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Quantifying Correlations Between Winter Severity, Road Conditions, and VTrans' Snow and Ice Control Activities: Final Report

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16. Abstract

Season-to-season variability in winter weather and the absence of quantifiable methods for measuring either winter severity or snow and ice control (SIC) performance have made planning and budgeting for SIC activities challenging. Recent research initiatives undertaken by VTrans and other snowbelt DOTs have established objective measures for weather severity and SIC effectiveness, creating the opportunity to quantify the relationships among winter severity, SIC costs, and SIC performance. For this project, the research team utilized these recently established severity measures and VTrans SIC cost data from the MATS database to develop a cost estimation tool that projects expected SIC costs for user-specified winter severity levels. This tool will support VTrans in making data-driven decisions about appropriate levels of investment in SIC for a given winter forecast and potentially improve SIC performance management by comparing current cost-effectiveness to that seen in the historical data. The algorithm used in the tool was based on the strong correlations between SIC costs and AWSSI at the Snow Region level. The tool can be used to estimate SIC cost statewide, regionally, by maintenance district, or by individual VTrans garage. To generate the cost estimates, the tool simulates 10,000 winter seasons matching the user's specification and calculates SIC costs for each simulation.

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Disclaimer

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Table of Contents

List of Tables

List of Figures

Executive Summary

Historically, season-to-season variability in winter weather and the absence of quantifiable methods for measuring either winter severity or snow and ice control (SIC) performance have made planning and budgeting for SIC activities challenging. Recent research initiatives undertaken by VTrans and other snowbelt DOTs have established objective measures for weather severity and SIC effectiveness, creating the opportunity to quantify the relationships among winter severity, SIC costs, and SIC performance. For this project, the research team utilized these recently established severity measures and VTrans SIC cost data to develop a cost estimation tool that projects expected SIC costs for user-specified winter severity levels. This tool will support VTrans in making data-driven decisions about appropriate levels of investment in SIC for a given winter forecast and potentially improve SIC performance management by comparing current cost-effectiveness to that seen in the historical data.

This project is the culmination of prior VTrans research examining methods for quantifying winter severity and SIC performance (Dowds & Sullivan, 2019). That project concluded that the Accumulated Winter Season Severity Index (AWSSI), and variants of this severity measure developed by the Midwestern Regional Climate Center (MRCC), could be an effective tool for quantifying winter severity on a daily basis at locations across the state of Vermont. It also concluded that "Grip," Vaisala's imputed friction metric calculated at road weather information stations (RWIS), was a promising road condition measure that could form the basis for SIC performance measurement. Low Grip measurements coincided with VTrans supervisors' assessment of the need for ongoing SIC activities and showed a strong co-occurrence with crashes and other snow and ice-related incidents. Based on feedback from that project's Technical Advisory Committee (TAC), the final report recommended exploration of the historical relationship between the AWSSI, "Grip," and SIC costs, which has been completed here.

In order to quantify the relationships among winter severity, SIC costs, and SIC performance, the research team acquired SIC cost data from the VTrans MATS database, weather data from NOAA weather stations, and Grip data from VTrans RWIS sites. NOAA weather data were used to calculate daily severity scores based on the AWSSI and two variants of this severity measure, the road AWSSI (rAWSSI) and the precipitation-based AWSSI (pAWSSI). After aggregating cost and severity data into storm events, storm severity (as measured by daily AWSSI scores) and

SIC costs showed a strong, linear relationship with some regional variability across the northwest, northeast, and southern parts of the state as shown in Figure E-1.

