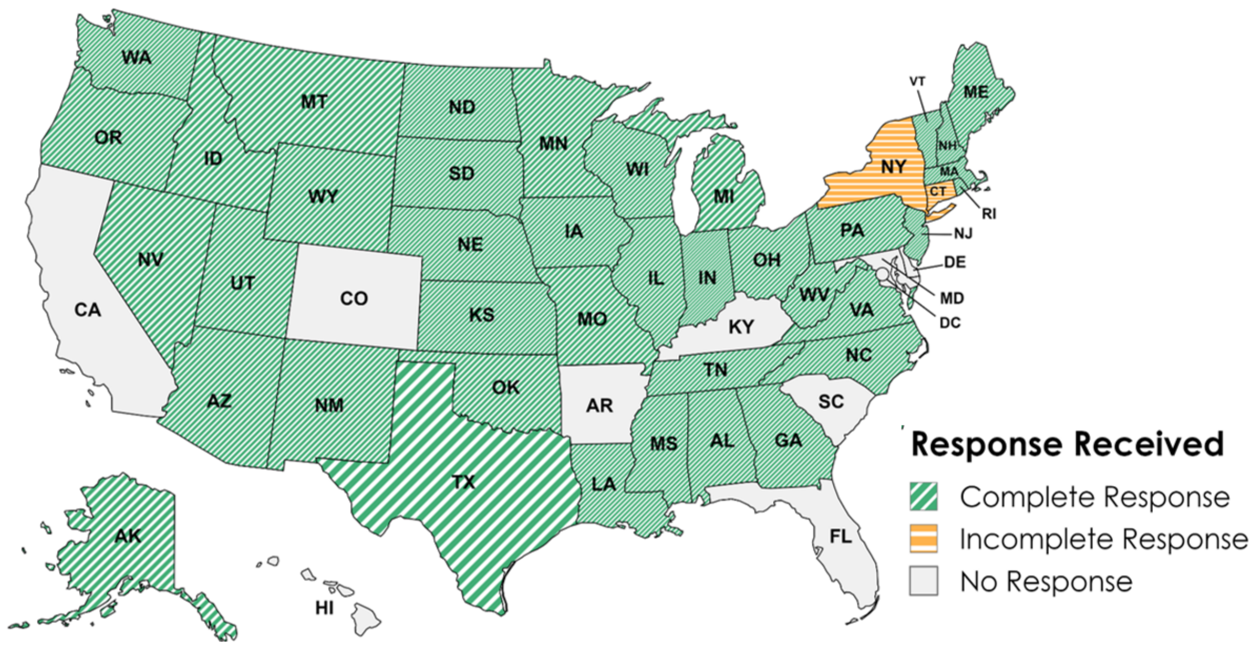


Figure 4-1: Spatial distribution of state DOTs that responded to the survey

4.3.2 Survey Analysis & Insights

Section 2: WSI Utilization

The survey inquired about agencies' utilization of WSIs and revealed several noteworthy findings. Out of the responding state DOTs, 19 reported actively using a WSI. Among these, a mix of index types emerged—some agencies rely on established indices such as the SHRP winter index, AWSSI, and RAWSSI, while others have developed proprietary models tailored to their operational needs (Figure 4-2).

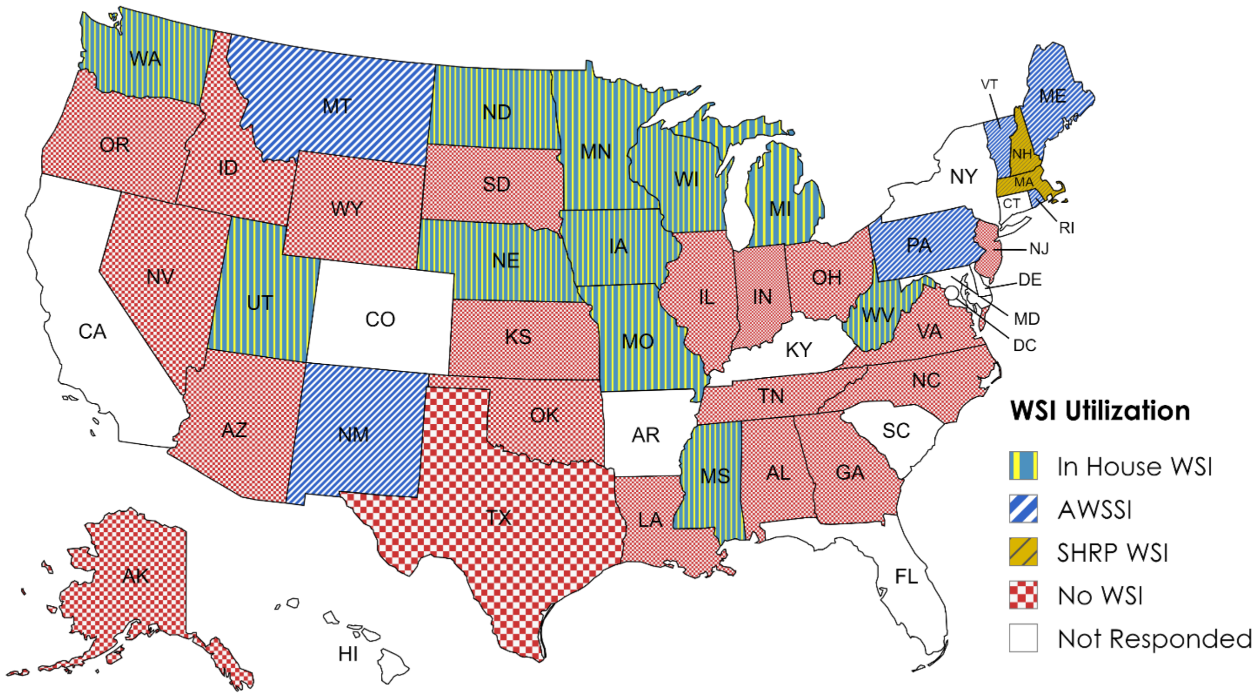


Figure 4-2: Spatial distribution of state DOTs WSI utilization

Agencies were further asked about the primary purposes for employing WSIs. The responses indicate that WSIs are used mainly for fiscal planning and material budgeting, as well as for guiding ground operations, including crew deployment and safety management (Figure 4-3). In addition, two state DOTs indicated that they are currently evaluating their indices. The Missouri Index is intended to measure the performance of ground operations and the costs associated with traffic crashes and delays. In contrast, the NE index is meant to be used predictively, aiding in the preparation for ground operations.

In addition, the survey examined whether agencies perform cross-analysis between WSIs and other datasets. Approximately 10 states indicated that they integrate WSI data with metrics such as maintenance costs and material usage, as shown in Table 4-1. This cross-analysis supports the refinement of planning models and helps optimize resource allocation.

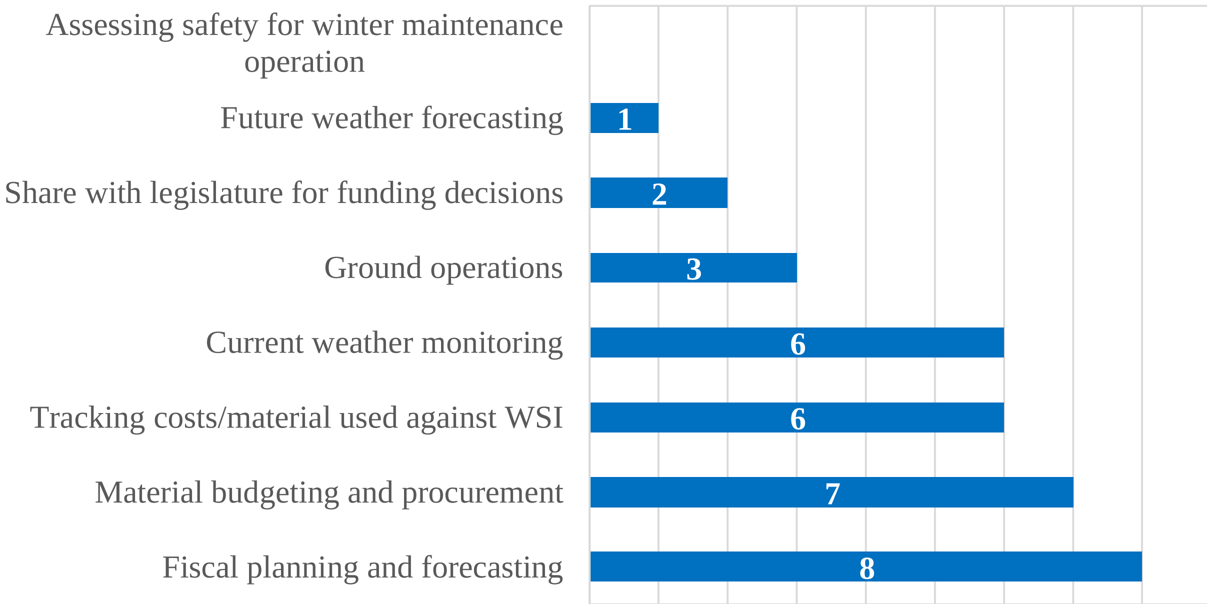


Figure 4-3: Different applications of WSIs for state DOTs

Table 4-1: Cross-analysis of WSIs with other metrics

State	Cross-analysis		
	Maintenance cost	Material usage	Notes
IA	X	X	
MA		X	Linear Regression
MO			Still Evaluating
NH	X	X	Correlating WSI to Snowfall
ND	X	X	Graphed Correlations
PA		X	
UT	X		
VT	X	X	
WI	X	X	
WA	X		

Nearly all respondents (37 out of 38) reported using weather forecasting tools to monitor conditions for winter maintenance. Methods range from national meteorological services and weather radar to satellite imagery and RWIS (Figure 4-4). In addition, some agencies have reported using various tools to enhance their weather response strategies. For example, Georgia DOT utilizes the Weather Systems Processor (WSP), while Oregon DOT employs Pikealert, which provides a weather forecast up to 72 hours in advance and offers recommendations for specific highway segments, such as when and where to plow or apply chemicals. Additionally, Washington DOT uses Pathfinder, a collaborative strategy designed for the proactive management of transportation systems before and during adverse weather events.

Section 3: Weather Index Configurations

The survey asked agencies about the key components and variables used in their WSIs. Respondents indicated that common components include air temperature, road temperature, wind, freezing rain, snow amount, snow frequency, event duration, and blowing/drifting conditions (Table 4-2).

Agencies reported diverse practices regarding how often they calculate or apply their WSIs. While most respondents indicated that they use the index on a daily basis, a few states calculate their WSI less frequently (Figure 4-5). In addition, the Utah DOT calculates its WSI every 10 minutes.

When it comes to spatial scale, responses varied widely. Some agencies compute WSIs at the sensor or road segment level, while others aggregate data at the city, county, or district/region levels. Many respondents noted that a regional or district scale is most effective for operational planning, as it strikes a balance between capturing localized variations and providing actionable insights across larger areas (Figure 4-6).

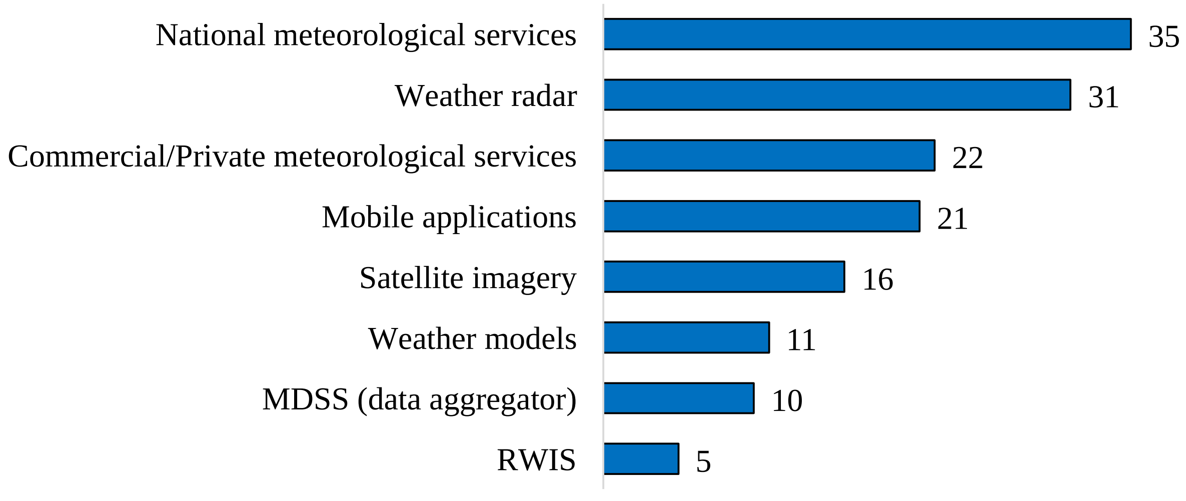


Figure 4-4: Methods used by DOTs to monitor weather conditions and predict winter maintenance needs

Table 4-2: Weather Elements Used in WSI definitions by different state DOTs

State	WSI Factors							
	Road Temp	**Winds speed**	**Freezing Rain Events**	**Event Duration**	**Blowing Snow**	**Air Temp**	**Snow Amount**	**Snow Events**
IA	X	X	X	X	X		X	X
MA						X	X	
ME						X	X	
MI			X	X	X		X	X
MN	X	X	X	X	X	X	X	X
MO		X	X				X	
MT						X	X	
ND				X	X		X	
NE	X	X	X	X	X	X	X	X
NH						X	X	
NM						X	X	
PA						X	X	
RI						X	X	
UT	X	X	X	X	X	X	X	X
VT						X	X	
WA		X	X			X		X
WI				X	X	X	X	X

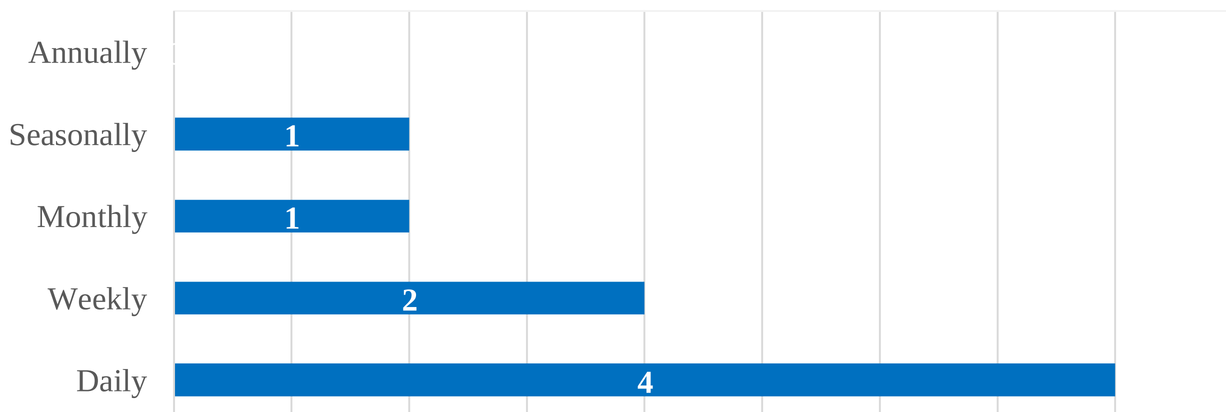


Figure 4-5: Frequency of WSI application or calculation

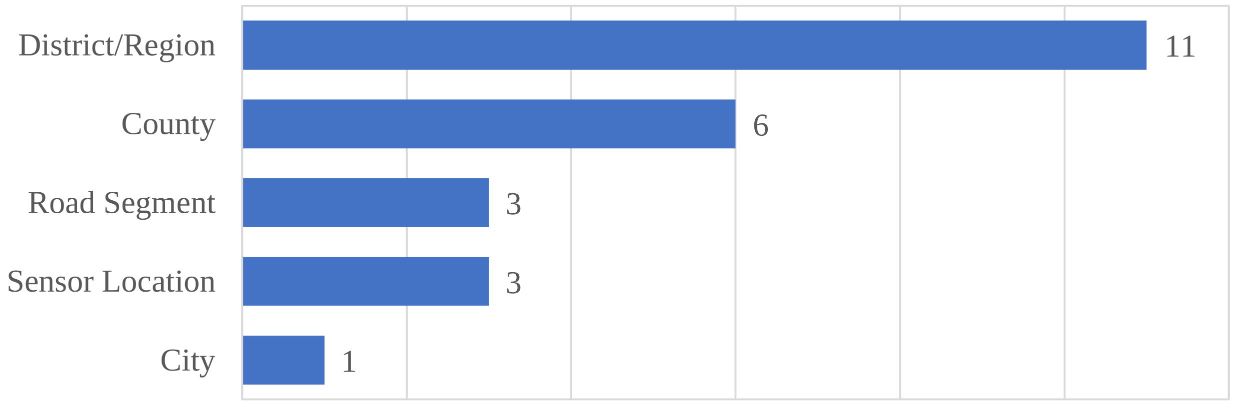


Figure 4-6: Spatial scale used to calculate or apply WSIs by state DOTS

Agencies were also inquired about the criteria used to define the regions or boundaries for WSI calculations. The responses revealed that common criteria include climate zones, average altitudes, administrative boundaries (e.g., counties or districts), and specific geographical characteristics. This range of criteria underscores the need to customize the index to the local context and ensure that the WSI accurately reflects regional weather patterns (Figure 4-7).

Regarding data sources, most agencies rely on a blend of inputs. Predominantly, they use agency-operated sensors (e.g., RWIS/probes) complemented by national weather service products and, in some cases, private weather service providers (Figure 4-8).

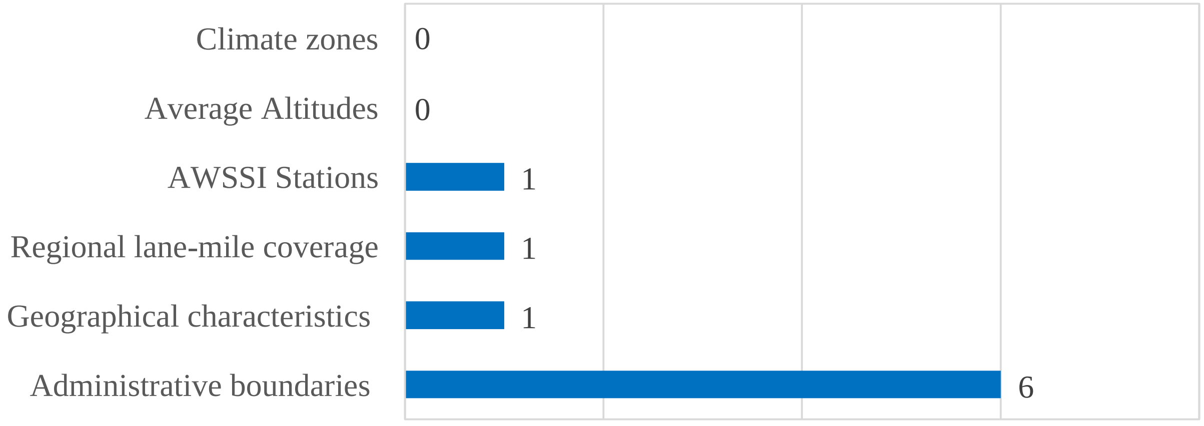


Figure 4-7: The criteria used to define the regions/boundaries for calculating or applying WSI

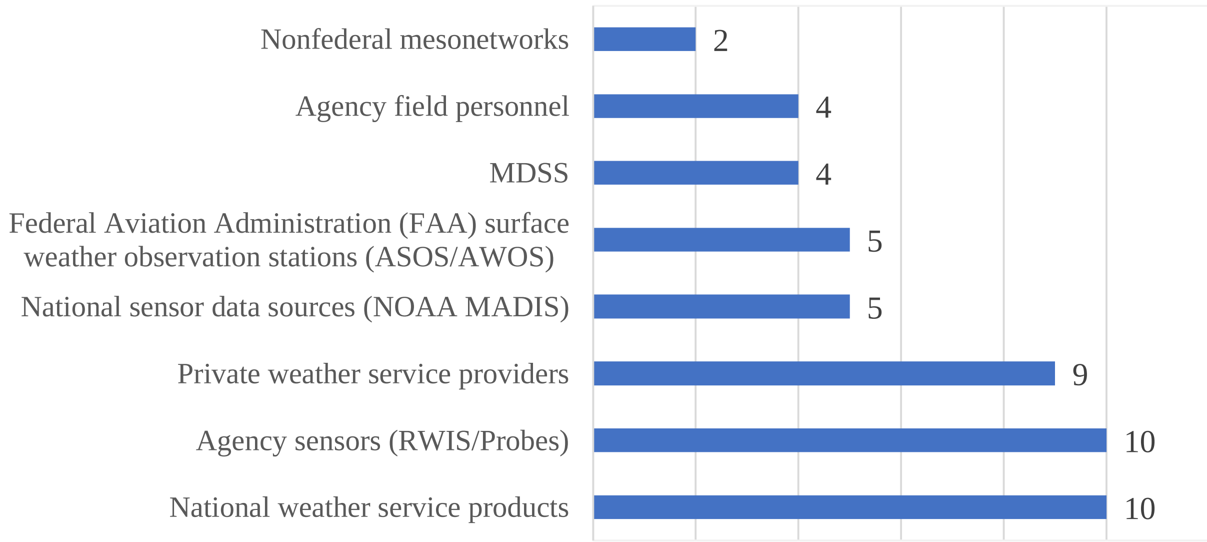
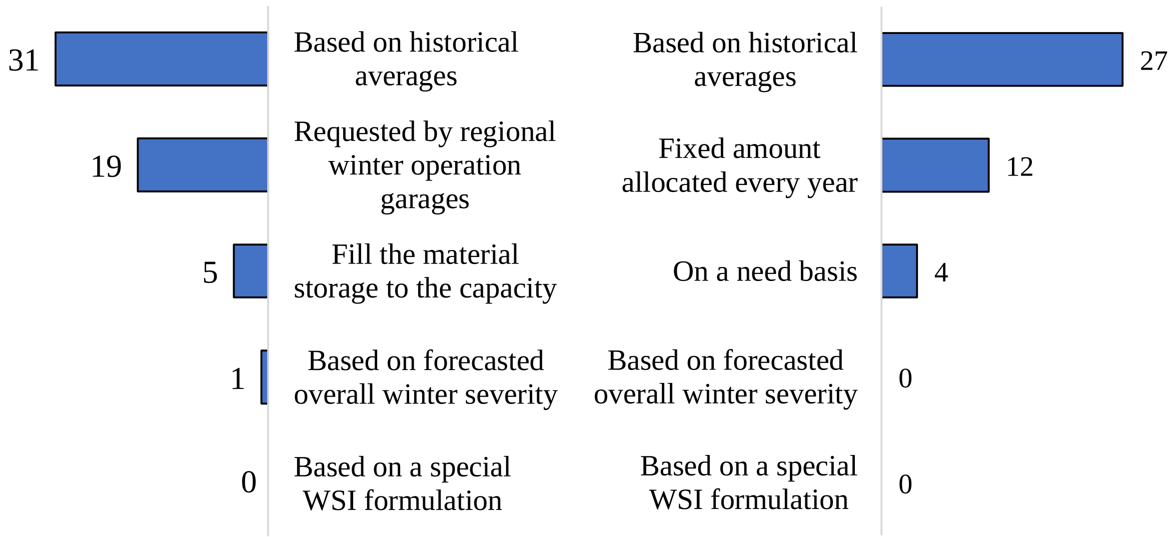


Figure 4-8: Data sources used to calculate WSIs by different state DOTs

Finally, respondents provided feedback on the limitations of their current WSIs and offered suggestions for improvement. Common challenges include the inability of existing indices to fully account for freezing rain and icing, limited sensor coverage, and difficulties linking the index to material usage and budget planning. In response, several agencies recommended exploring alternative WSI formulation methods, integrating short-term forecasts, expanding the RWIS network, and adopting new technologies such as mobile sensors. These suggestions are vital for evolving WSIs into more comprehensive tools that better support operational decision-making and cost management.