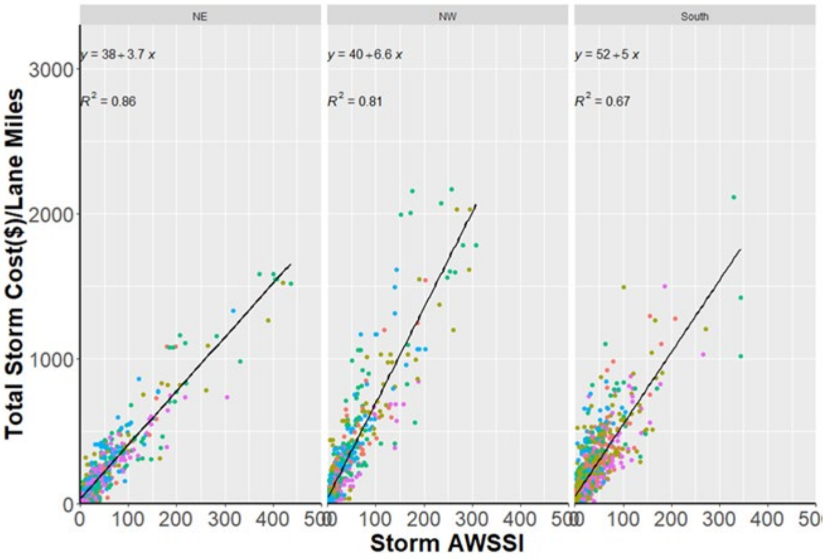

Figure E - 1 Regional linear models for storm-event cost and severity

RWIS Grip data was used to calculate the weighted Grip loss (WGL) for each storm event but variations in WGL did not clearly differentiate among different SIC cost-severity relationships. This is likely indicative of the high level of consistency in VTrans SIC performance as well as homogeneity in the siting of current RWIS stations capable of measuring Grip, most of which are located on Interstates. While WGL could not be incorporated into the cost estimation tool given the limitations of the current dataset, there are indications that it works as a meaningful SIC performance measure. The WGL-severity ratio was closely related to VTrans SIC priority levels. Increased storm severity was positively associated with increased WGL in all regions and for all road priority levels. The correlation was stronger and the slope steeper for lower priority roadways than for higher priority roadways, suggesting that the SIC resources allocated to higher priority roadways can mitigate the impact of storm severity more effectively than can be managed with resources allocated to providing SIC on lower priority roadways. These findings are consistent with the stated goals of VTrans' winter maintenance policy.

The final SIC Cost Estimation Tool was developed based on the strong regional correlations between SIC costs and AWSSI. The tool can be used to estimate SIC cost statewide, regionally, by maintenance district, or by individual VTrans garage. Guided by historical information about the typical number and severity of winter storms for the geographic area of interest, the user can input information about the expected winter severity and get estimates of total and per-lane mile SIC costs for that area. To generate the cost estimates, the tool simulates 10,000 winter seasons matching the user's specification and calculates SIC costs for each simulation. The average costs across all simulations and the 25th and 75th percentile results are reported on the results tab of the tool.

1 Introduction

Historically, season-to-season variability in winter weather and the absence of quantifiable methods for measuring winter severity or snow and ice control (SIC) performance have made planning and budgeting for SIC activities challenging. Recent research by VTrans (Dowds & Sullivan, 2019; Sullivan et al., 2016) and other snowbelt DOTs (Boustead et al., 2015; Jensen et al., 2014; Mewes, 2012; MRCC, 2019) have helped establish objective measures of storm severity and SIC effectiveness, creating the opportunity to quantify relationships among winter severity, SIC costs, and SIC performance. For this project, the research team utilized established severity measures and SIC cost data to develop an estimation tool that forecasts SIC costs for a user-specified winter severity. This tool will support VTrans in making data-driven decisions about budgeting for SIC and potentially improves SIC performance management by comparing current cost-effectiveness to that seen in the historical data.

This project is the culmination of prior VTrans research examining methods for quantifying winter severity and SIC performance (Dowds & Sullivan, 2019). That project concluded that the Accumulated Winter Season Severity Index (AWSSI), and variants of this severity measure developed by the Midwestern Regional Climate Center (MRCC), would be the most effective tool for quantifying winter severity on a daily basis at locations across the state of Vermont. It also concluded that "Grip," Vaisala's imputed friction metric calculated at road weather information stations (RWIS), was a promising road condition measure that could form the basis for SIC performance measurement. Low Grip measurements coincided with VTrans' supervisors' assessments of the need for ongoing SIC activities and showed a strong co-occurrence with crashes due to icy roads and other snow and ice-related incidents. Feedback from the Technical Advisory Committee (TAC) for that project, recommended the exploration of the relationship between the AWSSI, "Grip," and SIC costs, which formed the rationale and scope for this project.

1.1 Report Organization

Section 2 summarizes recent advancements in the measurement of winter severity and SIC performance that were used in this project. Section 3 describes the data sources used in the project. The methods used to calculate SIC performance measures are described in Sections 4 and 5. Section 6 documents the modeling between SIC cost and winter severity as well as an exploration of the relationship of these variables with SIC performance. The SIC cost forecasting tool is described in Section 7.

2 Literature Review

Before beginning data analysis for this project, the research team reviewed the state of the practice of measurement of winter severity and SIC performance. This review built upon previous reviews conducted by this project team in 2016 and 2019 (Sullivan et al., 2016; Dowds & Sullivan, 2019). The purpose of this literature review was to ensure that new developments in these areas since 2019 were not excluded from this project.

2.1 Weather Severity Measures

Through previous reviews, this research team determined that an ideal severity measure for this project would:

- be able to be calculated at many locations across the state,
- have a long historical data record with good accuracy,
- function on both the daily- and season-level, and
- be independent of SIC activities.

Few severity measures satisfy all of these requirements. Some rely on weather variables that are not widely available or are related to SIC activities, like the depth of snow on the road surface. An initial examination of the AWSSI and precipitation-based AWSSI (pAWSSI) suggested that these measures satisfy all of the requirements of this project and would be well-suited to this application (Dowds & Sullivan, 2019). Therefore, the literature review focused on recent updates to these measures. Recent work for Clear Roads (MRCC, 2019) expanded the number of weather stations for which the AWSSI is calculated and continued the calculations nationwide on an ongoing basis[1]. For Vermont, this meant expanding the number of locations from 1 (Burlington) to 2 (Burlington and Rutland). In the process of conducting the expanded calculation, a new extension of the AWSSI was introduced, called the roadway-based AWSSI (rAWSSI), which was designed to correlate more closely with SIC maintenance burden than the original AWSSI (MRCC, 2019). The rAWSSI differs from the AWSSI by excluding days without active snowfall and omitting existing snow depth from the scoring calculation. This variation is intended to be more correlated to SIC activities since it eliminates days that generally do not require SIC. Days without snowfall contribute to the original AWSSI on the basis of temperature and previously accumulated snow depth. The rAWSSI showed a higher correlation with SIC labor-hours in several test states, although the correlation varied considerably by state (MRCC, 2019).

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[1] https://mrcc.illinois.edu/research/awssi/indexAwssi.jsp

A Canadian research group developed a new winter severity index called the Weather Severity Score (WSS) (Matthews et al., 2017). This severity index was developed using daily snowfall, pavement ice warnings (from RWIS), rainfall accumulation at low temperatures, consecutive cold days, and blowing snow (high wind with snowfall). Triggers and thresholds for scoring are created, then tuned to improve their correlation with resource inputs – specifically vehicle-hours of travel of the SIC fleet. Unfortunately, this approach omits the evaluation of objective outcomes, focusing instead on the calibration of the WSS by maximizing its correlation to inputs. Another drawback to this research is that it requires calculation over a 14-day period to maximize the correlation, making it a more useful seasonal index than an event-based one. While this approach is not useful for performance measurement, but the methodology used to develop the WSS may be useful when translated to this project's approach.

Concurrent with this project, researchers at the Western Transportation Institute and National Center for Atmospheric Research completed a white paper that described ongoing challenges with the development and integration of weather severity indices for use by state DOTs (Villwock-Witte et al., 2021). The issues that they identified are similar to those described previously and include data quality and spatial/temporal resolution (especially for road surface data), the difficulty with collecting some SIC-relevant variables such as storm timing, temperature changes during the storm, freezing rain/drizzle, and blowing snow, and the data collection and computational trade-offs between complexity and simplicity.