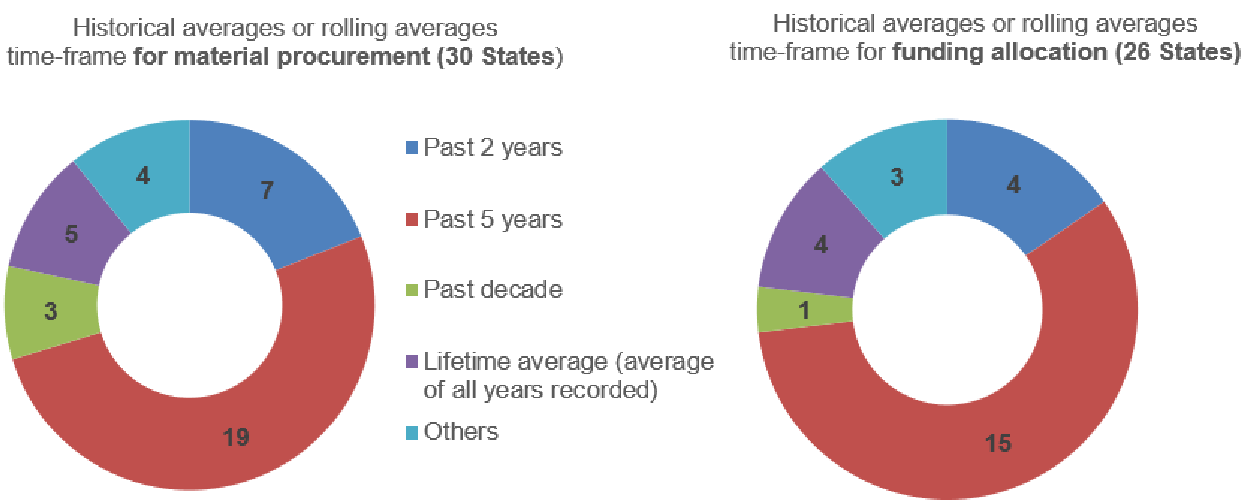
Section 4: Asset Management

The survey also explored how agencies determine the amount of materials to be procured and the funding to be allocated for winter maintenance operations. The results revealed that most agencies rely on historical and rolling averages (Figure 4-9). Respondents also shared the time frames they use when calculating averages to inform procurement decisions. While many state DOTs typically use rolling averages over the past 5 years, others reported using 2-year or 3-year periods to capture more recent trends (Figure 4-10).



(a) (b)

Figure 4-9: Frequency of how state DOTs decide (a) the amount of material to be procured and (b) the amount of funding in the next winter season



(a) (b)

Figure 4-10: Time frame used for calculating the average values (a) for material procurement (b) for funding allocation

In terms of operational application, some agencies leverage their WSIs as a metric to track and control material usage and overall winter maintenance costs. For instance, Pennsylvania DOT mentioned that they compare their county-level salt usage directly with the WSI value, aiming for a consistent Salt/WSI ratio year over year. Wisconsin DOT monitors the month-to-month trend of their current WSI against a historical 5-year average to fine-tune their budgeting and resource allocation throughout the season. This data-driven approach helps in identifying both potential over-utilization and under-utilization of materials, leading to better cost savings and more efficient deployment of resources.

Finally, the survey revealed several perceived benefits of using WSIs in winter maintenance operations. Respondents noted that employing a WSI can enhance cost savings, optimize material procurement, and reduce waste by providing a more dynamic basis for decision-making (Figure 4-11).

Section 5: Coordination and Communication

The survey also asked respondents to indicate what percentage of winter maintenance operations are contracted through local service providers. 17 out of 38 states noted they use local service providers. The responses varied significantly, with some agencies reporting complete reliance on local services and others indicating minimal external contracting (Figure 4-12).

Next, respondents were asked about the systems they use to collect data for winter maintenance operations. A variety of systems were identified, including MDSS utilized by states such as Michigan, Wisconsin, Indiana, South Dakota, Nebraska, and Minnesota. Additionally, RWIS networks were used by Alaska, Massachusetts, and Arizona. There were also Automatic Vehicle Location (AVL) systems and Data Transmission Networks (DTN) employed by Arizona and Tennessee, respectively. This highlights the diversity of data delivery approaches currently in use.

The survey then examined the percentage of the state's road network that is represented within each agency's MDSS. 23 state DOTs noted they currently don't use this system. The results showed considerable variability, reflecting differing levels of network integration and data availability across agencies (Figure 4-13).

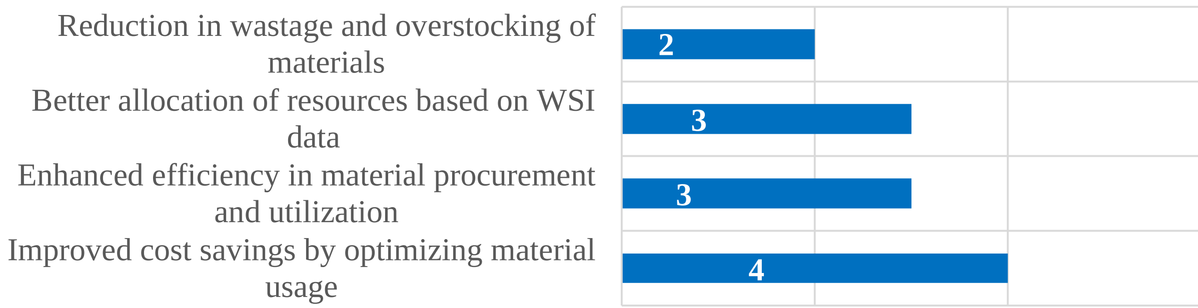


Figure 4-11: Perceived benefits of WSI application for winter maintenance operations

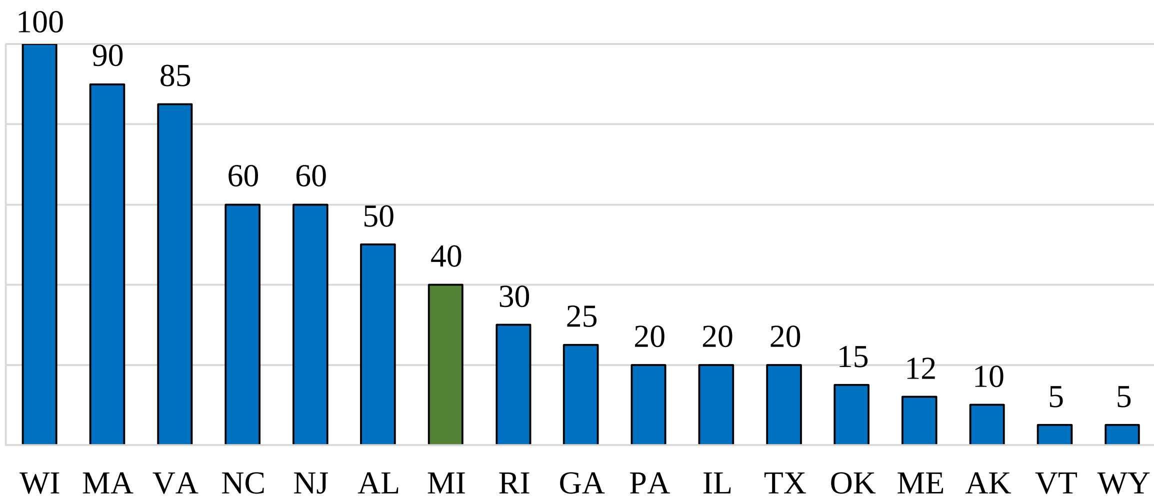


Figure 4-12: Percentage of winter maintenance operations contracted through local service providers

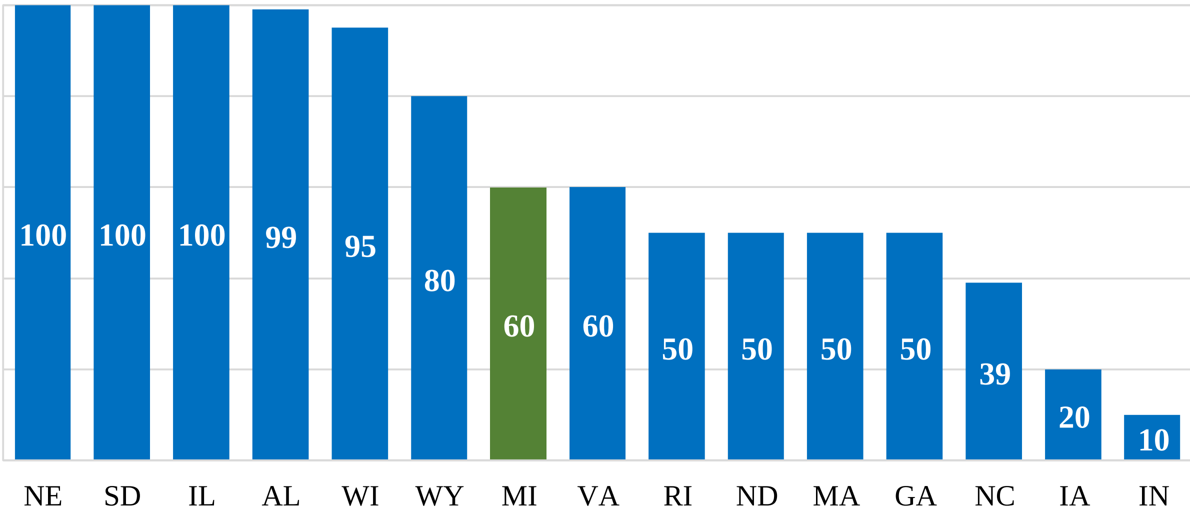


Figure 4-13: Percentage of the roads in the state, available on the MDSS

Seventeen agencies that utilize the MDSS were asked how they disseminate their formulated WSIs to winter maintenance operators. While a few utilize dedicated dashboards or MDSS interface to relay this information in real-time, many continue to rely on more traditional, manual reporting methods (Figure 4-14). Respondents also provided insights into whether they have published guidelines on material application rates (Table 4-3). While 23 agencies do have formal guidelines in place, the guidelines and the degree of enforcement vary, suggesting room for standardization. Only about half of the agencies indicated that material application rates are rigorously enforced. The remaining agencies tend to leave these decisions to the discretion of the drivers, which may lead to variability in maintenance outcomes. (Figure 4-15).

The survey further explored how agencies facilitate effective coordination and information exchange with local service providers. Many agencies highlighted the use of regular calls, meetings, and training sessions; however, some noted that interagency agreements and formal coordination protocols are still limited. The other comments are summarized in Table 4-4.

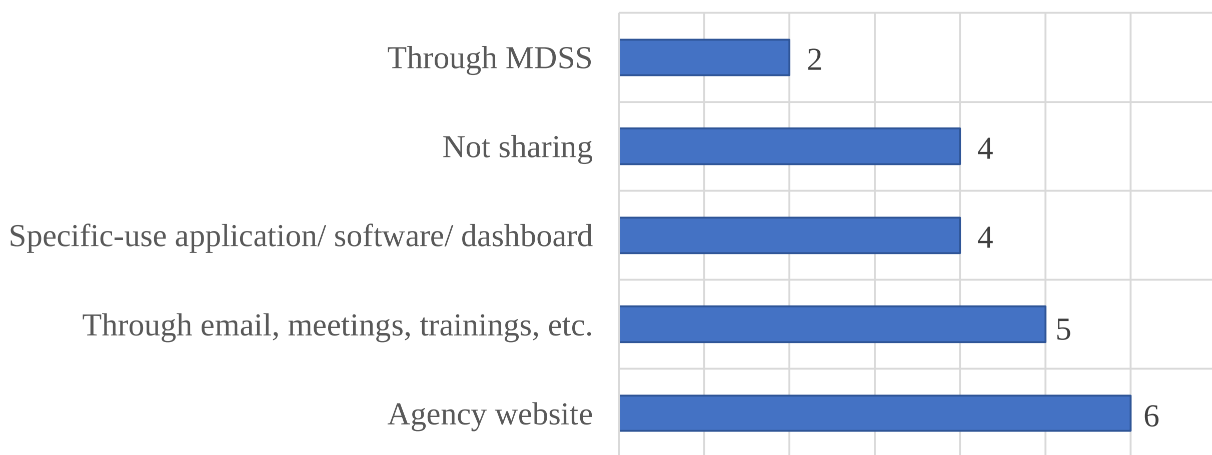


Figure 4-14: Approaches for sharing formulated WSIs with winter maintenance operators

Table 4-3: Guidelines used by agencies for material application rates during winter maintenance events

	Clear Roads/ FHWA Guidelines	Internal Guidelines	Other Guidelines (not specified)
AZ	X		
ID	X		
WA	X		
PA			X
OR			X
NM			X
KS			X
MI		X	
AK		X	
GA		X	
IL		X	
NV		X	
OH		X	
TN		X	
TX		X	
VA		X	
WV		X	
IA		X	
MA		X	
NJ		X	
NH		X	
VT		X	
WI		X	

Table 4-4: Facilitating coordination and information exchange with local service providers

State	Other Comments
GA	Using WebEOC (an internet-based crisis management system for situation awareness during an incident), RWIS, and situation reporting internally and externally
OK	Establishing service contracts before the winter season with local contractors to identify if state forces' assistance would be needed
TX	Utilizing a dashboard to track equipment and material stockpiles on a map
AZ	Coordinating Major storms with NWS, State police, and the State Emergency Operations Center (EOC)
WV	Downloading material application data from the dump trucks periodically using software to check application rates

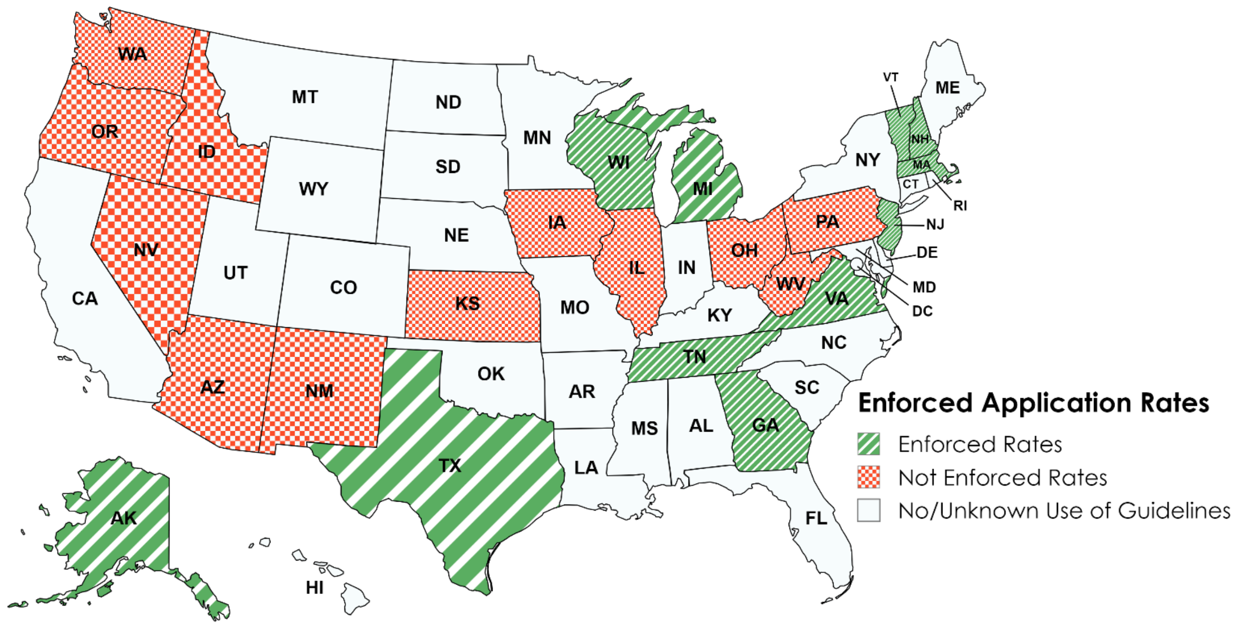


Figure 4-15: State DOTs with enforced material application rates

Maintenance service providers' feedback regarding WSI usage was mixed. Some providers (e.g., in MI and VT) expressed challenges in fully understanding or operationalizing the index, while others noted that the WSI offers valuable storm-by-storm performance insights. When asked about their agency's current utilization of the WSI, many expressed a strong desire for enhancements or using one to better address operational and budgeting needs (Figure 4-16). Most of the agencies that mentioned they don't plan to use a WSI, are located in the southern regions, where winter maintenance challenges are less critical compared to more severe climates.

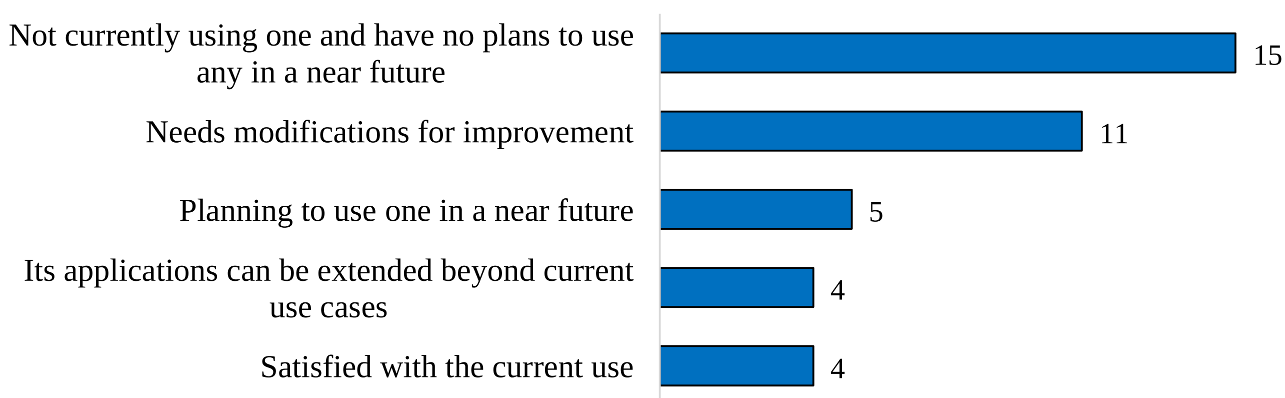


Figure 4-16: State DOTs' perception on WSI utilization

- **Integration and Utilization of WSI:**
  - Utilizing WSI to forecast required budgets for snow removal services (MI, ND, RI, UT)
  - Enhancing understanding and communication of the WSI index among all users, including direct and contracted forces (MI, UT)
  - Enhancing integration of broader measures and higher sensor resolution by expanding the RWIS network (ME)
  - Deploying as a tool for decision-making and performance evaluation (MO)
  - Utilizing WSI at an earlier stage than MDSS for operational decisions (NE)
  - Automating the comparison of WSI data with costs/materials is proposed to streamline response evaluations (VT)
- **Refinement of WSI Metrics:**
  - Focusing on individual storm severity rather than solely seasonal cumulative metrics is envisioned (IA)
  - Modifying WSI definition to give particular weight to freezing rain events (MA)
- **Localization and Equitability of WSI:**
  - Developing district-specific WSIs for more localized and effective winter maintenance strategies (NH)
  - Expansion of potential benefits to all counties instead of focusing on certain counties (PA)
- **Integration with Operational Improvements:**
  - Establishing a connection between the WSI and an improved Level of Service (LOS) to enhance planning winter maintenance operations (WA)

Different perspectives were provided regarding the potential to expand the use of WSIs to encompass material procurement and budget management. Most respondents see the WSI as a retrospective tool for justifying or assessing performance and allocated budgets post-season. They generally do not rely on it for predictive planning or material procurement, favoring established weather services and historical data. While a few respondents are open to WSI’s potential for future predictive use, the consensus is that its current role remains primarily post-season evaluation rather than pre-season forecasting.