2.2 SIC Performance Measures

Common outcome-oriented measures for SIC performance measurement include "time-to-normal" measures (traffic speed-based and visually-based), friction measurements, public surveys, and automated visual imagery assessments. This research team previously developed a speed-based "time-to-normal" metric called the average distribution deviation (ADD), which is based on the time needed for the speed distribution of the entire traffic stream to recover after being reduced by a snow and ice event (Sullivan et al., 2016). Public surveys are useful for assessing seasonal performance whereas image-based assessments are more applicable to the measurement of performance during a storm (event-based). "Time-to-normal" measures and friction measurements are useful at all temporal scales (during the storm and at the end of the winter season).

In 2019, the National Cooperative Highway Research Program (NCHRP) issued a report on performance measures for SIC operations (National Academies of Sciences, Engineering, and Medicine, 2019). Much of the material in this report is based on initiatives from 2015 or earlier that had previously been considered by the project team (Dowds & Sullivan, 2019; Sullivan et al., 2016). The NCHRP report's prescribed steps for developing an analytic approach to measuring SIC performance align with the research plan for this project, in that event-specific and seasonal inputs will be compared to calculated performance outcomes and normalized by winter severity to develop winter performance models. The report outlines four key steps involved with SIC performance measurement:

1. Define and use a "weather event" as the starting point for performance measurement
2. Develop both a storm severity (event-based) index and a seasonal severity index
3. Pick a consistent level of service (LOS) and recovery criteria and how they are measured across the agency
4. Report performance

The report notes that effective performance measures need to be easily understood by agency staff and stakeholders and, given data collection limitations, will likely need to be calculated based on only a sample of roadway segments. The report identifies seven components that are necessary for an effective SIC performance measurement program. These components are:

- Ability to distinguish between weather and non-weather event conditions
- Ability to determine LOS before, during, and after an event
- Ability to track materials, labor, and fuel use
- An existing technique to normalize conditions
- Ability to obtain road condition reports
- Ability to collect both weather and road weather observations
- Ability to monitor traffic impacts

The NCHRP report also identified three event-based and four seasonal performance measures. The event-based measures are:

- Percent of time road segments meet agency-defined LOS thresholds during winter storms
- Percent of segments meeting time to regain or recover to acceptable criteria for agency-defined segments after the end of an event
- Percent of trips within the accepted difference between measured travel time index and additional expected travel time index for snow and ice events

The seasonal measures are:

- A five-year rolling average of fatalities and injuries (number, rate) during a winter season
- Customer satisfaction ratings for snow and ice response

- Cost of snow and ice control to meet established performance criteria for a given winter severity
- Agency within the acceptable difference between the expected and actual use of salt and other materials in a season

The data requirements to assess the event-based measures for all segments are not realistic for Vermont, as data about the traffic stream or trip-level travel times are not available for the vast majority of the segments in Vermont's highway system.

Since 2006, FHWA has conducted a periodic assessment of its Road Weather Management Program effectiveness in improving the performance of the transportation system during adverse weather conditions (FHWA, 2019). Assessments of the program were conducted and documented in 2009, 2012, 2015, 2017, and 2019. These updates assess the continued suitability, strengths, and weaknesses of existing measures for the evaluation of program performance. The 2019 assessment provides a useful framework for performance measurement of SIC, in its characterization of inputs (labor-hours, friction materials), outputs (lane-miles plowed, pounds of salt spread, etc.), and *outcomes* (recovery of speed, increase in road surface friction, decrease in traffic crashes, etc.). Although the goal of FHWA's report is assessment, it includes a survey of state DOTs to find out what performance measures are being used and how effective they have been. 40 states responded to the survey, and nearly 50% of those reported using a "winter severity index" to compare SIC performance across events or years, but only about 10% reported evaluating the net benefit of their SIC investments. The focus of this project can be reframed in the language of the FHWA report as the use of performance *outcomes* evaluated against SIC inputs for the purpose of forecasting future SIC inputs (converted to costs) from seasonal expectations for winter weather severity.