Finally, respondents offered additional comments emphasizing the need for improved data quality, enhanced training for operators, and better interagency communication protocols to fully leverage WSI benefits in optimizing winter maintenance operations. In addition to the WSI, a few respondents mentioned complementary tools and technologies to improve winter maintenance operations (Table 4-5).

Table 4-5: Other tools or technologies considered to improve winter maintenance operations

Category	Comments
Infrastructure Enhancement	Adding RWIS devices to increase area coverage and to get more accurate input data (Al, ID, NE, NJ)
	Measuring salt piles and expanding brine capacity and facilities (GA)
	Increasing storage and modifying contract language (WA)
Technological Integration	Using mobile friction sensors (AZ)
	Lidar salt measuring for salt storage facilities to capture more accurate inventories (IN)
	Implementing automatic data collection (telematics) on plow trucks to map material use over time based on location (OR)
	Using connected vehicle technology and CCTV footage (UT)
Data Management and Analysis	Budget tracking dashboards (IA)
	Using a management system and data warehouse (MT)
	Participating in Clear Roads to remain aware of promising materials, equipment, and innovative practices (ME)
	Using Clear Path software (IL)

4.3.3 Summary of Findings

The nationwide survey of state DOTS provided a comprehensive overview of current practices and perspectives on the use and configuration of WSIs across the United States. The survey achieved robust participation, with responses reflecting a diverse range of geographic and climatic conditions, and offered detailed insights into how WSIs are integrated into operational planning. Respondents revealed that while many agencies employ standardized indices such as AWSSI or develop agency-specific versions, the utility of these tools varies considerably across regions due to differences in weather patterns and local operational challenges. Most state DOTs rely on a combination of national meteorological data, advanced forecasting tools, and proprietary systems such as MDSS to monitor weather conditions, yet they also face challenges in capturing localized phenomena such as freezing rain that can significantly impact maintenance operations. The survey findings underscore the importance of incorporating WSIs into material procurement, budgeting, and cost control processes, while also highlighting the need for enhanced coordination and continuous refinement of these indices to ensure they remain relevant and accurate. Overall, the survey validates the potential of WSIs as valuable decision-support tools while pointing out the necessity for tailored, region-specific improvements to better inform winter maintenance planning and resource allocation.

CHAPTER 5 - WINTER MAINTENANCE DATA ANALYSIS THROUGH CLEAR ROADS ANNUAL SURVEY

To support the development of a cost-informed Weather Severity Index, this chapter investigates the statistical relationship between winter severity and maintenance expenditures at a national scale. While previous chapters addressed current practices and survey insights, this chapter shifts toward a data-driven analysis using the Clear Roads Annual Survey—a comprehensive nationwide dataset on winter maintenance costs. By integrating this cost data with the AWSSI, the chapter evaluates how well existing weather indices predict operational costs across different U.S. climate regions. The chapter is structured as follows: The first section introduces the Clear Roads dataset and its role in this study. The second section outlines the research framework, including data integration and normalization methods. The third section describes the correlation analysis between AWSSI and cost, while the fourth section presents regression results across climate divisions. The chapter concludes in the last section with a summary and interpretation of findings that inform the design of Michigan's modified index.

5.1 Clear Roads Annual Survey

The Clear Roads Annual Survey is a critical resource for state DOTs, offering a detailed account of winter maintenance expenditures and operations for comparative analyses. This survey—administered annually—collects quantitative data on many different factors, including but not limited to material usage, labor, equipment costs, and lane mile coverage (*3*). In this study, the Clear Roads survey plays a dual role. First, it provides the empirical foundation for correlating weather severity with operational expenditures, and second, it offers state-level insights that help to pinpoint best practices and areas for improvement in winter maintenance planning. By capturing data over multiple winter seasons, the survey enables a robust trend analysis, allowing us to explore how variations in winter severity—quantified by AWSSI—correlate with maintenance costs. This extended dataset not only reinforces the potential of WSIs as predictive tools for budgeting but also helps bridge the gap between theoretical models and real-world operational applications.

5.2 Research Framework: Leveraging the Clear Roads Survey Data

Our research framework employs a dual-approach methodology. While the nationwide state DOT survey (covered in Chapter 4) gathers broad insights on WSI utilization and operational challenges, the Clear Roads Annual Survey data is utilized to perform a quantitative analysis of winter maintenance costs. Specifically, the framework involves:

- **Data Integration:** Correlating maintenance expenditure data with AWSSI values to explore this index as a standardized measure of winter severity across different states.
- **Normalization and Regression Analysis:** Normalizing the data across all states and applying linear regression models to assess the relationship between AWSSI and winter maintenance costs. This allows for a direct comparison of how well AWSSI predicts operational expenditures in various regions.
- **Regional Differentiation:** The study further refines the analysis by categorizing states into distinct climate divisions (as defined by NOAA) to account for regional climatic variability. This framework ensures that the model captures both the nationwide trends and the localized nuances in winter weather impacts.

5.3 AWSSI Correlation Analyses

The Clear Roads Annual Survey of State Winter Maintenance is utilized to explore the correlation between winter maintenance expenditures and weather severity. The data includes detailed information on winter maintenance costs and the AWSSI for each state, which is chosen to quantify winter severity. As mentioned in section 2-1-1, AWSSI is a weather severity index calculated based on temperature, snowfall, and snow depth, with higher values indicating more severe winter conditions. It is a point-based index that computes winter seasonal severity by accumulating points for daily values of minimum and maximum temperatures, snowfall amounts, and depths (*4*, *35*). This provides a standardized measure to compare winter severity across different climate divisions and periods.

5.3.1 Clustering States into Climate Divisions

Recognizing that winter maintenance challenges vary significantly by geography. Different states experience various weather conditions and, as a result, have different scales of maintenance operations. Thus, Clustering states into climate divisions is essential for accounting for the diverse weather conditions that influence the scale and type of maintenance operations across regions. To achieve this, the analysis began by grouping states into nine climate divisions based on the established NOAA boundaries. These divisions, defined using long-term climatological data (*32*), delineating regions with homogeneous weather patterns, enabling researchers to establish reliable baselines for comparison. By aggregating data within these divisions, current climate anomalies can be contextualized against historical trends, leading to more precise analyses. Figure 5-1 shows NOAA US climate divisions.

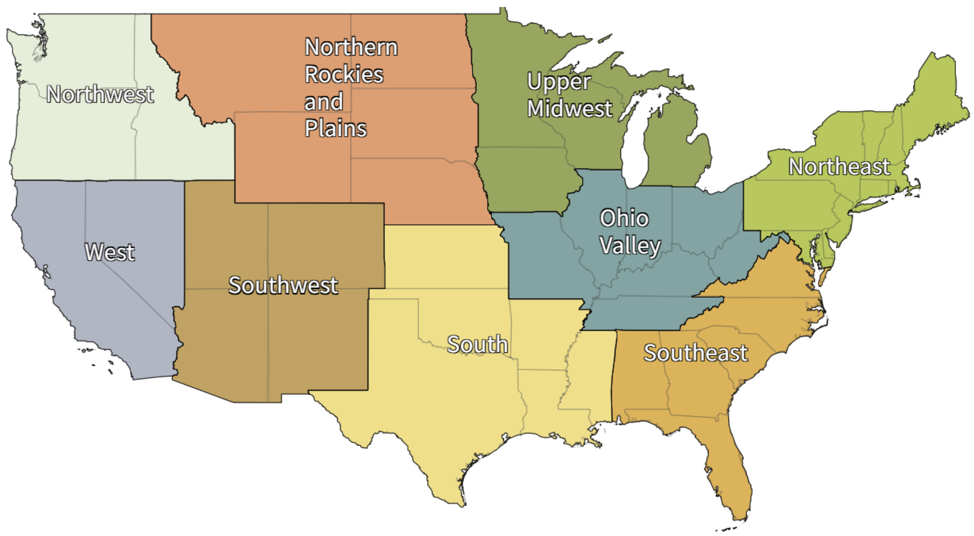


Figure 5-1: U.S climate divisions defined by NOAA (*36*)

5.3.2 Data Normalization

Next, the AWSSI and cost data across the country were normalized. This process involved normalizing the data based on all available years of data for all states, ensuring a consistent basis for comparison nationwide. Data normalization scales numerical values to a standard range without distorting their differences. This step ensures that data is comparable across different climate divisions and states by adjusting values measured on different scales to a common scale. Normalizing the data mitigates the effects of scale differences, enabling a fair comparison of winter severity and maintenance costs across climate divisions. A common method used is Min-Max normalization, which typically transforms data to fit within a specified range [0, 1] using equation (5-1).

$$x_{normalized\ i,t} = \frac{x_{i,t} - x_{min}}{x_{max} - x_{min}} \tag{5-1}$$

Where:

- $x_{i,t}$ is the original value associated with state i in year t

- x_{min} is the minimum value in the data set
- x_{max} is the maximum value in the data set
- $x_{normalized\ i,t}$ is the normalized value associated with state i in year t

While normalization enables cross-agency comparisons, it does not eliminate inherent variations in data collection methodologies across state DOTs. This limitation should be considered when interpreting results, as agencies may measure and report data differently.

5.3.3 Linear Regression Analysis

After normalizing the data points for AWSSI and costs, linear regression analyses were conducted for all NOAA climate divisions. The relationship between winter maintenance costs (dependent variable) and AWSSI (independent variable) was modeled using a linear regression approach. The regression line is determined by minimizing the sum of squared differences between the observed and estimated values (*24*). To evaluate the model, the coefficient of determination, R^2, was used, which indicates how much variation in costs can be explained by AWSSI. The R^2 value is calculated using equation (5-2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5-2}$$

In which y_i is the actual value, $\hat{y}_i$ is the predicted value, and $\bar{y}$ is the mean of the actual values.

An R^2 value exceeding 0.70 was set as the criterion for a significant correlation, suggesting that AWSSI effectively predicts maintenance costs in those climate divisions. While R^2 provides a metric for assessing the model's goodness of fit, it is crucial to validate the model's performance before applying it to a new dataset. Partitioning the dataset into calibration and validation subsets is a common approach to evaluate estimation accuracy and generalize model performance. This rigorous process ensures the model's reliability for future applications. However, this paper does not delve into such advanced validation techniques, focusing instead on the preliminary correlation analyses indicated by R^2 values.

5.4 AWSSI Correlation Analysis Results

5.4.1 Data Overview

The cost data for winter maintenance was obtained from the Clear Roads survey, which provides detailed information on winter maintenance expenditures across various states from 2014-2015 to the 2023-2024 winter seasons (*3*). This dataset includes lane mile coverage, total costs, labor, equipment, materials, and other operational costs required to maintain clear and safe winter roads. Utilizing this comprehensive dataset allows for an accurate assessment of the financial impact of winter severity on state budgets. The distribution of cost per lane mile data across climate divisions and nationwide is summarized in Figure 5-2.

Figure 5-3 shows the AWSSI index for different climate divisions nationwide, highlighting the variability in winter severity across states within each climate division. The Northeast, Northwest, Southeast, and Southwest climate divisions show high variability in AWSSI, indicating significant differences in winter severity across the states in these climate divisions. Conversely, the Ohio Valley, Northern Rockies and Plains, Upper Midwest, and West climate divisions show low variability in AWSSI, suggesting more consistent winter severity across the states within these climate divisions.

Figures 5-2 and 5-3 illustrate the distribution of winter maintenance costs and AWSSI values across climate divisions. While a direct one-to-one correlation may not always be observed due to operational differences and budget constraints across agencies, the general trend highlights that higher AWSSI values tend to be associated with increased maintenance expenditures. The variation seen in some climate divisions suggests that additional local factors, such as policy decisions, application rate guidelines, workforce availability, and emergency response strategies, also influence winter maintenance costs.

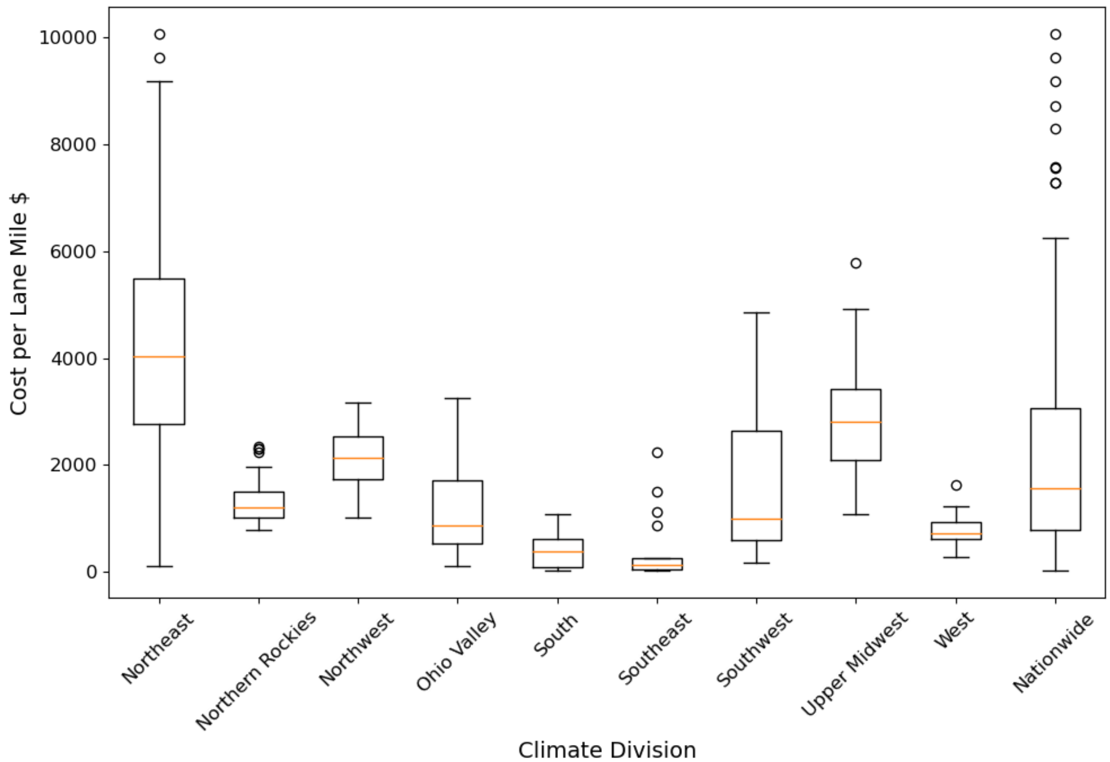


Figure 5-2: Distribution of annual winter maintenance cost per lane mile by climate divisions

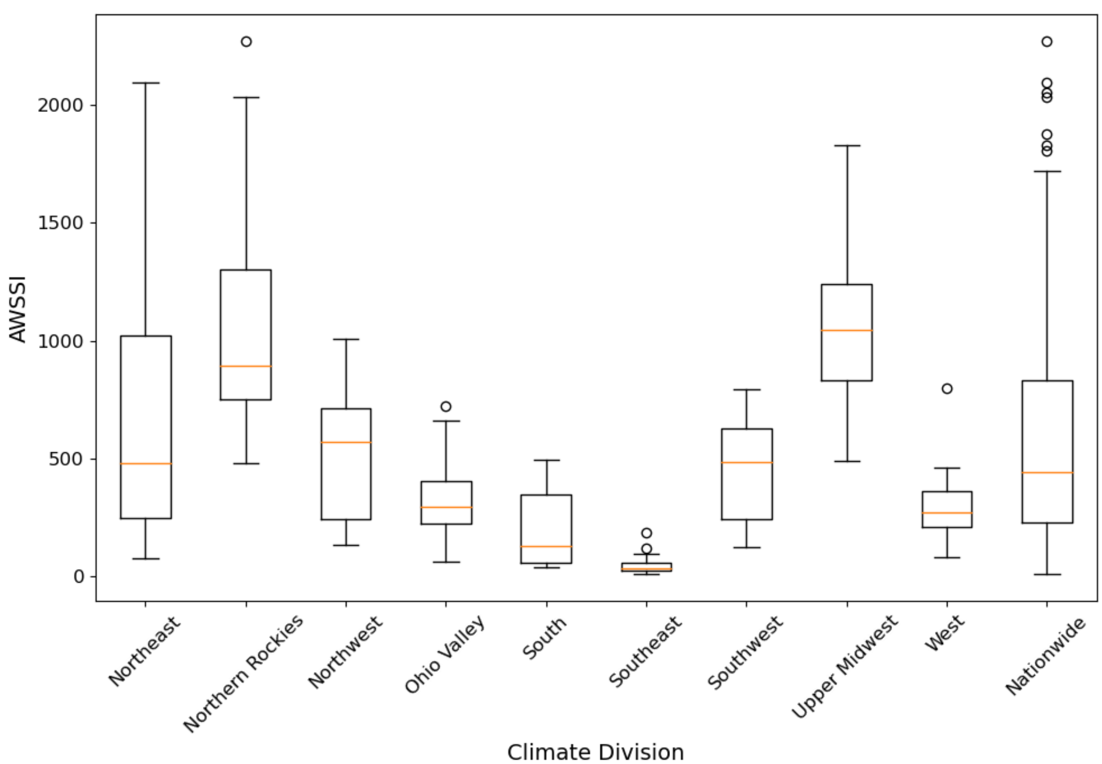


Figure 5-3: Distribution of AWSSI values by climate divisions

5.4.2 Regression Results

Table 5-1 summarizes the regression equations, R^2, and the coefficient of variation (CV) of AWSSI values for each climate division and nationwide. These results illustrate the relationship between normalized AWSSI and winter maintenance costs.

Table 5-1: Climate division regression analysis relating AWSSI to normalized winter maintenance cost

Climate division	Regression Line	R^2	AWSSI Coefficient of Variation
Northeast	y = 0.40x + 0.29	0.18	0.77
Northern Rockies	y = 0.12x + 0.08	0.10	0.40
Northwest	y = 0.01x + 0.22	0.00	0.54
Ohio Valley	y = 0.74x + 0.01	0.32	0.44
South	y = 0.45x + 0.00	**0.85***	0.75
Southeast	y = 2.86x - 0.02	**0.83**	0.87
Southwest	y = 1.03x - 0.05	**0.70**	0.48
Upper Midwest	y = 0.58x + 0.01	**0.70**	0.32
West	y = 0.41x + 0.02	**0.79**	0.53
Nationwide	y = 0.42x + 0.10	0.21	0.78

** Bold values show climate divisions with R^2 above 0.7, indicating a strong correlation between AWSSI and winter maintenance costs.*

In Table 5-1, “y” indicates the normalized total winter maintenance cost per lane mile, and “x” shows normalized AWSSI values. For climate divisions where R^2 values exceed 0.70 (South, Southeast, West, Upper Midwest, and Southwest), the regression lines show a significant correlation between winter maintenance costs and the AWSSI index. However, the slopes of these regression lines vary across climate divisions, indicating geographical differences in the sensitivity of maintenance costs to winter severity. Figure 5-4 shows the Regression Lines for these climate divisions.

- **South (R^2 = 0.85):** The regression suggests a steady cost increase with increasing winter severity, though the rate is lower compared to the Southwest.
- **Southeast (R^2 = 0.83):** The regression line indicates the highest sensitivity among all climate divisions, with costs increasing by 2.86 units for each unit increase in AWSSI,

highlighting the substantial impact of winter severity on maintenance costs in this climate division.

- **West (R^2 = 0.79)**: The regression line suggests that maintenance costs in this region are the least sensitive to rising winter severity. For each unit increase in normalized AWSSI, maintenance costs rise by only 0.41 units.
- **Upper Midwest (R^2 = 0.70):** The regression line indicates that for every unit increase in normalized AWSSI, the maintenance costs increase by 0.68 units, suggesting moderate sensitivity of maintenance costs to winter severity.
- **Southwest (R^2 = 0.70):** The regression shows a higher sensitivity, with maintenance costs increasing by 1.03 units for each unit increase in normalized AWSSI value.

The regression line for the Southeast region should be interpreted with caution due to the limited sample size, which may be influenced by outliers. While the observed trend aligns with expectations, further data collection is recommended to confirm the robustness of this relationship.

For climate divisions with low R^2 values (Ohio Valley, Northwest, Northern Rockies, and Northeast), the regression analysis does not show a strong correlation between winter maintenance costs and the AWSSI index. This could be due to the variability in weather patterns or state policies and budget allocations for winter maintenance, variations in the efficiency and effectiveness of winter maintenance operations, the presence of unique geographical features affecting snow and ice accumulation, and socioeconomic factors that impact the resources available for winter maintenance services. While AWSSI provides a valuable measure of weather severity, incorporating additional variables into the analysis and customizing a new weather severity index specifically for each climate division may improve the fit and provide a better understanding of the relationship.