Two states make annual reports of winter maintenance program performance available to the public – Minnesota, and Wisconsin (MnDOT, 2019; WisDOT, 2019). Indiana completed reports in 2012 and 2013, but none could be found since 2013.

WisDOT's report is more comprehensive, with a complete discussion of all inputs to SIC, including: materials, equipment, and labor; an investigation of SIC performance, including: response times, times to bare pavement, and crash rates; and a description of the winter weather including total snowfall and a severity index (WisDOT, 2019). WisDOT's Winter Severity Index (WSI) is a seasonal index developed in 1995 that is based on:

- Number of snow events
- Number of freezing rain events
- Total snow amount

- Total storm duration
- Total number of incidents

WisDOT's report also breaks down these figures by County, so that geographic variations are observable and the relationship between winter season severity, resources used, and SIC performance is more evident. WisDOT is able to measure time to bare pavement through the use of its online Winter Storm Report System (https://transportal.cee.wisc.edu/storm-report/documents.html), hosted by the University of Wisconsin Traffic Operations and Safety (TOPS) Laboratory. Time to reach bare pavement for a roadway or a certain class of roadways is self-reported by the SIC district. Crash rates are tracked externally and represent a more objective, though less granular, performance measure. Crash rates are plotted alongside winter severity to investigate their relationship, but no predictive modeling is conducted. Throughout the report, the use of the winter severity index is evident as a consistent normalizing tool for the assessment of SIC performance.

MnDOT produces an 11-page "dashboard" style report with a variety of data tables about SIC inputs and outputs like total lane-miles in the state highway system serviced, friction material (salt, sand, and salt brine) used, monetary costs expended, and labor hours (regular and overtime) (MnDOT, 2019). The report also provides winter severity data including total seasonal snowfall (in inches), number of winter storm events, and a WSI, along with one outcome performance measure – the frequency of achieving 70% bare pavement lanes after a winter storm. It is not clear if MnDOT's WSI is the same as WisDOT's. These data points are reported for the current year and the previous 2-5 years. The report concludes with basic information about how friction materials work and a case study of a difficult storm in February 2019.

2.3 Recommended Measures

The AWSSI continues to be the leading indicator of winter storm events and winter season severity. Therefore, the research team utilized the AWSSI and two variants of this measure, the pAWSSI, and rAWSSI in this project, and created the cost estimation tool using the AWSSI. Grip was utilized for SIC performance measurement for Vermont.

3 Data Acquisition

Large historical datasets are desirable for investigating correlations between winter severity and SIC activities. Fortunately, over a decade of data on winter weather and SIC expenditures were available for this analysis. Roadway condition data, in the form of Grip readings, are available for a limited number of RWIS locations over 5 winter seasons (2016-2017 through 2020-2021). From all sources, data were acquired for the months of November through April to represent each winter season. Data on winter weather, Grip, and SIC expenditures are described below.

3.1 Winter Weather

The AWSSI, pAWSSI, and rAWSSI are calculated from daily records of temperature, precipitation, snowfall, and snow depth (Boustead et al., 2015). National Oceanic and Atmosphere Administration (NOAA) weather stations provide the longest and most comprehensive continuous data history for these variables. Though the locations of NOAA weather stations do not correspond directly with the locations where Grip and SIC expenditures are measured in Vermont, they are frequently used in the calculation of severity indices because of their reliability and broad geographic distribution.

A total of 27 NOAA stations in Vermont collect the data required to calculate the AWSSI family of severity measures. In order to compensate for the relative sparsity of weather stations in southern Vermont, four additional NOAA stations (one each in New York and Massachusetts, and two in New Hampshire) were also identified and included in the dataset, bringing the total number of stations used to 31. The locations of these NOAA stations are shown in Figure 1.