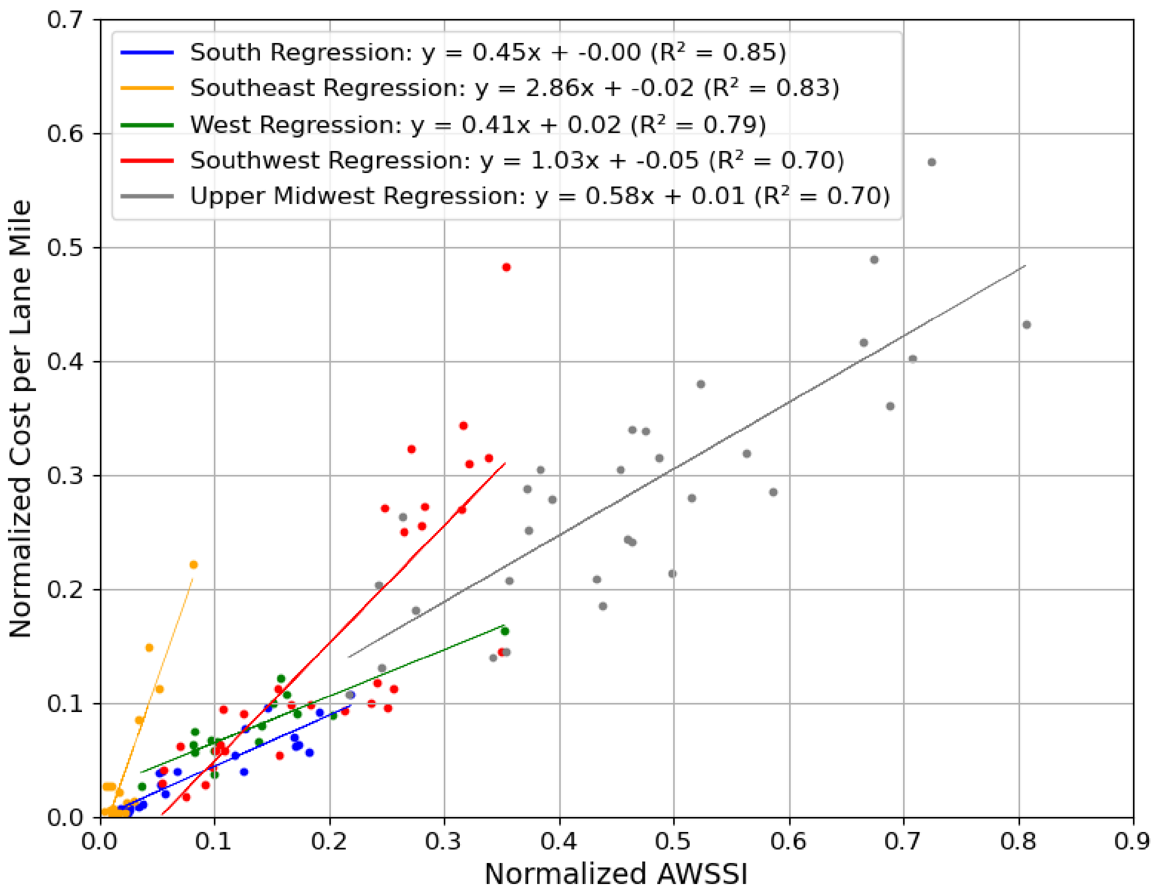


Figure 5-4: Linear regression lines on climate divisions with a high correlation between winter maintenance cost and AWSSI

A coefficient of variation test for AWSSI has also been performed to further analyze the differences between climate divisions. This test demonstrates the relative variability of winter severity across different climate divisions, providing insights into why certain climate divisions may have higher or lower R^2 values. The coefficient of variation is calculated as the ratio of the standard deviation to the mean, assessing the consistency of winter severity within each climate division. The Northeast, Southeast, and South exhibit the highest AWSSI CVs, according to Table 5-1, indicating the greatest variability in winter severity. These climate divisions experience significant fluctuations in winter conditions, with some winters being mild and others severe. Conversely, climate divisions like the Upper Midwest and Northern Rockies and Plains show the lowest CV, indicating more consistent winter severity. Winters in these climate divisions are generally severe. Climate divisions with more moderate CVs, such as Southwest, Ohio Valley, West, and Northwest, experience intermediate variability in winter conditions.

Despite strong correlation coefficients in some climate divisions in Table 5-1, the high coefficient of variation values suggests significant variability within each climate division. This implies that statewide averages may mask local fluctuations in winter severity, underscoring the need for more granular classifications that better capture the heterogeneous nature of winter weather impacts across different regions. Based on the CV results, the current climate divisions may not accurately capture the lower variations within each climate division. High CV values in the Northeast, Southeast, and South climate divisions suggest significant variability in winter severity, indicating that these climate divisions might be too broad. Conversely, low CV values in climate divisions such as the Upper Midwest and Northern Rockies and Plains suggest consistent winter severity but may overlook localized climatic differences. These findings suggest a need for more granular climate divisions that consider localized climatic conditions to improve the accuracy of climate characterization.

5.4.2.1 Analysis of Winter Maintenance Cost Estimation Practices

The nationwide survey identified that most agencies estimate their required winter maintenance costs based on historical averages. The accuracy of current estimation practices used by agencies is assessed by comparing the actual costs, sourced from the Clear Roads survey (*3*), with the estimated costs. Table 5-2 presents the actual and two sets of estimated costs for winter maintenance over the past couple of years for various states, along with the percentage error for each year. The error term here is defined as the absolute value of the difference between the actual and estimated values divided by the actual value and multiplied by 100.

To evaluate the effectiveness of using AWSSI for winter maintenance cost estimation, comparisons were made against the traditional historical average method. AWSSI cost estimations for each year are based on the regression line fitted to data points from previous years. The states included in this comparison were selected from those that reported using historical averages to determine their next year's budget, as identified in Chapter 4, through the nationwide State DOT survey. It should be noted that this analysis assumes AWSSI values are known in advance, which is a hypothetical scenario for the sake of comparison. In reality, AWSSI is calculated post-season and would require an accurate forecasting model for predictive use. While the accuracy of short-term weather forecasts is satisfactory, this is not the case for long-term forecasts (such as pre-season ones). Thus, the analysis in this section is merely to establish a relation based on post-season analyses to demonstrate the merits of WSI to be applied for budget and resource management using short-term forecasts throughout the winter maintenance operations.

Table 5-2: Cost Estimation Errors Using Historical Average Method and AWSSI

Year		State						
		IN	MO	OH	PA	VT	WA	WV
2023	AWSSI	290	224	238	281	847	572	184
	Actual Costs (M$)	35.72	31.75	75.31	192.20	31.56	60.03	8.95
	Historical Average Cost Estimation (M$)	34.86	54.51	111.84	282.20	38.70	49.79	30.46
	Error %	2%	72%	48%	47%	23%	17%	240%
	AWSSI Cost Estimation (M$)	31.32	36.03	87.53	235.60	31.79	54.18	19.49
	Error %	12%	14%	16%	23%	1%	10%	118%
2024	AWSSI	240	226	207	265	642	242	228
	Actual Costs (M$)	35.88	42.67	67.02	208.97	34.18	58.97	9.40
	Historical Average Cost Estimation (M$)	37.34	52.57	103.79	260.04	36.91	52.06	21.05
	Error %	4%	23%	55%	24%	8%	12%	124%
	AWSSI Cost Estimation (M$)	30.92	35.31	81.21	220.66	28.39	44.68	22.61
	Error %	14%	17%	21%	6%	17%	24%	140%

As depicted in Table 5-2, while AWSSI-based estimates were more accurate for some states (e.g., Missouri), they underperformed for others (e.g., West Virginia). This highlights the potential benefits and limitations of using a WSI for cost estimation over traditional cost estimations based on historical averages. This calls for more dynamic forecasting tools and models that account for changing weather patterns and other influencing factors by defining region-specific WSIs. A noticeable limitation of these analyses is the availability of Clear Roads survey data only for up to 10 years, resulting in a limited dataset for some states/regions. This limitation can affect the robustness of regression analyses and the general applicability of findings. Expanding the dataset and using region-specific WSIs would enhance the reliability of the results and key findings.

5.5 Summary and Discussion

The AWSSI correlation analyses using Clear Roads survey data provide a detailed view of the link between winter severity and maintenance costs. The AWSSI analyses reveal significant correlations in several climate divisions—particularly in the Upper Midwest, West, Southwest, South, and Southeast—indicating that higher winter severity often leads to increased maintenance expenditures.

Moreover, the results highlight substantial regional differences in the effectiveness and utility of WSIs. In climate divisions with relatively consistent winter conditions, such as the Upper Midwest and Northern Rockies, standardized WSIs perform well by accurately capturing typical weather patterns and informing material and budget management. In contrast, regions like the Northeast and Southeast, which experience higher variability in winter conditions, face challenges with incorporating a universal WSI.

Adopting more granular climate divisions that reflect localized conditions can enhance the accuracy of WSIs, leading to better resource allocation and more effective budget management. Continuous refinement of WSIs is essential to ensure their robustness and adaptability across diverse regional climates. By investing in advanced weather forecasting and data management tools, state agencies can further improve their winter maintenance planning through more precise, and data-centric strategies.

CHAPTER 6 - MICHIGAN MODIFIED WSI AND RATING SCHEME

This chapter describes the development of a modified WSI and its accompanying rating scheme. The goal is to create a more accurate and actionable proxy for material costs in winter maintenance operations by integrating region-specific weather data, standardized material cost calculations, and advanced statistical modeling. Developing such a modified WSI requires conducting certain interconnected tasks, which are described as follows: The chapter begins in Section 6.1 with the rationale and selection of Michigan's regional framework, followed by Section 6.2, which outlines the method used to standardize and calculate material costs. Section 6.3 describes the process of identifying relevant weather variables through rigorous feature selection techniques. Section 6.4 presents the development of robust linear regression models tailored to each region. Section 6.5 introduces the final MC-WSI and its associated rating scheme, and Section 6.6 evaluates the performance of the new index against traditional MDOT methods. This modeling framework serves as the foundation for improving operational planning and budget forecasting for winter maintenance in Michigan.

6.1 Region Selection

The initial step in developing the modified WSI involves selecting an optimal regional framework capable of accurately reflecting Michigan's diverse geographic and climatic conditions. Two primary frameworks were assessed: the existing MDOT regions and the NOAA climate divisions. Initially, the existing MDOT regions, comprising seven operational areas coordinated through Transportation Service Centers, were considered (Figure 6-1). These regions have traditionally guided resource allocation and operational planning. However, responses from the statewide survey of MDOT and county garages (Chapter 3) indicated significant variability in weather challenges faced even within these administratively defined boundaries. Garages explicitly highlighted localized weather phenomena, such as lake-effect snowfall, as critical drivers for their operational practices and decision-making. The survey revealed a clear need for a weather-centric grouping that can address these specific and varied weather impacts on winter maintenance operations.

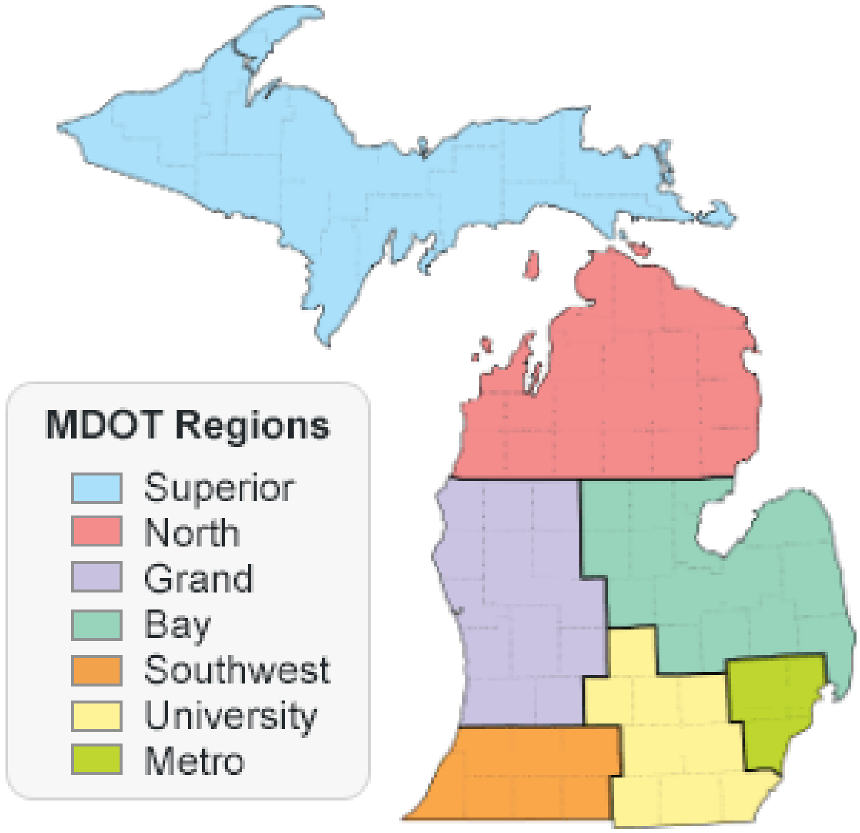


Figure 6-1: MDOT administrative regions

Furthermore, insights obtained from the nationwide survey of state DOTs (Chapter 4) reinforced the advantages of adopting weather-based regions. Other states also employ climate divisions to better align resource allocation with actual weather conditions, enhancing both operational efficiency and budget predictability. Consequently, to better reflect the weather-driven aspects of winter maintenance operations, a weather-centric regional framework developed by NOAA was also adopted. NOAA's approach divides the United States into climate divisions based on long-term weather data, ensuring that regions are as climatologically homogeneous as possible (*33*). For Michigan, this framework segments the state into 10 distinct climate regions. These divisions take into account the moderating influence of the Great Lakes, the pronounced differences between the Upper and Lower Peninsulas, and localized phenomena such as the lake effect snow (Figure 6-2).

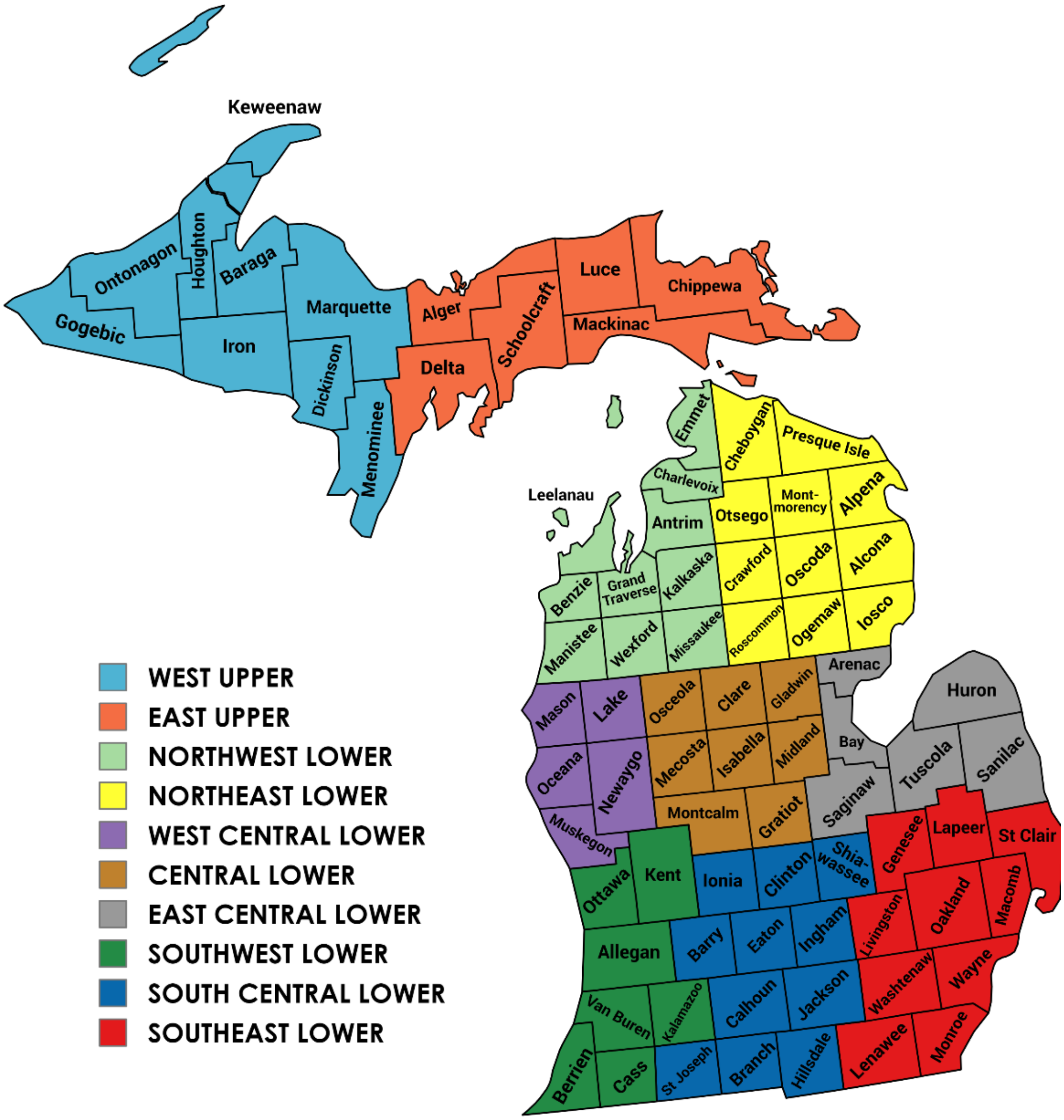


Figure 6-2: NOAA climate divisions

Adopting NOAA's regional criteria, counties and MDOT garages can be grouped according to shared climatic patterns. This approach directly addresses the garage survey feedback, reflecting on-the-ground experience of local service providers. Garages specifically mentioned lake-effect snowfall, freezing rain, and blowing snow as essential weather variables prompting specific maintenance responses, aligning perfectly with NOAA's climate-driven regional delineation. Grouping of counties and garages by shared weather challenges, enhances a regional approach to yield more accurate analyses of weather severity, material usage, and winter maintenance cost estimates. Such an alignment will improve the fidelity of subsequent modeling efforts, facilitating precise correlations between weather severity, winter maintenance practices, and their associated expenditures. A list of counties and garages within each region is provided in Appendix D.

6.2 Winter Maintenance Cost Calculation

A critical application of the modified WSI is to estimate winter maintenance costs. Ideally, this calculation would include detailed maintenance expenditures such as labor, equipment usage, materials, and additional operational activities. Different winter events necessitate diverse treatment strategies; for instance, similar snowfall amounts can lead to substantially different maintenance responses based on pavement type, roadway classification, and prevailing road conditions. In some cases, garages may respond to a minor snowfall by applying salt and sand, while in others, simply plowing without material application is sufficient. However, relying exclusively on material costs does not reflect the complete spectrum of winter maintenance activities, especially plowing operations. This limitation can lead to notable discrepancies where similar weather conditions produce significantly different recorded material costs.

Furthermore, based on the insights from the statewide garage survey, several critical operational variables—such as sunlight exposure, time of day, previous material applications, and local policies—substantially influence winter maintenance decisions. These factors, while impactful, are challenging to be systematically included in the modeling efforts due lack of data availability, consistency, length, and quality. Additionally, integrating such a detailed array of variables into predictive models would significantly increase complexity, thereby potentially limiting the model's practicality and interpretability.

Given these constraints, the project team focused on the most reliably available data: the material usage data. MDOT provided historical records of monthly material usage (salt, sand, and liquid deicers) across each county and garage over a 14-year period (2011–2025). Although the research team initially sought actual expenditure data from MDOT, such detailed records were not readily available. Consequently, a comprehensive review of publicly accessible resources, such as bid tabulations from select counties and limited timeframes, was undertaken. By examining these bid documents, a representative range of prices for each winter maintenance material was established. Based on averages derived from these sources, the following unit prices were applied consistently across all analyses:

- Salt: $60 per ton
- Sand: $10 per ton
- Liquid deicer: $0.5 per gallon

Next, for each garage, the monthly material usage was multiplied by the respective unit prices to compute the cost (equation 6-1). These individual costs were then aggregated across each region and normalized by the total lane miles maintained. This produces a consistent "material cost per lane mile" metric that serves as the basis for the regional cost-based index (equation 6-2).

$$\text{Material Cost (Garage)} = (\text{Salt Usage} \times 60) + (\text{Sand Usage} \times 10) + (\text{Liquid Usage} \times 0.5) \tag{6-1}$$

$$\text{Material Usage (Region)} = \frac{\sum \text{Material Usage (Garages within Region)}}{\text{Total Lane Miles of Region}} \tag{6-2}$$

6.3 Feature Selection

6.3.1 Available Weather Features

Accurate and consistent weather data are critical for establishing robust relationships between environmental conditions and winter maintenance material usage. Initially, several potential sources of weather data were assessed for their reliability, completeness, and applicability to Michigan's winter maintenance context.

NOAA's Local Climatological Data (LCD) provides extensive historical climate summaries across Michigan, with data from approximately 1950 onward. This dataset includes hourly, daily, and monthly observations for numerous climatic parameters such as temperature, humidity, wind characteristics, sky conditions, and precipitation type. While promising for detailed trend analysis, the LCD data exhibited significant completeness issues; several datasets for critical locations contained substantial gaps, rendering them unsuitable for consistent analysis (discussed further in Chapter 3).

Another considered resource was DTN weather data, which is widely used in operational contexts. However, due to the lack of adequate aggregation and centralized access, DTN data could not be practically utilized for statewide modeling.

Ultimately, MDSS WMRI was identified as the most viable and MDOT-approved source of weather information. This system has consistently provided detailed weather observations since December 2014, recording an extensive array of weather variables directly relevant to winter road maintenance operations.

Based on their operational significance and demonstrated influence on material usage decisions, 13 weather variables were selected (Table 6-1). These variables were carefully aligned with MDOT's material usage reporting intervals to ensure coherence and consistency between observed weather conditions and recorded material expenditures. This carefully curated dataset underpins the subsequent analysis aimed at quantifying how variations in weather conditions affect winter maintenance material consumption.

Table 6-1: Available weather features via MDSS WMRI

Category	Selected Variables
Meteorological Indicators	Air Temperature
	Long Wave Radiation
	Short Wave Radiation
	Pavement Temperature
Precipitation Metrics	Hours of Freezing Rain
	Hours of Snowfall
	Snow Accumulation
	Hours of Blowing Snow
	Ice Accumulation
Additional Factors	Hours of Strong Wind
	Snow Events
	Frost Events
	Freezing Rain Events

6.3.2 Weather Features Selection

To develop a robust predictive model, it was necessary to determine which weather features most strongly correlate with material costs. Multiple statistical techniques were employed:

- **Pearson Correlation Analysis** identified variables that share a strong linear relationship with material costs.
- **Variance Inflation Factor (VIF) Testing** was used to minimize multicollinearity, ensuring that no redundant features cloud the analysis.
- **Correlation Analysis Between Features** was used to eliminate variables that were highly correlated with each other.
- **Lasso Regression** was applied as a regularization method to further refine the list of predictors by penalizing less significant variables.

This rigorous feature selection process ensured that only the most relevant and independent weather variables were used in the modeling stage, enhancing the predictive accuracy of the subsequent models. Table 6-2 shows the final features selected using the feature selection method.

Table 6-2: Selected Features by Regions

Region	Final Selected Features		
West Upper	Pavement Temperature	Hours of Snowfall	
East Upper	Pavement Temperature	Hours of Snowfall	
Northwest Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
Northeast Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
West Central Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
Central Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
East Central Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
Southwest Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
South Central Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall
Southeast Lower	Pavement Temperature	Hours of Freezing Rain	Hours of Snowfall

6.4 Material Cost Estimate Model Development

6.4.1 Modeling Approach

With the selected weather features finalized, the next step was to develop a predictive model relating weather conditions to monthly material costs. In this modeling context, the dependent variable (or outcome) is the monthly material cost per lane mile, reflecting maintenance resource use. The independent variables (or predictors) are the selected weather variables listed in Section 6.3.1, which represent environmental conditions influencing maintenance practices.

The modeling process began by aggregating monthly weather and corresponding material cost data at the regional level, producing a dataset where each record reflects one month of observations within a region. A statistical modeling approach was then employed to quantitatively uncover and describe the underlying relationships and trends within the data. Through this process, the model captures patterns by assigning weights (coefficients) to each weather variable, indicating their relative influence on monthly material costs.

Several modeling techniques were evaluated based on their statistical robustness, interpretability, and practical applicability. Ultimately, a **Robust Linear Regression** approach was selected due to its specific advantages:

- **Effectively handling outliers**: Reducing the distortion of model results by extreme observations.
- **Relaxed assumptions about residuals**: Not requiring the residuals (differences between observed and predicted values) to follow a normal distribution.
- **Accommodating variable variance (heteroscedasticity)**: Ensuring the model remains valid even if the variability of material costs changes with the magnitude of the weather conditions.

To assess model reliability and avoid overfitting (i.e., capturing noise rather than meaningful trends), a 5-fold cross-validation technique was employed. In this approach, the dataset was partitioned into five subsets; each subset served sequentially as a test set, while the remaining subsets were used for training. This validation approach confirms that the model accurately represents the underlying patterns and can be generalized effectively across different periods and conditions. More details on this approach and numerical results on validation are provided in Chapter 7.

6.4.2 Building the Region-Based Models

Following the defined modeling approach described above, individual robust linear regression models were developed separately for each of the 10 NOAA-based regions. This approach recognizes and addresses Michigan's unique regional climatic variability, allowing the resulting models to more accurately capture local weather impacts on material costs. Table 6-3 summarizes the final regression coefficients, along with key model performance metrics.

Table 6-3: Regression coefficients and performance metrics for predicting material costs

Regions	Model Coefficients*				5-fold CV Average R^2**	Average Material Cost ($/lane mile/month)	5-fold CV RMSE** ($/lane mile/month)
	Intercept	Pavement Temperature (F°) (β_1) (per month)	Hours of Snowfall (hr) (β_2) (per month)	Hours of Freezing Rain (hr) (β_3) (per month)			
West Upper	245.56	-4.75	1.92	0.00	0.69	276.48	61.79
East Upper	99.71	-1.81	2.14	0.00	0.76	223.88	52.11
Northwest Lower	121.26	-2.55	1.29	8.31	0.82	167.45	34.45
Northeast Lower	79.97	-2.10	2.50	3.11	0.78	177.66	46.28
West Central Lower	256.40	-4.75	2.26	3.80	0.84	240.79	66.61
Central Lower	37.92	-1.06	2.64	4.94	0.81	128.47	38.75
East Central Lower	64.79	-1.65	1.87	2.55	0.80	91.71	27.21
Southwest Lower	113.98	-2.33	2.10	4.85	0.88	158.23	39.78
South Central Lower	79.38	-1.74	2.59	5.60	0.87	139.85	36.45
Southeast Lower	248.52	-5.31	3.53	6.23	0.75	171.68	60.57
Statewide	**178.98**	**-3.60**	**1.82**	**5.68**	**0.68**	**177.62**	**69.85**

** Statistical analyses of the models confirm that all models and regression coefficients were statistically significant ($p < 0.05$). This indicates that each predictor meaningfully contributes to the estimation of material costs and reinforces the robustness of the modeling approach.*

*** All models were validated using cross-validation techniques, where data from several years were systematically excluded to evaluate model performance across five different sets of years.*

Final Model Structure and Variables:

The robust linear regression method provides a stable and statistically rigorous basis for understanding the link between weather conditions and material usage. Equation 6-3 illustrates the calculation details of the estimated material cost per lane mile using robust regression modeling. The equation is expressed as:

$$\text{Materials Estimated Cost (\$/lane mile/month)}_j = \text{Intercept} + \beta_1 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Pavement Temperature}_{ij}\right) + \beta_2 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of Snowfall}_{ij}\right) + \beta_3 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of Freezing Rain}_{ij}\right) \quad (6\text{-}3)$$

Where:

- β_1 ,β_2 ,and β_3 are the coefficients for the respective variables.
- N is the number of counties in the region.
- i refers to each individual county within the region.
- j represents the month for which the cost is being estimated.

An example of how to implement this equation is provided in Appendix E.

Interpreting the Final Models:

1. **Intercept**: The intercept in each model represents the baseline material cost per lane mile when all weather-related predictors are zero. In practice, a nonzero intercept is expected because it accounts for essential maintenance costs—such as labor, equipment, and baseline operations—that occur even in the absence of extreme weather conditions. Additionally, a nonzero intercept reflects that even a "zero" value for weather predictors (for instance, a pavement temperature of 0°F) can already indicate conditions that require winter maintenance, thereby driving up costs. This term captures both the fixed costs of regular maintenance and the costs induced by baseline adverse weather conditions.
2. **Pavement Temperature (β_1)**: Across all regions, pavement temperature has a negative coefficient. This negative relationship indicates that as pavement temperature increases (i.e., conditions become less severe), the material cost decreases. Warmer pavements typically reduce the need for intensive deicing or salting, thereby lowering overall costs. Notably, the Southeast Lower region exhibits the highest sensitivity to pavement temperature, with a coefficient of -5.31, meaning that a decrease of one-degree Fahrenheit in pavement

temperature is associated with an increment of $5.31 per lane mile in material costs. In contrast, the Central Lower region shows the lowest sensitivity, with a coefficient of -1.06, indicating a modest increment in material usage.

3. **Hours of Snowfall (β_2)**: The positive coefficients for hours of snowfall indicate that increased snowfall duration tends to raise material costs. Snowfall requires more frequent maintenance—be it through salt application, sanding, or plowing—which directly contributes to higher costs. The magnitude of β_2 varies by region, reflecting how different areas respond to snowfall intensity. According to Table 6-3, the Southeast Lower region has the highest sensitivity with a coefficient of 3.53, meaning that every additional hour of snowfall in this region results in an estimated $3.53 increase in material costs per lane mile. In other regions, while the trend remains positive, the impact per hour of snowfall is less pronounced, reflecting regional differences in maintenance practices and local weather conditions.
4. **Hours of Freezing Rain (β_3)**: Notably, some regions (such as Northwest Lower and Southeast Lower) exhibit a high positive coefficient for freezing rain hours. This suggests that even relatively short durations of freezing rain in these regions lead to a substantial increase in material costs. Freezing rain creates hazardous conditions that demand intensive intervention (e.g., deicing), making it a critical factor in cost estimation. In contrast, in regions where β_3 is near zero (e.g., West Upper and East Upper), freezing rain may be less frequent or less impactful due to local operational practices or climatic conditions.
5. **Regional Variations**: The differences in coefficients across regions highlight that the impact of each weather variable on material costs is not uniform statewide. For instance, a higher β_3 in one region indicates that freezing rain is a significant driver of maintenance costs there, while another region may experience a greater influence from snowfall or temperature variations. These regional differences allow for tailored models that better capture local weather–maintenance cost dynamics. In these densely populated urban areas, high traffic volumes and extensive roadway networks amplify operational challenges during heavy snowfall, so even small deviations in weather conditions (such as slightly colder temperatures or a few extra hours of snowfall) result in substantial increases in material consumption and maintenance costs. This heightened sensitivity is largely attributed to factors unique to urban settings, including complex infrastructure, stricter maintenance standards, and the cumulative impact of cold precipitation on road surfaces in areas with high vehicular activity.

Overall, these observations highlight the importance of incorporating region-specific weather sensitivities into the modeling process. Models that account for localized conditions are better equipped to reflect the true variability in maintenance needs across Michigan's diverse regions. In contrast, the model developed without considering regional nuances underperformed in comparison to the regional models. This is evident from the substantially higher RMSE value of the statewide model ($69.85 per lane mile deviation from the average), which demonstrates its limited ability to capture localized weather patterns and maintenance cost dynamics. These findings reinforce the value of disaggregated modeling for generating more accurate, regionally responsive cost estimates.

By accurately capturing the pronounced impacts of cold weather and precipitation in urban regions, the modified WSI can provide more reliable guidance for planning and resource allocation in high-density areas like the Southeast Lower region.

6.4.3 Comparison with MDOT Administrative Regions

To further evaluate the effectiveness of the NOAA-based regional modeling framework, a parallel set of models was developed using MDOT's seven administrative regions. These models followed the same methodology and used consistent weather features to ensure a fair comparison.

Table 6-4 presents the model coefficients and performance metrics for each MDOT region. While several regions show strong individual performance—such as Grand, Bay, and University—the overall predictive accuracy, as measured by RMSE, was generally lower than that of the NOAA-based regional models.

In particular, RMSE values in critical regions such as Metro and Southwest were substantially higher in the MDOT-based models compared to their NOAA counterparts. For example, the Metro region model produced an RMSE of 88.71, compared to 60.57 in the Southeast Lower NOAA region. The Superior region had an RMSE of 56.34, slightly lower than the West Upper NOAA region (61.79), but it is still higher than the East Upper NOAA region (52.11).

Moreover, the NOAA-based regions align more closely with natural weather patterns and microclimatic variations, offering a more accurate and geographically relevant segmentation. This alignment allows the models to better capture weather-cost relationships and enhances the model's interpretability and application in operational planning.

Table 6-4: Regression Results for MDOT Administrative Regions

Regions	Model Coefficients				5-fold CV Average R^2	Average Material Cost ($/lane mile/month)	5-fold CV RMSE ($/lane mile/month)
	Intercept	Pavement Temperature (F°) (β_1) (per month)	Hours of Snowfall (hr) (β_2) (per month)	Hours of Freezing Rain (hr) (β_3) (per month)			
Superior	177.8	-3.39	0.00	2.04	0.77	251.98	56.34
North	64.14	-1.65	5.62	1.98	0.88	172.92	36.73
Grand	138.99	-2.77	7.68	2.06	0.91	182.46	41.96
Bay	98.46	-2.2937	3.046	2.23	0.87	109.41	30.81
Southwest	46.56	-1.11	3.53	2.47	0.88	135.53	43.13
University	140.64	-2.40	5.12	3.24	0.90	144.37	41.20
Metro	306.78	-6.43	7.51	3.19	0.79	197.53	88.71

Overall, the comparison confirms that NOAA-based regional models offer more accurate and consistent performance in predicting material costs. These results support the use of NOAA climatic boundaries over administrative divisions when developing data-driven winter maintenance planning tools.

6.5 Modified WSI and Rating Scheme

The Modified WSI, termed as Material Cost-based Winter Severity Index (MC-WSI)**,** transforms raw material cost estimates into a standardized, easy-to-interpret index. This index accurately reflects both the severity of winter weather conditions and their associated financial impacts on maintenance operations. The MC-WSI provides decision-makers with a reliable and practical proxy for actual winter maintenance costs, enhancing the accuracy of budgeting, resource planning, and operational preparedness. The process follows a series of steps:

1. **Conversion of Material Costs**

   Monthly material costs are estimated for each region using robust regression models that incorporate key weather variables. These models capture the influence of factors such as pavement temperature, snowfall, and freezing rain on maintenance expenses.

2. **Normalization and Scaling**

   To ensure meaningful comparisons across regions and time periods, the estimated monthly cost for each region is normalized. This is achieved by dividing a region's monthly cost by the maximum monthly cost observed across all regions and years, then multiplying by 100. The result is a cost-based index that ranges from 0 to 100, where higher values indicate greater cost intensity and, by extension, more severe winter conditions.

   One should note that the maximum monthly cost value used for normalization is not fixed; it must be recalibrated each month. If any region's monthly cost exceeds the historical maximum, the maximum value should be updated accordingly and all WSI values need to be updated for prior years. This dynamic adjustment ensures that the MC-WSI remains accurately calibrated against current cost trends, maintains consistency across seasons, and supports precise budgeting and resource allocation for winter maintenance planning.

3. **Final Rating Scheme**

   The standardized index is then used to classify winter severity into distinct categories. To enable clear interpretation and practical use of model outputs, estimated monthly material costs were normalized and converted into a standardized index ranging from 0 (indicating low severity) to 100 (indicating extreme severity). The MC-WSI, represents the relative severity of winter conditions based on the material costs incurred.

   Normalization is based on the highest estimated material cost recorded across all regions and months in the dataset. Each MC-WSI value reflects the severity of winter conditions in a specific region and month relative to this historical maximum.

   This relative framework allows for consistent comparisons across both geographic regions and time periods, giving MDOT a unified approach to assess and plan for winter maintenance needs. It is important to note, however, that MC-WSI values do not reflect absolute operational thresholds and should be interpreted in the context of each region's historical performance.

6.6 Index Assessment

This section compares three indices against a baseline actual cost index, which is computed by dividing the observed monthly cost for each region by the maximum observed cost across all regions and years. This baseline (actual cost index) provides a standardized metric (ranging from 0 to 100) against which the performance of other indices is evaluated. The three indices under comparison are:

1. **MC_WSI (Derived via Feature Selection):**
   This index is calculated using the robust regression model that incorporates carefully selected weather features. It converts the estimated material cost (derived from equation 6-3) into a standardized index and serves as the primary benchmark. The process for calculating this index is explained in detail in Section 6-5.
2. **MDOT WSI Modified Index (Region-Based Approach):**
   In order to enable direct comparison with the proposed method, the MDOT current WSI (Equation 3-1) was modified to a region-based approach. Key changes include:
   Normalization: The denominators now represent the highest historical monthly values recorded for each weather feature across all regions, ensuring that the resulting scale approaches 100 points.
   Regional Averaging: The nominator represents the monthly average value of each feature within a specific region.
   This modification allows the MDOT WSI to be directly compared with the actual cost index by aligning their scales and regional characteristics.
3. **Estimated Cost Index Using Current MDOT WSI's Weather Features:**
   This index is derived by calibrating a robust regression model using the same weather features that form the basis of the current MDOT WSI (see Equation 3-1). Table 6-5 presents the regression coefficients along with key performance metrics, using the weather features described below:

   - $\boldsymbol{\beta_0}$: The intercept terms
   - $\boldsymbol{\beta_1}$: The snow accumulation per month (in)
   - $\boldsymbol{\beta_2}$: Hours of blowing snow per month (hr)
   - $\boldsymbol{\beta_3}$: The number of freezing rain events per month
   - $\boldsymbol{\beta_4}$: The number of snow events per month
   - $\boldsymbol{\beta_5}$: Hours of cold precipitation per month (hr)

Table 6-5: Regression coefficients and performance metrics for predicting material costs using MDOT current WSI weather features

Regions	Model Coefficients* β_0	β_1	β_2	β_3	β_4	β_5	5-fold CV Average R^2	Average Material Cost ($/lane mile/month)	5-fold CV RMSE ($/lane mile/month)
West Upper	19.74	**2.05**	**-1.00**	**-50.16**	**5.38**	2.30	0.54	276.48	84.34
East Upper	14.73	**-0.48**	**-3.56**	**42.99**	**10.02**	2.26	0.78	223.88	51.89
Northwest Lower	-21.69	**2.38**	**0.59**	**41.60**	**5.55**	1.16	0.84	167.45	40.45
Northeast Lower	-25.20	-8.53	**-2.90**	**-16.05**	**3.82**	5.29	0.74	177.66	54.36
West Central Lower	-17.59	**-2.63**	**0.42**	**35.59**	18.41	2.94	0.84	240.79	68.04
Central Lower	-10.83	-7.90	**-0.18**	**9.38**	**-6.90**	5.17	0.70	128.47	49.29
East Central Lower	-24.43	**1.83**	**-1.01**	**14.53**	**4.57**	1.69	0.77	91.71	34.14
Southwest Lower	-15.67	**-2.54**	**5.51**	**37.35**	**7.44**	2.57	0.84	158.23	54.34
South Central Lower	-8.98	**-0.11**	**-2.02**	**20.92**	**-2.01**	3.33	0.86	139.85	43.55
Southeast Lower	-18.98	**-3.73**	**-1.67**	**19.05**	**-7.97**	6.81	0.78	171.68	75.02
Statewide	-15.99	**-0.35**	**-0.86**	42.5	8.67	2.32	0.70	177.62	74.55

** For the bolded coefficient values, statistical analyses show that not all models and regression coefficients were statistically significant ($p \geq 0.05$). This suggests that some predictors do not meaningfully contribute to estimating material costs, indicating weaknesses in the model and a lack of robustness in its predictive capability.*

Equation 6-4 illustrates the calculation details of the estimated material cost per lane mile using MDOT's current WSI weather features. The equation is expressed as:

$$\begin{aligned} &\text{Materials Estimated Cost (\$/lane mile/month)}_j = \text{Intercept} + \\ &\beta_1 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{The snow accumulation }_{ij}\right) + \beta_2 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of blowing snow }_{ij}\right) + \\ &\beta_3 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{The number of freezing rain events }_{ij}\right) + \\ &\beta_4 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{The number of snow events }_{ij}\right) + \beta_5 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of cold precipitation }_{ij}\right) \end{aligned} \quad (6\text{-}4)$$

Where:

- β_1 ,β_2 ,β_3,β_4 ,and β_5 are the coefficients for the respective variables.
- N is the number of counties in the region.
- i refers to each individual county within the region.
- j represents the month for which the cost is being estimated.

The estimated cost index using MDOT's current WSI features is computed by dividing the estimated monthly cost for each region by the maximum estimated cost across all regions and years. Figure 6-3 illustrates a visual comparison of the MDOT WSI modified index and the Estimated Cost Index, both in relation to the Cost-Based Index.

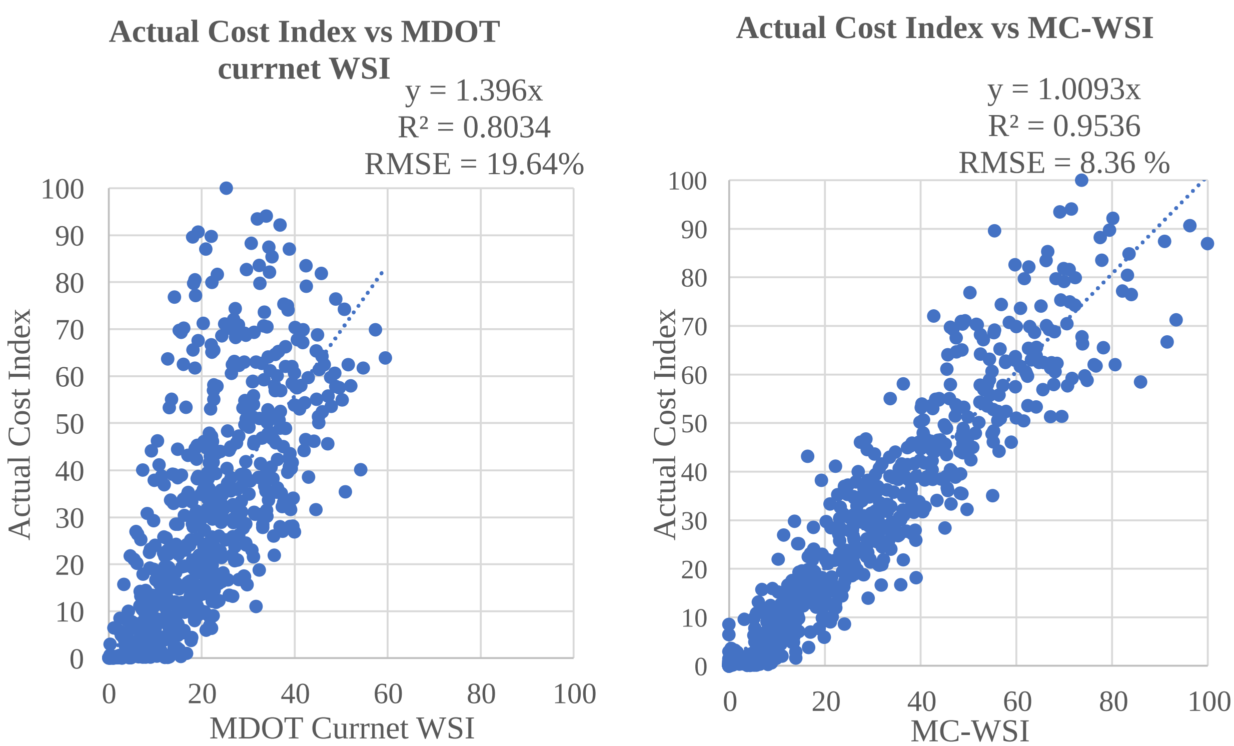


Figure 6-3: Comparison of the current MDOT WSI and MC-WSI related to the actual cost index

The performance evaluation clearly demonstrates that MC-WSI significantly outperforms the traditional MDOT WSI in both correlation and accuracy, establishing it as the most reliable proxy for actual material costs. In quantitative terms, the cost-based index exhibits an outstanding coefficient of determination ($R^2 = 0.9536$) and a low root mean square error (RMSE = 8.36%), underscoring its robust predictive capability. This superior performance indicates that the estimated cost-based approach captures the nuances of regional material usage more effectively than the current MDOT WSI, thereby providing a more precise and actionable tool for operational planning and budgeting in winter maintenance. Figure 6-4 provides a visual comparison of the Estimated Cost Index using MDOT current WSI's weather features and the Estimated Cost Index in relation to the Cost-Based Index.