Daily summary data from all 31 of these NOAA stations were downloaded from November 2011 through April 2021. In total, this produced over 50,000 daily weather records.

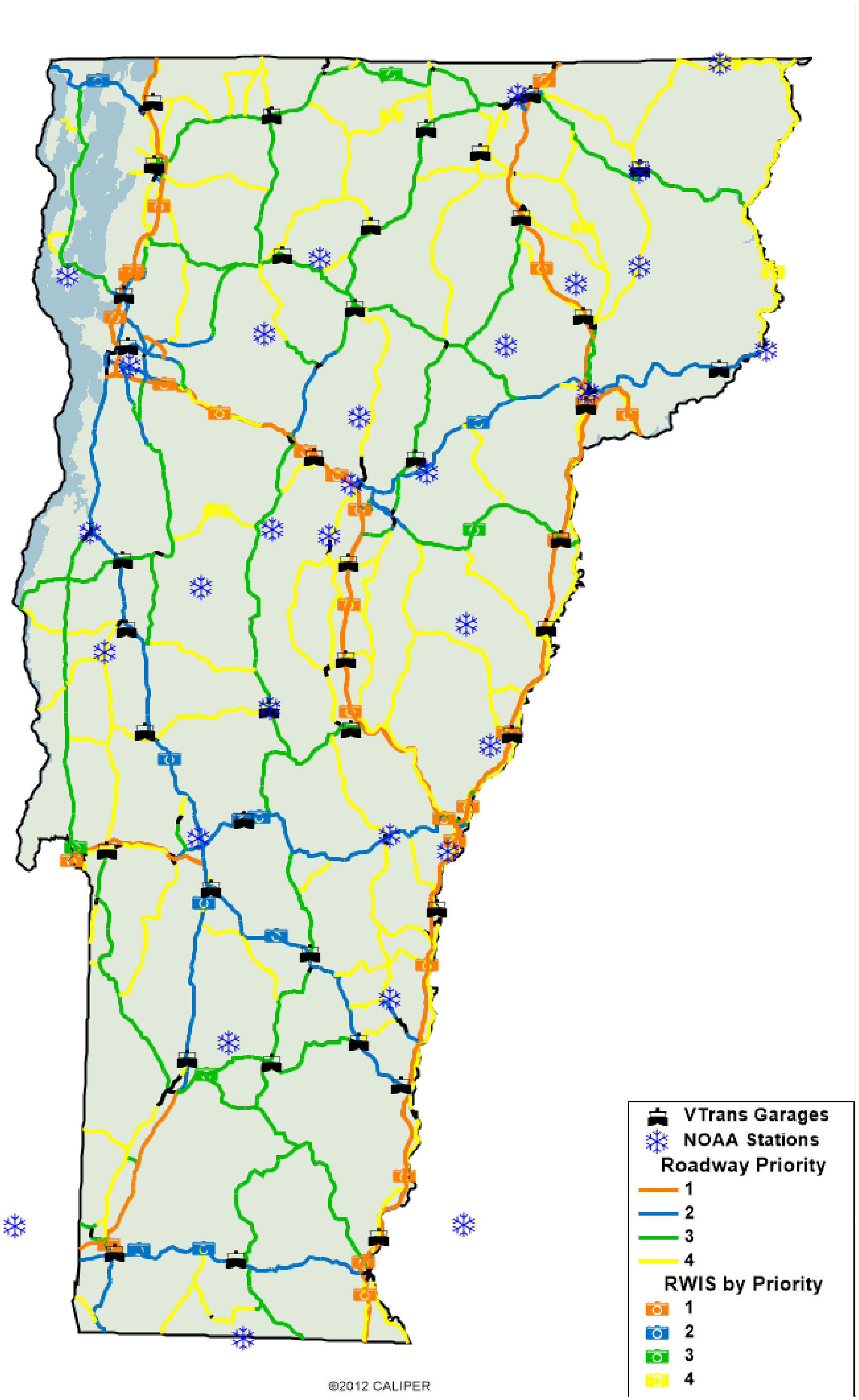

Figure 1 Locations of RWIS and NOAA weather stations in Vermont

3.2 Grip

The RWIS stations used by VTrans can be equipped to calculate Grip, a proxy for surface friction calculated from the estimated thickness of water, snow, and ice on the road surface. Grip is measured on a scale from 0.00 – 0.82 and values below 0.60 are considered to indicate compromised road surface conditions (Jensen et al., 2013). Reduced Grip is correlated with the need for additional SIC activities and with adverse safety outcomes when vehicle speeds are not reduced appropriately (Dowds & Sullivan, 2019). Because it is an objective measure of road surface conditions, Grip is well suited for SIC performance measurement.

VTrans has rapidly increased the number of RWIS stations that collect data needed to calculate Grip. In 2016-2017, 20 RWIS stations were equipped to collect the data needed to calculate Grip in either 10- or 15-minute increments. Currently, 44 RWIS stations allow the calculation of Grip. The locations of these RWIS stations are shown in Figure 1. The project team downloaded and processed 1,011 months of Grip data available across 44 sites for the five winter seasons from November 2016 through April 2021. Grip data availability by RWIS station is shown in Table 1.

3.3 SIC Expenditures

SIC costs data were exported from the VTrans *Managing Assets for Transportation Systems* (MATS) database. The MATS database records daily labor, equipment usage, and material application in physical units (hours of labor/equipment, tons of material) and monetary costs at the garage and route level, for a variety