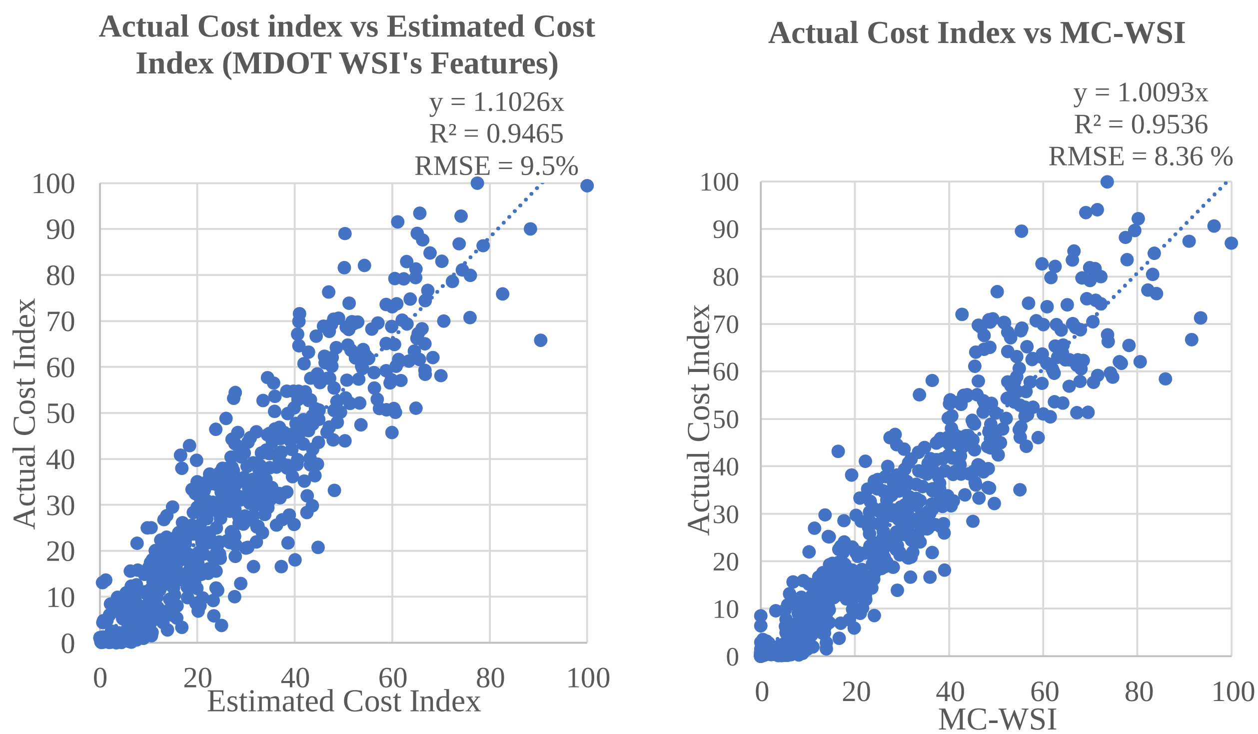


Figure 6-4: Comparison of the Estimated Cost Index (using MDOT's current WSI weather features) and MC-WSI related to the actual cost index

While the model calibrated using MDOT’s fixed set of weather features (Equation 6-4) represents a meaningful improvement over the existing MDOT WSI, it still falls short when compared to the performance of the MC-WSI developed through the feature selection approach (Equation 6-3). The difference in predictive accuracy is evident in the RMSE values: as shown in Table 6-5, the models built with the fixed feature set consistently produced higher RMSEs than those using feature-selected inputs (see Table 6-3). This indicates that the feature-selected models are better at estimating actual material costs and provide more reliable guidance for winter maintenance planning.

Moreover, the statistical strength of the models further supports this conclusion. Several coefficients in the fixed-feature models, using MDOT's current WSI weather features, were not statistically significant, suggesting that some predictors included in the model did not meaningfully influence material costs. In contrast, every coefficient in the feature-selected models was statistically significant, underscoring the robustness and practical value of the feature selection approach. By identifying and utilizing only the most relevant variables, the feature-selected models not only enhance accuracy, but also ensure that each input meaningfully contributes to the cost estimation process.

In essence, although both models improve upon the baseline, the Estimated Cost Index derived from the customized feature selection methodology achieves the highest predictive accuracy and correlation with actual costs, confirming its robustness as a tool for operational decision-making in winter maintenance planning.

6.7 Summary of Findings

This chapter outlined the development of a refined Weather Severity Index (WSI) that serves as a reliable proxy for estimating material costs for winter maintenance operations in Michigan. The work begins with a careful selection of regional frameworks—shifting from administrative MDOT regions to NOAA-based climate divisions—to better capture local weather nuances, as revealed by statewide surveys.

A standardized material cost measure was derived by applying robust regression models to MDOT material usage data. These models use key monthly weather features—such as pavement temperature, hours of snowfall, and hours of freezing rain—to predict monthly costs per lane mile. The predicted material costs are then normalized and scaled to create an estimated material cost-based index (MC-WSI) ranging from 0 to 100, which is further transformed into a final rating scheme. This index categorizes winter severity into distinct classes—from low to extreme—allowing decision-makers to quickly assess operational challenges and budget impacts. Comparative evaluations show that this newly developed index significantly outperforms the traditional MDOT WSI in terms of predictive accuracy and correlation with actual costs, providing a robust, actionable tool for winter maintenance planning and resource allocation.

CHAPTER 7 - PILOT PHASE FOR MC-WSI VALIDATION AND VERIFICATION

7.1 Validation and Verification

Due to the inherent limitations of a short-duration pilot study, it became evident early in the project that relying solely on a single winter season would not yield a robust basis for verifying the MC-WSI performance. For example, an unusually warm winter could distort the relationship between winter severity and maintenance costs, leading to potentially erroneous interpretations if that year alone were used. Moreover, even an analysis based on two consecutive years might produce misleading results, particularly if recent operational changes—such as new cost-cutting policies implemented by some garages—mask the true impact of severe weather conditions. Consequently, it is essential to investigate data from at least two nonconsecutive years to adequately capture the natural variability in winter conditions and operational performance. However, given the project's timeline constraint, conducting such an extended pilot study was not feasible. To address these challenges, a K-fold cross-validation (CV) approach was adopted, which effectively simulates the benefits of multi-year analysis by partitioning the available dataset, thereby ensuring a more reliable and comprehensive evaluation of the MC-WSI.

7.1.1 K-Fold Cross-Validation and Evaluation

A 5-fold cross-validation strategy is implemented:

- **Data Division:** The entire dataset is divided into five distinct folds.
- **Training and Testing:** In each iteration, the model is trained on four-folds, representing eight years of data (80% of the data), and tested on the remaining fold, two years of data (20% of the data). This process is repeated so that each fold serves as the test set once.
- **Performance Metrics:** Evaluation metrics such as the coefficient of determination (R^2) and root mean square error (RMSE) are calculated for each iteration. The overall performance is then averaged across all folds, ensuring that the model's predictive accuracy is assessed comprehensively.

Advantages of K-Fold Cross-Validation and Future Recommendations:

K-fold CV offers several significant advantages:

- **Maximized Data Utilization:** Every data point is used for both training and testing, which enhances the reliability of performance estimates.
- **Robust Validation:** The approach minimizes overfitting and provides a robust assessment of model performance across diverse subsets of data.
- **Continuous Improvement:** As new data becomes available, the model can be re-evaluated periodically. This ensures that the model remains current and reflective of evolving weather patterns and maintenance practices.

Given these benefits, it is recommended that this cross-validation framework be repeated at regular intervals—every couple of years—to continuously refine the model and maintain its relevance and accuracy. In summary, the limitations of a pilot study based on a single winter season have been effectively mitigated by employing K-fold cross-validation. This approach not only provides a robust means of verification and validation, but also lays the foundation for ongoing model improvement and adaptation to changing conditions.

7.2 Pilot Study Results

The pilot study results in Table 7-1 summarize the key performance metrics across the five folds. Table 7-2 displays the years that were randomly selected to serve as the test set for each fold. The pilot phase results, derived from the 5-fold cross-validation, confirm the robustness of the MC-WSI model:

- **Consistency Across Folds:** The R^2 and RMSE values were relatively consistent across all five folds. This indicates that the model is stable and does not rely on a particular subset of data to achieve strong performance.
- **High Predictive Power:** The averaged R^2 values demonstrate that the model can explain a substantial portion of the variance in the monthly material costs. An R^2 close to 1.0 signifies excellent predictive capability.
- **Low Error Margin:** The averaged RMSE values remained relatively low, signifying that the predicted costs closely track the actual values. This is particularly impressive given the natural variability of winter weather and the differences in regional maintenance practices.
- **Minimized Overfitting:** By rotating the training and testing subsets, 5-fold CV reduces the likelihood that the model is merely fitting idiosyncrasies in one particular

portion of the data. Instead, the model must perform consistently well across multiple data splits.

Table 7-1: 5-Fold Cross-Validation results for material cost estimate model from Equation 6-3

Region	Fold 1		Fold 2		Fold 3		Fold 4		Fold 5		**Average**		Average Material Cost ($/lane mile/month)	Error Proportion to Average Cost
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	**R^2**	**RMSE**		
West Upper	0.73	56.58	0.61	68.33	0.63	72.37	0.78	42.56	0.72	69.15	**0.69**	**61.79**	276.48	22%
East Upper	0.82	45.28	0.68	53.24	0.76	59.39	0.83	39.23	0.71	63.44	**0.76**	**52.11**	223.88	23%
Northwest Lower	0.83	30.07	0.80	31.07	0.80	49.26	0.84	30.35	0.85	31.54	**0.82**	**34.45**	167.45	21%
Northeast Lower	0.82	42.71	0.74	44.5	0.80	47.10	0.89	36.51	0.63	60.57	**0.78**	**46.28**	177.66	26%
West Central Lower	0.91	49.25	0.79	66.77	0.84	70.99	0.87	63.17	0.81	82.94	**0.84**	**66.61**	240.79	28%
Central Lower	0.84	39.14	0.79	39.98	0.83	41.03	0.91	22.99	0.68	50.65	**0.81**	**38.75**	128.47	29%
East Central Lower	0.85	21.81	0.76	30.43	0.79	30.15	0.84	21.69	0.80	32.01	**0.80**	**27.21**	91.71	29%
Southwest Lower	0.86	44.79	0.87	42.43	0.85	45.59	0.90	35.35	0.91	30.72	**0.88**	**39.78**	158.23	25%
South Central Lower	0.90	31.41	0.83	43.48	0.89	32.37	0.89	32.35	0.83	42.65	**0.87**	**36.45**	139.85	26%
Southeast Lower	0.77	68.44	0.75	64.40	0.78	44.44	0.77	51.94	0.70	73.64	**0.75**	**60.57**	171.68	35%

Table 7-2: Years randomly selected for the test set (excluded systematically from the dataset) in each fold

Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
2018 and 2022	2017 and 2023	2019 and 2021	2020 and 2024	2015 and 2016

Key performance metrics are consistent across folds, with the averaged R^2 and RMSE values demonstrating reliable predictive performance. These results validate the efficacy of the MC-WSI and support its adoption for enhanced material usage forecasting and resource planning in winter maintenance operations. In addition, the RMSE ratio to the average cost value is below 30% for most regions, which is an acceptable level of error, given the variational nature of winter conditions and maintenance operations over different years and locations.

In summary, the pilot phase not only confirms the accuracy of the MC-WSI through robust verification and validation using K-fold cross-validation, but also provides a clear roadmap for continuous model improvement and adaptation to changing conditions. This approach lays a strong foundation for ongoing enhancements, ensuring that MDOT and local service providers can rely on this tool for informed decision-making during winter operations.

7.3 Comparative Performance of Regional vs. Statewide Model

To further validate the effectiveness of the region-specific modeling approach, Table 7-3 compares the root mean square error (RMSE) of each regional model against that of a single statewide model (see Table 6-3), evaluated across the same regions. The table also includes relative error, defined as ratio of the RMSE values to the average material cost for each region, to contextualize the prediction error relative to actual cost.

Table 7-3: Comparison of RMSE Between Regional Models and Statewide Model by Region

Region	Average Material Cost ($/lane mile/month)	RMSE (Regional models) ($/lane mile/month) [Relative Error %]*	RMSE (Statewide model) ($/lane mile/month) [Relative Error %]
West Upper	276.48	61.79 [22%]	70.14 [25%]
East Upper	223.88	52.11 [23%]	52.49 [23%]
Northwest Lower	167.45	34.45 [21%]	93.07 [56%]
Northeast Lower	177.66	46.28 [26%]	54.48 [31%]
West Central Lower	240.79	66.61 [28%]	89.32 [37%]
Central Lower	128.47	38.75 [29%]	45.46 [35%]
East Central Lower	91.71	27.21 [29%]	55.47 [60%]
Southwest Lower	158.23	39.78 [25%]	39.94 [25%]
South Central Lower	139.85	36.45 [26%]	39.72 [28%]
Southeast Lower	171.68	60.57 [35%]	105.06 [61%]

$$*Relative\ Error = \frac{RMSE}{Average\ material\ cost} \times 100$$

In nearly all cases, the regional models demonstrate significantly lower RMSE values, indicating stronger predictive performance. This improvement is especially pronounced in regions such as Northwest Lower, West Central Lower, and Southeast Lower, where the statewide model struggles to account for localized variations in weather severity and material usage. These findings reinforce the advantages of a disaggregated modeling approach and highlight the importance of incorporating regional climate variability into predictive tools like the MC-WSI.

CHAPTER 8 - CONCLUSIONS

This chapter summarizes the project's key findings, offers actionable recommendations for improving winter maintenance practices, acknowledges existing limitations, and outlines areas for future research. The insights gained from this study aim to support MDOT and other agencies in making informed, efficient, and proactive winter maintenance decisions.

8.1 Key Findings

The purpose of this research was to develop a robust, accurate, and region-specific Modified Weather Severity Index to improve winter maintenance operations and budget management and allocation for the Michigan Department of Transportation (MDOT). Through an extensive literature review, statewide and nationwide surveys, rigorous statistical analyses, and advanced modeling techniques, the project identified critical insights and generated meaningful conclusions. This section synthesizes the most important findings from each key component of the research effort, highlighting the implications for MDOT's operational planning, budgeting, and future policy considerations.

Nationwide Literature Review and Current Practices

1. **Limitations of Existing Weather Severity Indices (WSIs):**
   - Current WSIs employed by many state DOTs often use generalized historical averages that fail to accurately reflect regional or localized weather variability.
   - Customized indices, based on local climatic factors such as lake-effect snow and freezing rain, are essential to be developed to correlate with material usage.
2. **Best Practices and Innovations:**
   - DOTs successfully implementing proactive winter maintenance strategies rely heavily on automated tools, real-time forecasting, and flexible, region-specific severity indices.
   - Enhanced communication between state agencies and local garages has proven to be critical in managing winter operations efficiently.

Insights from the Survey of Michigan Garages

3. **Variability in Local Practices:**
    - Garages across Michigan highlighted significant variations in material application strategies, influenced by localized weather conditions, road types, pavement characteristics, and historical maintenance experiences.
    - Decision-making remains heavily reliant on local expertise and real-time observations, underscoring the need for improved predictive tools and more effective operational guidelines from MDOT.
4. **Communication and Coordination Needs:**
    - Strong demand was expressed for more explicit operational guidelines, improved real-time weather and road-condition data sharing, and better resource allocation transparency between MDOT headquarters and regional garages.

Nationwide State DOT Survey Results

5. **WSI Usage and Limitations:**
    - Most state DOTs primarily use WSIs retrospectively to justify budgetary requests rather than proactively adjusting resources throughout the winter season.
    - Few states have integrated short-term weather forecasts or automated systems into their operational decision-making; however, states that have implemented these changes reported significantly improved outcomes in the resource allocation process.
6. **Budget and Material Planning Practices Among State DOTs:**
    - Most state DOTs, including MDOT, rely on historical averages—mainly five-year averages—to determine budget allocations and material procurement needs.
    - Some agencies reported using shorter timeframes (e.g., three-year averages), fixed quantities, or on a demand basis.
7. **Funding and Resource Allocation Insights:**
    - State DOTs prioritizing detailed weather-data integration and proactive winter management experienced improved accuracy in budget forecasting and significant cost savings.
    - The survey reinforced the potential advantages Michigan could gain from enhancing its current WSI to incorporate more localized and predictive components.

Correlation Analysis Between Weather Severity and Maintenance Costs

8. **Strong Predictive Relationships:**
    - Comprehensive correlation analyses demonstrated a robust relationship between winter severity, as quantified by indices like AWSSI, and winter maintenance costs across the States.
    - Results confirmed that tailored regional indices could significantly enhance the State DOTs' ability to estimate material usage and associated costs, thereby improving budget management.

Proposed Material Cost-based WSI (MC-WSI) for Michigan

9. **Importance of Specific Weather Variables:**
    - Pavement temperature, snowfall duration, and freezing rain consistently emerged as the most influential variables, each significantly impacting winter maintenance material consumption.
10. **Robust Statistical Models:**
    - Region-specific robust linear regression models were developed, incorporating critical weather variables identified from surveys and statistical analyses.
    - Validation via 5-fold cross-validation confirmed high predictive reliability across all regions, demonstrating superior accuracy compared to MDOT's traditional WSI approach.
11. **Impact of Pavement Temperature:**
    - Across all regions, pavement temperature was negatively correlated with maintenance costs, indicating that higher temperatures reduce material demands and costs.
    - Southeast Lower region, including densely populated urban centers, demonstrated the highest sensitivity (-$5.31 per Fahrenheit degree), meaning small temperature changes significantly affect maintenance operations and budgetary needs per lane mile.
12. **Impact of Snowfall and Freezing Rain:**
    - Both snowfall duration and freezing rain showed consistently positive correlations with material usage and costs.
    - Southeast Lower Michigan again emerged as particularly sensitive, with snowfall duration ($3.53 per hour) and freezing rain ($6.23 per hour) causing substantial

incremental material cost per lane mile increases, highlighting the challenges urban areas face in winter maintenance operations.

13. **Regional Variation Insights:**
    - The varying magnitude of coefficients across regions demonstrated that local geographic and climatic characteristics greatly influence operational resource needs.
    - The models effectively captured these local differences, underscoring the importance of customized regional approaches for operational budgeting and resource management.
14. **Intuitive and Practical Severity Index:**
    - Estimated regional material costs were normalized and converted into a clear, standardized index (0-100 scale), creating intuitive severity categories (Low, Mild, Average, Moderate, High, Very High, and Extreme).
    - The rating scheme allows straightforward interpretation and rapid decision-making regarding operational responses, resource management, and budgetary adjustments.
15. **Operational and Strategic Utility:**
    - The new rating scheme enhances MDOT's ability to identify high-risk periods and regions, enabling more proactive resource allocation and improved operational preparedness.
16. **Superior Predictive Accuracy:**
    - Achieving a high predictive accuracy ($R^2 = 0.954$) and significantly lower error rates (RMSE = 8.36%), MC-WSI not only outperformed the current MDOT WSI, but also showed significantly higher accuracy than an alternative cost-based index developed using MDOT existing WSI weather features.
    - This validates the practical effectiveness of the MC-WSI as a powerful tool for MDOT in budget planning, operational decision-making, and proactive winter management.

8.2 Recommendations

This section provides detailed recommendations structured into five subsections designed to collectively enhance winter maintenance operations through improved data integration, resource management, and forecasting accuracy. These include recommendations informed by feedback from Michigan garages, nationwide State DOT surveys, and targeted guidance for adopting and utilizing the Michigan MC-WSI. Together, these recommendations aim to streamline decision-making, optimize resource allocation, and support continual operational improvements within MDOT and other state DOTs.

Recommendations Based on Survey of Michigan Garages

1. **Localized Weather Stations to Improve MDSS Inputs**

   It is recommended that MDOT expand the deployment of localized weather sensors, RWIS units, and camera systems to capture the nuanced microclimatic variations across different garage service areas. Enhancing these data collection methods will improve the granularity and accuracy of real-time MDSS inputs, ultimately enabling garages to make more informed and effective winter maintenance decisions. This recommendation applies specifically to MDOT-owned infrastructure and is not applicable to contracted county garages, which manage their own equipment procurement and operational protocols.

2. **Strengthening Coordination Among Garages for Resource Allocation**

   - It is recommended that MDOT develop a structured, formal framework to streamline emergency redistribution of materials during unexpected shortages, with clearly defined communication channels, predefined financial arrangements, and simplified administrative procedures. Establishing real-time communication networks among neighboring garages can be useful to ensure the timely dissemination of critical operational information during severe weather events.
   - A robust central inventory management system managed by MDOT is also recommended. This system may regularly track and report current stock levels and expenditures, allowing real-time monitoring and early detection of potential material shortages. This system should be designed for MDOT use but may optionally allow visibility for contracted counties, pending internal interests.
   - MDOT may also host regular forums—annually, biennially, or as operationally necessary—to facilitate collaboration, share best practices, discuss emerging technologies, and review innovative maintenance strategies across both MDOT and contracted garage operations.

3. **Increasing MDSS Utilization with Targeted Training**
    - Targeted training initiatives are needed to enhance consistent and effective MDSS utilization across MDOT-operated garages. These structured training programs should focus on increasing garages' awareness of MDSS capabilities, thereby improving reporting accuracy and overall decision-making reliability.
    - While contracted county garages operate independently, participation in similar training—where feasible—should be encouraged, particularly in areas with large service coverage or frequent severe winter conditions. Training opportunities, if offered by MDOT or through partnerships, should be made available to interested county agencies as a means to support consistent statewide practices and enhance public safety. MDOT's role in such cases would be to facilitate access to knowledge and resources.
    - MDOT should also consider expanding MDSS access for contracted county garages by providing a simplified interface or selected functionalities. This would allow interested counties to contribute consistent weather and operations data, and to benefit from automated MC-WSI estimations, while staying within the bounds of existing system access policies. As shown in Figure 4-13, only about 60% of Michigan's roadways are currently integrated into the MDSS (due to lack of funding to support contract counties' garages), compared to 100% in several peer states such as Nebraska, South Dakota, and Illinois. Increasing coverage across the state would align Michigan with national best practices and improve consistency in data reporting, operational planning, and severity index estimation.
4. **Microclimatic Data Limitations:**

    Currently, MDOT's regional weather data collection methods are insufficient in fully capturing the nuanced microclimatic variations across different garage service areas. This limitation may negatively impact the precision and effectiveness of real-time MDSS inputs.

Strategic Recommendations Based on Survey of State DOTs

5. **Material Storage Capacity Assessment and Usage Monitoring**

    MDOT should systematically assess and evaluate the material storage capacities at garages that regularly experience shortages. Identifying the feasibility of expanding storage infrastructure at these locations will improve material procurement processes, alleviate resource constraints, and significantly enhance operational readiness for winter maintenance activities.

6. **Benchmarking Michigan's MC-WSI Performance with Peer States**

   MDOT may initiate collaborative benchmarking efforts with neighboring states and encourage undertaking similar research on winter severity indices and operational outcomes. By aligning methodologies and comparing key performance metrics, MDOT can better understand how different states address winter maintenance challenges. This collaborative approach will promote the sharing of best practices, innovative solutions, and lessons learned, ultimately positioning Michigan as a leader in winter maintenance innovation.

7. **Develop Region-Specific Indices:**

   State DOTs should consider developing customized winter severity indices that account for local climatic nuances. Instead of relying solely on broad indices like AWSSI, which correlate with costs but may neglect local variations, agencies can cluster their state into distinct regions or even tailor indices for individual counties. This approach will provide more precise forecasting and better inform material procurement and budgeting decisions.

8. **Leverage Integrated Data Systems:**

   It is recommended to enhance existing data collection efforts by integrating diverse sources—such as historical weather records, real-time meteorological data, and maintenance expenditure reports—into a unified decision support system. This integrated approach ensures that all relevant factors are considered in the budget management and resource allocation processes, ultimately driving more informed and timely decisions.

Recommendations for Michigan MC-WSI

9. **Utility and Adoption**

   - **Encouraging Alignment of MC-WSI Use Across Contracted and State Operations**:

     To maximize the utility and impact of the MC-WSI, it is recommended that MDOT actively promote widespread adoption of the MC-WSI internally and among contracted service providers to enhance consistency in winter maintenance operations, resource allocation, and financial planning.

- **Developing a Publicly Accessible MC-WSI Dashboard**:
  It is recommended that MDOT develop a publicly accessible MC-WSI dashboard that visually presents severity trends, material usage, and maintenance activities, enhancing transparency and stakeholder engagement. Additionally, creating a simplified operational dashboard for frontline staff, with clear action thresholds based on MC-WSI values, is recommended to facilitate timely, and practical decision-making.

- **Implement Specific MC-WSI Use Cases:**
  MDOT should adopt the MC-WSI for both mid-season and post-season reporting to continuously monitor and manage winter maintenance costs. Integrating the MC-WSI into both mid-season and post-season reporting provides a comprehensive framework for dynamic decision-making and continuous improvement. Throughout the winter season, regular MC-WSI updates enable MDOT to monitor current material cost trends in relation to weather severity. This real-time insight not only supports proactive mid-season resource reallocation and contingency budgeting—triggering early-warning signals when thresholds are reached-but also informs mid-season adjustments to ensure effective resource reallocation. On the other hand, these continuous updates establish a robust baseline for post-season performance assessment. Comparing current material usage and expenditures against historical benchmarks provides key operational insights for budget management and resource allocation.
- **Training and Support:**
  MDOT should develop and regularly update comprehensive training programs tailored to MDOT staff and local service providers. Ongoing support and refresher training sessions will sustain user proficiency, ensuring consistent and effective application of the MC-WSI across the board.

10. Performance Monitoring and Evaluation

- **Exploring Vehicle Telematics to Enhance MC-WSI Calibration:**
  It is recommended that MDOT review existing vehicle telematics capabilities and expand data collection to include additional metrics such as material application rates

within its own fleet, thereby improving real-time MC-WSI calibration and enhancing operational decision-making accuracy.

- **Real-time Integration into MDSS:**
  MDOT may consider incorporating MC-WSI as a tool within MDOT's MDSS to enable real-time operational decision-making. This can help establish a systematic approach to continuously monitor MC-WSI performance during winter events, using insights gained for iterative refinements of the index.

11. Refinement and Future Recalibration

- **Monthly Material Cost Monitoring and Update:**
  The MC-WSI is calculated by standardizing estimated (or actual) material costs, which involves dividing each region's monthly cost by the maximum estimated (or actual) cost observed and then scaling the value to a 0-100 range. MDOT should establish a process to continuously track these estimated (or actual observed) costs and update the maximum value on a monthly basis. If the maximum cost changes, the index must be recalibrated accordingly to ensure it remains accurately aligned with current cost trends.
- **Establishing a Review Process for MC-WSI Adjustments**:
  Since winter dynamics evolve over time, periodic recalibration of MC-WSI methodologies based on post-season analyses could help improve MC-WSI model precision and ensure continued alignment with operational needs. To this end, MDOT may set up a protocol to recalibrate the MC-WSI every 3-5 years with additional data points relative to what were available for the current MC-WSI calibration.

8.3 Limitations and Future Works

This section acknowledges limitations identified during the study and outlines opportunities for future research. Recognizing these constraints and areas for improvement helps guide ongoing enhancements in developing winter severity indices and supports more effective and proactive operational planning in the future.

8.3.1 Limitations

1. **Addressing Data Collection Gaps**

   - **Implement Statewide Data Standardization:**

     MDOT should initiate a statewide data standardization effort to ensure consistent and uniform reporting protocols across all regions consistent with MV-WSI definition. This standardization will enhance the accuracy and reliability of MC-WSI assessments.

   - **Systematic Cost Data Collection:**

     Establish a regular, systematic data collection process for maintenance cost information across MDOT and contract counties. Consistent reporting standards will enable more integrated analyses, directly linking winter severity and financial performance, thereby facilitating data-driven budgeting and resource allocation decisions.

   - **Enhance Data Quality and Efficiency:**

     MDOT should implement improved data collection mechanisms, such as standardized Excel templates or a dedicated online data-entry portal, to reduce administrative burden and improve data accuracy and consistency. The inclusion of clear data-reporting requirements within annual contract agreements is recommended to ensure widespread participation.

   - **Inconsistent MDSS Adoption:**

     The level of MDSS adoption and proficiency varies significantly across garages. While MDOT-operated garages generally have access, contracted county garages face additional barriers, including restricted system credentials and limited resources for training. These limitations contribute to inconsistent usage, reduced reporting accuracy, and uneven decision-making support across the state.

2. **Limitations of Michigan MC-WSI**

   - **Predictive Capability Constraints:**

     The MC-WSI, as presently developed, primarily focuses on monitoring real-time winter severity and retrospective cost correlation. The predictive capability for pre-season forecasting or proactive decision-making remains limited and requires future research, particularly through enhanced forecasting methods and probabilistic modeling.

- **Data Management and Governance Issues:**

  Regular and standardized collection of high-quality, granular operational cost data is essential for accurate MC-WSI calibration and utility. Current challenges in maintaining consistent data standards across regions and providers represent a critical limitation, necessitating future improvements in data governance and management systems.

3. **Limitations identified in data management, governance, and MDSS integration**

- **Limited Historical Coverage in WMRI Tool:**

  A key limitation of the WMRI tool within MDSS is its restricted historical data availability. Specifically, archived weather and response data are only accessible from December 2014 onward. This limited timeframe constrains the tool's usefulness for long-term analysis, historical benchmarking, and integration with older maintenance cost records.

- **Challenges with Cost Data Aggregation:**

  Existing Excel-based submission practices, varying formats, and administrative complexities contribute to inefficient data collection processes, impacting timeliness and accuracy. Aggregating and standardizing maintenance cost data across MDOT and contract counties are key factors in improving the MC-WSI model.

  Limited Real-Time Data Integration:

  Currently, many counties and regions are not covered by MDOT's MDSS, limiting access to real-time, data-driven decision support for winter maintenance operations in these areas. More comprehensive and seamless integration would enhance operational responsiveness and predictive accuracy of maintenance activities.

  Relying Only on Material Cost for MC-WSI:

  The proposed MC-WSI in this study only incorporates material usage data. Other indices can be developed based on total maintenance costs, including material procurement, vehicle operational cost (maintenance and fuel), labor, and inventory costs, to improve model accuracy. The total cost data in this study was only available for a limited number of years and only for the entire season instead of monthly data. Future analyses require monthly region-specific total maintenance costs for a longer period of time to improve proposed MC-WSI models in this study.

8.3.2 Recommended Future Works

1. Enhancing Automation and Reducing Operational Variability

It is recommended that MDOT explore the development of a dedicated estimator tool to enhance automation in MC-WSI computation and reporting. This tool would leverage regional models to convert MDSS-generated weather data into precise monthly MC-WSI values and corresponding cost estimates, requiring only basic inputs. By automating data cleaning and calculation processes, the tool will not only reduce the labor-intensive manual workload but also minimize human error.

2. Expanding Management Capabilities

The tool could be designed with the flexibility to integrate comprehensive winter datasets, supporting both monthly and seasonal MC-WSI calculations and providing historical trend analysis for each region. This capability would improve performance tracking and enable more informed decision-making. A customizable dashboard with seamless data integration and export options would further tailor the solution to the specific operational needs of MDOT and its regional garages, ultimately contributing to more efficient budget reporting and resource planning.

Furthermore, the tool could incorporate an in-season budget adjustment methodology. By comparing current season MC-WSI values with five-year historical averages, the tool would enable real-time budget recalibration based on deviations from established cost benchmarks. Integrating this functionality as an add-on to the Regional MC-WSI and Material Cost Calculator would offer MDOT a proactive mechanism to adjust financial allocations throughout the winter season, thereby enhancing overall resource management and operational efficiency.

3. Expanding Forecasting Capabilities

It is recommended that MDOT invest in developing a forecasting tool that actively predicts the MC-WSI using short-term weather estimation data. By incorporating 10-day probabilistic forecasts into the model, this tool would provide real-time, forecasted MC-WSI values and automatically recommend corresponding material usage adjustments. This proactive approach would enable MDOT to optimize resource distribution early in the season, improve operational efficiency, and ultimately reduce costs by aligning material orders with expected weather severity.

REFERENCES

1. FHWA. Snow & Ice - FHWA Road Weather Management. Snow & Ice - FHWA Road Weather Management. https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm. Accessed Jul. 5, 2024.
2. Walker, C. L., S. Hasanzadeh, B. Esmaeili, M. R. Anderson, and B. Dao. Developing a Winter Severity Index: A Critical Review. *Cold Regions Science and Technology*, Vol. 160, 2019, pp. 139–149. https://doi.org/10.1016/j.coldregions.2019.02.005.
3. Annual Survey of State Winter Maintenance Data - Clear Roads. https://www.clearroads.org/winter-maintenance-survey/. Accessed Mar. 11, 2025.
4. Boustead, B. E., S. D. Hilberg, M. D. Shulski, and K. G. Hubbard. The Accumulated Winter Season Severity Index (AWSSI). *Journal of Applied Meteorology and Climatology*, Vol. 54, No. 8, 2015, pp. 1693–1712. https://doi.org/10.1175/JAMC-D-14-0217.1.
5. Clear Roads: Accumulated Winter Season Severity Index (AWSSI) Enhancements in Support of Winter Road Maintenance.
6. Boselly, S. E., I. G. S. Doore, J. E. Thornes, C. Ulberg, and D. D. Ernst. Road Weather Information Systems Volume 1: Research Report. 1993.
7. Kastman, J. S., D. M. Tobin, A. Nash, J. A. Nelson, D. K. Cobb Jr, and K. J. Harnos. The Winter Storm Severity Index. https://doi.org/10.1175/WAF-D-23-0230.1.
8. *MassDOT Snow and Ice Control Program 2022 Environmental Status and Planning Report PREPARED BY*. 2022.
9. Nixon, W. A., R. G. Alger, J. Brett, A. Richard, M. Balgowan, J. P. Burkhardt, T. Dahl, R. Decker, G. B. Gilfillan, S. N. Goodman, R. L. Hanneman, Y. Kajiya, D. Kroeger, G. Levasseur, M. Malmivuo, J. E. Meredith, L. David, M. Richard, J. Nelson, J. Olander, M. S. Perchanok, P. A. Pisano, L. D. Smithson, G. E. Thompson, A. Obiora, U. David, V. Donald, M. Walker, R. M. Balgowan, E. Boselly, D. M. Walker, F. N. Lisle, A. E. Petty, C. Hamann, K. M. Sawyer, J. G. Correro, J. J. Weeks, and J. Green. Sixth International Symposium on Snow Removal and Ice Control Technology Sponsored by COMMITTEE ON WINTER MAINTENANCE (AHD65) In Cooperation with WASHINGTON STATE DEPARTMENT OF TRANSPORTATION AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS FEDERAL HIGHWAY ADMINISTRATION. 2004.
10. Strong, C., and Y. Shvetsov. Development of Roadway Weather Severity Index. *Transportation Research Record*, Vol. 1948, 2006, pp. 161–169.
11. WisDOT. WINTER MAINTENANCE AT A GLANCE 2023-2024 Mild Winter + Better Salt Management = Least Amount of Salt Used in 35 Years.
12. Winter Maintenance Report - Maintenance - MnDOT. https://www.dot.state.mn.us/maintenance/winter-report.html. Accessed Mar. 11, 2025.

13. Cohen, S. J. User Oriented Climatic Information for Planning a Snow Removal Budget. *Journal of Applied Meteorology*, Vol. 20, No. 12, 1981, pp. 1420–1427. https://doi.org/10.1175/1520-0450(1981)020<1420:UOCIFP>2.0.CO;2.
14. Walsh, C., and V. Inc. *Winter Maintenance Performance Measure*. 2016.
15. Chien, S., J. Meegoda, J. Luo, P. Corrigan, L. Zhao, and N. J. I. of Technology. Road Weather Information System Statewide Implementation Plan. 2014. https://doi.org/10.21949/1503647.
16. Balasundaram, B., S. T. S. Bukkapatnam, Z. Kong, Y. Hong, O. S. University. S. of I. E. and Management, and U. of Oklahoma. S. of C. E. and E. Science. Proactive Approach to Transportation Resource Allocation under Severe Winter Weather Emergencies. 2012. https://doi.org/10.21949/1503647.
17. Thomas, R., R. Bennett, D. Hassan, Y. Adu-Gyamfi, P. Edara, and Inc. Wood Environment & Infrastructure Solutions. Development of a Surface Transportation Impact Factor for Winter Severity Indices. 2022. https://doi.org/10.21949/1503647.
18. Anderson, M. R., B. Esmaeili, C. L. Walker, D. Steinkruger, S. Hasanzadeh, A. Commons, M. R. ; Esmaeili, B. ; Walker, C. L. ; Steinkruger, D. ; Hasanzadeh, S. ; Gholizadeh, P. ; Dao, and " Development. Development of the Nebraska Department of Transportation Development of the Nebraska Department of Transportation Winter Severity Index Winter Severity Index. 2018.
19. Anderson, M. R., C. L. Walker, T. Kauzlarich, and U. of Nebraska-Lincoln. Development of the Nebraska Department of Transportation Winter Severity Index – Phase II. 2024. https://doi.org/10.21949/1503647.
20. Carmichael, C. G., W. A. Gallus, J. R. And, B. R. Temeyer, and M. K. Bryden. *NOTES AND CORRESPONDENCE A Winter Weather Index for Estimating Winter Roadway Maintenance Costs in the Midwest*. 2004.
21. Brinckerhoff, P. Investigator: Andrew Cadmus UNDERSTANDING THE TRUE COSTS OF WINTER MAINTENANCE RESULTS SUMMARY. 2014.
22. NAKAMAE, S., T. OKAWADO, F. HARA, J. OSHIMA, and S. TAKANO. Development of a Cost Management Method for Road Snow Removal in Cold, Snowy Regions. *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 8, 2010, pp. 311–324. https://doi.org/10.11175/EASTS.8.311.
23. Venäläinen, A., and M. Kangas. Estimation of Winter Road Maintenance Costs Using Climate Data. *Meteorological Applications*, Vol. 10, No. 1, 2003, pp. 69–73. https://doi.org/10.1017/S1350482703005073.
24. Qi, Y., and V. Reddy Velpur. Nonlinear Modelling of the Association between Winter Weather Severity and Maintenance Expenditures. https://doi.org/10.1139/cjce-2023-0203.
25. Ding, X., and T. J. Kwon. Enhancing Winter Road Maintenance with Explainable AI: SHAP Analysis for Interpreting Machine Learning Models in Road Friction Estimation. *Canadian Journal of Civil Engineering*, Vol.

51, No. 5, 2024, pp. 529–544. https://doi.org/10.1139/CJCE-2023-0410/ASSET/IMAGES/CJCE-2023-0410_F13.JPG.

26. Bingham, P. H. TRANSPORTATION RESEARCH BOARD 2008 EXECUTIVE COMMITTEE OFFICERS. 2008.
27. Robinson, M., and J. L. Sullivan. Quantifying Correlations Between Pavement Conditions and Snow and Ice Control Costs and Recalculating 2021-2022 Winter Performance Measures. 2022.
28. MDOT Regional Service Areas and Facilities . https://www.michigan.gov/-/media/Project/Websites/MDOT/Travel/Map/MDOT-Region-Map.pdf?rev=1651ac9f89c0410e9d130609fa9c1e28. Accessed Mar. 12, 2025.
29. Wang, E., J. LaCombe, and Reno. C. of E. University of Nevada. Maintenance Decision Support System : Pilot Study and Cost-Benefit Analysis (Phase 2). 2014. https://doi.org/10.21949/1503647.
30. OFS Region Support. *Michigan's Winter Severity Index with MDSS Data*. 2015.
31. AWSSI Chart. https://mrcc.purdue.edu/research/AWSSI/chart. Accessed Mar. 12, 2025.
32. Karl, T., and W. J. 1931- Koss. Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983. https://repository.library.noaa.gov/view/noaa/10238. Accessed Mar. 13, 2025.
33. Guttman, N. B., and R. G. Quayle. A Historical Perspective of U.S. Climate Divisions. *Bulletin of the American Meteorological Society*, Vol. 77, No. 2, 1996, pp. 293–304. https://doi.org/10.1175/1520-0477(1996)077.
34. Transportation Asset Management Council, Winter Maintenance Dashboard. https://www.mcgi.state.mi.us/mitrp/tamcDashboards/reports/maintenance?areaType=County&area=Alcona&reportType=comparison. Accessed Mar. 12, 2025.
35. *AWSSI Enhancements in Support of Winter Road Maintenance*. 2019.
36. National Oceanic and Atmospheric Administration (NOAA). US Climate Divisions. https://www.ncei.noaa.gov/access/monitoring/reference-maps/us-climate-regions. Accessed Jul. 6, 2024.

APPENDIX A – SURVEY OF LOCAL SERVICE PROVIDERS IN MICHIGAN

MDOT WSI Garage Survey

Q1.1 The Michigan Department of Transportation (MDOT) awarded a study to Michigan State University (MSU) **to evaluate the effectiveness of winter severity index (WSI)** for **winter operations**, **material procurement**, and **budget allocation planning**.

The project partly involves winter maintenance garages throughout Michigan, to understand unique **winter maintenance practices**, weather data considerations, and various operational and material cost data. The project is also assessing the existing coordination and communication structures between service garages with MDOT.

This survey will take you approximately **20 minutes** to complete. Please be advised this survey is more convenient to be completed using a laptop/desktop. Should you have further inquiries or comments, you may contact the research principal investigator, **Dr. Ali Zockaie**, at zockaiea@egr.msu.edu.

Q1.2 Garage Personnel Contact Information Name ____ Your Title / Position ____ Email ____ Phone Number ____ Garage Name/Location ____

Block 2: Material & Resource Management

Q2.1 In the following questions, we are interested in understanding the **selection, procurement, and use of materials** for your garage's winter maintenance operations.

Q2.2 What is your garage's total **lane-mile coverage** for winter operations?
(Lane-mile coverage refers to the total length of roadway lanes maintained. For instance, 1 mile of road with 2 lanes equals 2 lane-miles.)

____

____

Q2.3 How do **you determine your material application rates** (select all that apply), and in **what circumstances** are they being used?

- ▢ Driver's judgment ________________
- ▢ MDOT enforced rates (please specify) ______________________________
- ▢ Specific guidelines (please specify your primary guideline) ______________________________
- ▢ Others 1 (please specify) ____
- ▢ Others 2 (please specify) ____

Q2.4 If available, please write down your average material application rates? (please specify the units used)

	Application Rate	*Unit*
Salt		
Sand		
Liquid brine		
Liquid (boost)		
Liquid (SPC5000)		
Other material 1 (please specify)		
Other material 3 (please specify)		
Other material 3 (please specify)		

Q2.5 We are interested in understanding your practices around material **surpluses and deficits**.

Q2.6 How do you determine if you will **need more** materials, i.e. what are the **criteria and/or thresholds** that prompts you to order more?

____

____

Q2.7 How do you handle situations when you're **short** on materials? e.g., an unexpected winter storm occurs when material inventory is low/inadequate. (select all that apply)

- ▢ Rely on neighboring garages resources
- ▢ Order whenever you are below a certain amount (please specify) ____________________
- ▢ Use substitute materials (please specify) ________________________________
- ▢ Other arrangement (please specify) ____

Q2.8 Do you use any **Weather Severity Index** (WSI) for any **resource allocation/budget planning**? (select all that apply)

▢ No, we do not use any WSI to plan for resource allocation/budget planning
▢ Yes, we use WSI **formulated by MDOT**

▢ Yes, we use WSI **formulated by our own garage**

▢ Yes, we use WSI formulated by other agencies (please specify) ____________________

Q2.9 Briefly explain some details on the WSI being used (calculation methodology, formulation, etc.). Or you may **upload** any documents or **provide links** to relevant sources.

____

____

Q2.10 **Upload files** here:
**Shared data will be kept confidential and be used specifically for this MDOT-sponsored project only.*

Block 3: Winter Maintenance Tools and Practices

Q3.1 In the following questions, we are interested in understanding **the tools and resources** your garage employs for winter maintenance operations.

Q3.2 Do you use Maintenance Decision Support Systems **(MDSS)**?

o Yes

o No

Q3.3 Why does your garage choose **not to utilize** MDSS?

▢ lack of expertise or resources
▢ MDSS does not cover our service area
▢ Data reliability
▢ Others (briefly explain) ____

Q3.4 For **what purpose** do you use the MDSS? (select all that apply)

▢ Weather observations
▢ Operation planning
▢ Material procurement
▢ Budget planning
▢ Other purposes (please specify)
____

Q3.5 Are there any **challenges or issues** encountered when using MDSS for winter maintenance purposes?

____

Q3.6 Are there **other weather tools/software/data** your garage relies on for winter maintenance operations? (select all that apply)

▢ Road Weather Information System (RWIS)
▢ Automated Surface Observing System (ASOS)
▢ Automated Vehicle Location (AVL)
▢ Other tools (please specify)

____

Q3.7 What are the **important thresholds** that trigger winter maintenance operations, such as plowing and material spreading? (select all that apply)

▢ Based on weather predictions (please specify)

____

▢ Specific amount of snowfall/freezing rain (please specify)

____

▢ Other measures (please specify)

____

Q3.8 Which weather data points do you believe are **essential to consider** specifically for winter maintenance operations over the **service area of your garage**? (select all that apply)

▢ Weather temperature
▢ Road temperature
▢ Snowfall rate
▢ Snow amount
▢ Freezing rain amount
▢ Event Duration
▢ Sleet
▢ Wind speed
▢ Blowing/drifting
▢ Others (please specify as many)

____

Q3.9 Are there any unique challenges or considerations **specific to your region** that impact your winter maintenance practices (e.g. material selection/needs, application rates, etc.)?

____

____

Q3.10 Are there **any additional** winter maintenance practices or strategies that you would like to highlight, which haven't been covered in the survey questions?

____

____

Block 4: Collaboration & Information Sharing

Q4.1 In the following set of questions, we are interested to understand possible **improvement of your garage's collaboration and information sharing with MDOT** for winter maintenance operations.

Q4.2 Specifically around communication and information sharing, what are the **improvements** that can be made **to enhance operational efficiency, communication and coordination** between MDOT and your garage?

____

____

Q4.3 If MDOT designs a Weather Severity Index (WSI) **specifically tailored for your garage's region** that would aid material usage planning, **would you be willing** to participate in a **pilot test** to evaluate its effectiveness in assisting your winter maintenance operations?

o Yes

o No (Please specify why not) ____

o Maybe (please specify your conditions) __________________________________

Q4.4 For the proposed WSI, briefly explain what aspects of **operations and planning** do you hope it could facilitate?

____

____

Q4.5 Are there specific areas where you believe MDOT could provide more **support or resources to aid** in winter maintenance operations? (select all that apply)

▢ Access to advanced technology or equipment
▢ Provision of additional funding or grants
▢ Sharing of best practices
▢ Providing timely and accurate weather and road condition data

▢ Others (please specify) ____

Q4.6 Are there any **cooperative efforts or collaborations** with other roadway maintenance agencies in your area?

- o Yes
- o No

Q4.7 What specific **types of collaborative** efforts or projects have been undertaken with other roadway maintenance agencies in your area? (select all that apply)

▢ Joint equipment sharing programs
▢ Coordinated snow removal operations
▢ Shared material inventories
▢ Others (please specify) ____

Q4.8 Can you describe the **benefits or outcomes** that have resulted from these collaborative efforts? (select all that apply)

▢ Increased operational efficiency
▢ Cost savings through resource sharing
▢ Enhanced emergency response capabilities
▢ Others (please specify) ____

Q4.9 You have reached the end of the survey. Please provide **any additional comments or clarifications** regarding any section of the survey or your responses.

____

____

APPENDIX B – GARAGE PARTICIPATIONS IN THE STATEWIDE SURVEY

Garages participated in the statewide survey

Arenac	Marquette	Presque Isle	Sawyer Garage
Bay	Midland	Gogebic	South Haven Garage
Charlevoix	Missaukee	Saginaw West Garage	Engadin Garage
Chippewa	Muskegon	Saginaw East Garage	St. Ignace Garage
Clare	Newaygo	Mt. Pleasant Garage	Williamston Garage
Delta	Oakland	Blue Water Bridge	Brighton Garage
Dickinson	Ogemaw	Fennville Garage	East Monroe Garage
Emmet	Ontonagon	Plainwell Garage	West Monroe Garage
Gladwin	Roscommon	Detroit Garage	Bruce Crossing
Grand Traverse	Sanilac	Kalkaska Garage	
Iosco	Schoolcraft	Jones Garage	
Iron	Shiawassee	Marshall Garage	
Keweenaw	Wayne	Kalamazoo Garage	
Luce	Jackson	Coloma Garage	

Garages not participated in the statewide survey

Alger	Ionia	Tuscola
Alpena	Kent	Washtenaw
Antrim	Lapeer	Wexford
Benzie	Leelanau	Adrian Garage
Branch	Macomb	Marion Garage
Calhoun	Manistee	Atlanta Garage
Cheboygan	Mason	Hastings Garage
Clinton	Mecosta	Grand Ledge Garage
Crawford	Menominee	Niles Garage
Genesee	Montcalm	L'Anse Garage
Lake	Oceana	Houghton Garage
Gratiot	Otsego	Charlotte Garage
Hillsdale	Ottawa	Mason Garage
Huron	St. Clair	

APPENDIX C – NATIONWIDE STATE DOT SURVEY QUESTIONS

Winter Severity Index (WSI) Applications and Winter Operations Cost Management Survey

By Michigan DOT & Michigan State University

SURVEY DESCRIPTION

The Michigan Department of Transportation (MDOT) is exploring the relationship between **winter severity indices (WSI) and winter maintenance expenses and material usage**. In this regard, Michigan State University (MSU) has been awarded a project funded by MDOT to evaluate the effectiveness of a winter severity index for winter operations, material procurement, and budget allocation planning. Additionally, the project aims to identify **current uses and applications of Winter Severity Indices** and **weather conditions** in other states.

Proper planning for winter maintenance services, including materials and budget allocation for personnel and equipment, is crucial. Overspending early in the season can result in material and budget shortages for severe storms later on. A winter weather index may help **improve budget estimation and resource allocation** based on observed trends and predicted weather conditions. To this end, a state-of-the-practice review survey has been developed, and we appreciate your response.

This survey will take you approximately 20-30 minutes to complete. Please be advised this survey is more convenient to be completed using a laptop/desktop.

Should you have further inquiries or comments, you may contact the research principal investigator, Dr. Ali Zockaie, at zockaiea@egr.msu.edu.

Survey Link: https://msu.co1.qualtrics.com/jfe/form/SV_4MUd3qpk2meRlwW

SURVEY SECTIONS

Section 1: Respondent Details
Section 2: WSI Utility
Section 3: Weather Index Configuration
Section 4: Asset Management
Section 5: Coordination and Communication

SECTION 1: RESPONDENT DETAILS

Q1.1 Please provide your contact information:

- Name ____
- Agency____
- Role ____
- Email ____
- Contact Number ____________________________________

SECTION 2: WSI UTILITY

Through the next set of questions, we are interested in understanding **WSI applications** in your agency and state.

Q2.1 Does your agency utilize any winter severity indices for winter maintenance operations/planning?

- o No
- o Yes

Q2.2 Please select all winter severity indices that your agency utilizes:

- ☐ Strategic Highway Research Program (SHRP) Winter Index
- ☐ Accumulated Winter Season Severity Index (AWSSI)
- ☐ Road Accumulated Winter Season Severity Index (RAWSSI)
- ☐ WSI formulated by our own agency (please specify its name and brief description) ____
- ☐ Other (please specify) __________________________________

Q2.3 You indicated that your agency uses **winter index** measures for winter maintenance operations/planning. For what purposes is this WSI being used by your agency? *Please select all that apply*.

- ☐ Fiscal planning and forecasting
- ☐ Material budgeting and procurement
- ☐ Ground operations (snowplow deployment, personnel planning, etc.)
- ☐ Current weather monitoring
- ☐ Future weather forecasting
- ☐ Assessing safety for winter maintenance operation
- ☐ Other (please specify) ____

Q2.4 Has your agency conducted any **cross-analysis** between WSI indexes with other datasets, such as crash data, material usage, maintenance cost, etc., to assess **potential correlations** or insights into your winter maintenance strategies?

- o Yes (Please explain briefly) ________________________________
- o No

Through the next set of questions, we are interested to learn about your agency's capabilities/resources to **forecast weather** for upcoming winter operations.

Q2.5 Does your agency use any **weather forecasting tools** for winter maintenance operations/planning?

- o Yes
- o No

Q2.6 What methods does your agency use to monitor **weather conditions** and predict **winter maintenance needs?**

- ☐ National meteorological services (i.e., NWS)
- ☐ Weather radar
- ☐ Satellite imagery
- ☐ Commercial/Private meteorological services
- ☐ Weather models
- ☐ Mobile applications
- ☐ MDSS (data aggregator)
- ☐ Other (please specify) __________________________________

Q2.7 What are the forecast **timeframes of interest?**

- ☐ Upcoming hours
- ☐ Upcoming days
- ☐ Upcoming weeks
- ☐ Upcoming 1 month
- ☐ Upcoming 2-3 months
- ☐ Upcoming winter season
- ☐ Others (please specify) ____________________________

SECTION 3: WEATHER INDEX CONFIGURATION

Q3.1 Does your agency have any WSI **formulated or calibrated** specifically for winter maintenance operations and planning?

- o Yes
- o No

Q3.2 What are the **main components** and **variables** of interest of the winter severity index (WSI) used by your agency?

- ▯ Air temperature
- ▯ Road temperature
- ▯ Wind
- ▯ Freezing rain
- ▯ Snow amount
- ▯ Snow frequency
- ▯ Event duration
- ▯ Blowing/drifting
- ▯ Other (please specify) ____

Q3.3 How often do you calculate or apply your WSI?

- ▯ Daily
- ▯ Weekly
- ▯ Monthly
- ▯ Seasonally
- ▯ Annually
- ▯ Other (please specify) _____________________________________

Q3.4 In what format(s) do you report this WSI?

- o Intervals/ranges of 0-10
- o Intervals/ranges of 1-100
- o Color-coded scale (e.g.,green, yellow, red)
- o Other (please specify) _______________ _______________ _______________

Q3.5 What **spatial scale** does your agency use to calculate or apply the WSI?

- ▯ Sensor Location
- ▯ Road Segment
- ▯ City
- ▯ County

- ☐ District/Region

Q3.6 Does your agency consider any regional or geographical boundaries/clusters when reporting the winter severity index (WSI)?

- o Yes
- o No

Q3.7 What criteria does your agency use to define the regions/boundaries for calculating or applying WSI? *Please select all that apply.*

- ☐ Climate zones
- ☐ Average Altitudes
- ☐ Regional lane-mile coverage
- ☐ Administrative boundaries (e.g., counties, districts)
- ☐ Geographical characteristics (please specify) ____________________________
- ☐ Other (please specify) ____

Q3.8 Please upload or provide any links to reports or websites that contain details of the utilized WSI by your agency (calculation methodology, formulation, etc).

____

____

Q3.9 What data sources does your agency use for WSI and winter maintenance operations/planning? *Select all that apply*.

- ☐ National sensor data sources (NOAA MADIS)
- ☐ Federal Aviation Administration (FAA) surface weather observation stations (ASOS/AWOS)
- ☐ Public/social media
- ☐ Private weather service providers
- ☐ Nonfederal mesonetworks
- ☐ Agency field personnel
- ☐ Agency sensors (RWIS/Probes)
- ☐ National weather service products
- ☐ Not sure/unknown
- ☐ Other 1 (please specify) ____
- ☐ Others 2 (please specify) ____
- ☐ Others 3 (please specify) ____________________________________

Q3.10 Do you have any **comments/issues** on the overall performance of the **selected data sources** (e.g., reliability, accuracy, convenience, interface) when being used for winter operations/planning?

____

____

Q3.11 What are the **limitations** of your agency's WSI for winter maintenance ground operations and financial planning?

____

____

Q3.12 In your opinion, what steps or measures (if any) could be taken **to overcome the limitations** identified in your agency's WSI:

For winter maintenance **ground operations**?

____

____

For winter maintenance **financial planning**?

____

____

SECTION 4: ASSET MANAGEMENT

Q4.1 For **material procurement planning**, how does your agency decide the **amount of material** to procure in the upcoming winter season?

- ☐ Based on forecasted overall winter severity
- ☐ Determined and requested by regional/county winter operation garages
- ☐ Based on a special WSI formulation
- ☐ Based on historical averages or rolling averages
- ☐ Others 1 (please specify) ______________________________________
- ☐ Others 2 (please specify) _____________________________________
- ☐ Others 3 (please specify) ______________________________________

Q4.2 For winter operations **fiscal allocation**, how does your agency decide the **amount of funding** to allocate for winter maintenance operations in the upcoming winter season?

- ☐ Fixed amount allocated every year
- ☐ Based on forecasted overall winter severity
- ☐ Based on a special WSI formulation
- ☐ Based on historical averages or rolling averages

- ☐ Others 1 (please specify) ______________________________
- ☐ Others 2 (please specify) _______________________________
- ☐ Others 3 (please specify) ___________________________________

Q4.3 You mentioned your agency decides the amount of **material to procure** in the upcoming winter season based on **historical averages or rolling averages**. Could you please specify the time-frame used for calculating the average values over?

- ☐ Past 2 years
- ☐ Past 5 years
- ☐ Past decade
- ☐ Lifetime average (average of all years recorded)
- ☐ Other (please specify) ___________________________________

Q4.4 You mentioned that your agency decides the amount of **funding** to allocate for winter maintenance operations in the upcoming winter season based on **historical averages or rolling averages**. Please specify the data time frame used to calculate the average values

- o Past 2 years
- o Past 5 years
- o Past decade
- o Lifetime average (average of all years recorded)
- o Other (Please specify) ________________________________

Q4.5 How do you use the Winter Severity Index (WSI) for **winter material usage** and **cost control**?

____

____

Q4.6 How has the use of a WSI benefited your agency in terms of **cost savings** and/or **material usage efficiency**? *Please select all that apply*:

- ☐ Improved cost savings by optimizing material usage
- ☐ Enhanced efficiency in material procurement and utilization
- ☐ Better allocation of resources based on WSI data
- ☐ Reduction in wastage and overstocking of materials
- ☐ Other benefits (please specify) _________________________

SECTION 5: COORDINATION AND COMMUNICATION

Through the next set of questions, we are interested in understanding some **best practices in regard to coordination and communication** with winter maintenance contractors and regional garages in your state.

Q5.1 What percentage of your winter maintenance operations are contracted through local service providers?

0 10 20 30 40 50 60 70 80 90 100

Please insert your comments ()	

Q5.3 Do any of the local service providers in your area use **the Maintenance Decision Support System (MDSS)** or provide data for winter maintenance operations?

- o Yes (If selected, how does this collaboration affect your overall operations?) ______
- o No (If selected, please specify what common tools are being used.) ________

Q5.4 What percentage of **the roads in your state**, including those under contracted counties, is available on the MDSS? (A range of approximations would suffice.)

0 10 20 30 40 50 60 70 80 90 100

Please insert your comments ()	

Q5.5 How is the formulated WSI **shared and made available** to winter maintenance operators in your state?

- ☐ Through a Maintenance Decision Support System (MDSS)
- ☐ Agency website
- ☐ Specific-use application/software/dashboard
- ☐ Other 1 (please specify) ____________________________
- ☐ Other 2 (please specify) ____________________________
- ☐ Other 3 (please specify) ___________________________

Q5.6 Does your agency have any **published guidelines** on winter maintenance material **application rates** (e.g., recommended tonnage of salt to be applied across a certain stretch of road mile)?

- o Yes (Please specify) _________________________________
- o No (Please specify) ___________________________________

Q5.7 Are these **application rates** enforced on winter service garages and local contractors throughout the state?

- o Yes
- o No (Please briefly explain how application rates are determined. E.g., ad-hoc or driver's judgment) ________________________________

Q5.8 What percentage of your agency's winter material usage, both internally and externally sourced, aligns with **material usage guidelines**?

0 10 20 30 40 50 60 70 80 90 100

Internally sourced ()	
Externally sourced ()	

Q5.9 How does your agency facilitate effective coordination and information exchange with local service providers (e.g., regional garages, contractors, municipalities) to **optimize the utilization** of winter maintenance resources?

____

____

Q5.10 What **feedback** have local service providers provided regarding the benefits and challenges associated with incorporating and utilizing WSI?

____

____

Q5.11 What is your opinion regarding your agency's **current utilization** of a Winter Severity Index (WSI)?

- o Not currently using one and have no plans to use any in the near future
- o Planning to use one in the near future
- o Satisfied with the current use
- o Needs modifications for improvement
- o Its applications can be extended beyond current use cases

---

Q5.12 How do you envision **the future evolution** of the Winter Severity Index (WSI) in your agency's winter maintenance program?

____

Q5.13 From your perspective, how do you foresee **the potential expansion** of the Winter Severity Index (WSI) to encompass material procurement and cost planning within your agency?

____

____

Q5.14 Are there **any other tools or technologies** that your agency is considering to improve your winter maintenance material procurement and cost planning?

____

____

Q5.15 If available, please share any additional **comments or clarifications** regarding any portion of the survey, or winter maintenance practices at your agency in general.

____

____

____

APPENDIX D – MICHIGAN REGIONS BY NOAA

Region	County
WEST UPPER	Baraga Dickinson Gogebic Houghton Iron Keweenaw Marquette Menominee Ontonagon Houghton Garage L'Anse Garage
EAST UPPER	Alger Chippewa Delta Luce Mackinac Schoolcraft Engadine Garage St. Ignace Garage
NORTHWEST LOWER	Antrim Benzie Charlevoix Emmet Grand Traverse Kalkaska Leelanau Manistee Missaukee Wexford Kalkaska Garage
NORTHEAST LOWER	Alcona Alpena Cheboygan Crawford Iosco Montmorency Ogemaw Oscoda Otsego Presque Isle

Region	County
	Roscommon Atlanta Garage Mio Garage
WEST CENTRAL LOWER	Lake Mason Muskegon Newaygo Oceana
CENTRAL LOWER	Clare Gladwin Gratiot Isabella Mecosta Midland Montcalm Osceola Marion Garage Reed City Garage Mt. Pleasant Garage
EAST CENTRAL LOWER	Arenac Bay Huron Saginaw Sanilac Tuscola Saginaw East Side Garage Saginaw West Side Garage
SOUTHWEST LOWER	Allegan Berrien Cass Kalamazoo Kent Ottawa Van Buren Grand Rapids Garage Fennville Garage Plainwell Garage South Haven Garage Coloma Garage Sawyer Garage Niles Garage Jones Garage

Region	County
	Kalamazoo Garage.
SOUTH CENTRAL LOWER	Barry Branch Calhoun Clinton Eaton Hillsdale Ingham Ionia Jackson Shiawassee St Joseph Hastings Garage Grand Ledge Garage Charlotte Garage Williamston Garage Mason Garage Marshall Garage
SOUTHEAST LOWER	Genesee Lapeer Lenawee Livingston Macomb Monroe Oakland St Clair Washtenaw Wayne Port Huron Garage Brighton Garage Detroit Garage. West Monroe Garage East Monroe Garage Adrian Garage

APPENDIX E – HOW TO USE THE MATERIAL COST ESTIMATION EQUATION: AN EXAMPLE

Illustrative Example – West Central Lower Region (January 2022)

To illustrate how Equation 6-3 and the coefficients from Table 6-3 can be applied, assume the calculation of the **estimated material cost** for the "West Central Lower" region in **January 2022**, using the robust regression line and weather features tailored for this region is desired. First, the monthly weather data for the five counties/garages (N=5) within the "West Central Lower" region are obtained from the MDSS WMRI tool and summarized as follows:

West central lower region weather data for Month j (January 2022)

No.	Garage (i)	Pavement Temperature	Hours of Snowfall	Hours of Freezing Rain
1	Lake County	19.37	145	5
2	Mason County	21.37	247	4
3	Muskegon County	23.79	190	3
4	Newaygo County	20.68	119	7
5	Oceana County	20.76	207	4
	Average (N=5)	21.19	181.6	4.6

The equation for the **estimated material cost** ($/lane mile/month) is:

$$\text{Materials Estimated Cost (\$/lane mile/month)} = \text{Intercept} + \beta_1 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Pavement Temperature }_{ij}\right) + \beta_2 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of Snowfall }_{ij}\right) + \beta_3 \times \left(\frac{1}{N}\sum_{i=1}^{N} \text{Hours of Freezing Rain }_{ij}\right)$$

Where:

- β_1 ,β_2 ,and β_3 are the coefficients for the respective variables.
- N is the number of counties in the region.
- i refers to each individual county within the region.
- j represents the month for which the cost is being estimated.

Materials Estimated Cost in Jan 2022= 256.4 – 4.75 × (21.19) + 2.26 × (181.6) + 3.80 × (4.6)
= 583.49 $/lane mile/month