of activities undertaken by maintenance crews, including SIC. The locations of the VTrans garages where SIC costs were available are shown in Figure 1. SIC route length and total length of routes each garage is responsible for are also included, enabling the calculation of SIC activity expenditures per lane-mile in each garage's service territory. SIC activity is tracked separately for "snow and ice control activities" and for "supporting winter maintenance" activities. The dataset for this project includes 78,440 garage-level records from November 2011 through April 2021 and additional route-level records for each route that passes an RWIS station. All SIC costs described in this report have been converted into dollars per lane-mile of responsibility to allow for the comparison of costs across VTrans garages that are responsible for clearing different lengths of roadway.

Table 1 Grip Data Availability

RWIS Site	Months of Grip Data by Season					
	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	Total
Brookfield Guardian	6	6	6	6	6	30
I-89 Berlin	6	6	6	6	5	29
I-89 Bethel	0	5	6	6	6	23
I-89 Bolton	6	6	6	5	6	29
I-89 Brookfield	0	5	6	6	6	23
I-89 Colchester	0	6	6	6	6	24
I-89 Georgia	6	6	6	6	6	30
I-89 Hartford	5	6	6	6	6	29
I-89 Middlesex	0	6	6	6	6	24
I-89 Milton	0	0	6	6	6	18
I-89 Milton Bridge	0	6	6	3	6	21
I-89 Waterbury	0	5	6	6	3	20
I-89 Williston	6	6	6	6	6	30
I-91 Brattleboro	0	6	6	5	6	23
I-91 Derby	0	0	6	6	6	18
I-91 Guilford	5	6	6	6	6	29
I-91 Hartford	0	0	0	6	6	12
I-91 Newbury	5	6	3	6	6	26
I-91 Sheffield	0	4	6	6	6	22
I-91 St Johnsbury	4	6	6	6	6	28
I-91 Thetford	6	6	6	6	6	30
I-91 Weathersfield	0	0	0	6	6	12
I-91 Westminster	6	6	6	6	6	30
I-91 Wilder	0	6	6	6	6	24
VT-103 Mt Holly	6	6	6	3	6	27
VT-105 Jay	5	6	6	6	6	29
VT-11 Winhall	5	6	6	5	6	28
VT-17 Buels Gore	6	6	6	6	6	30
VT-22A Fairhaven	6	6	6	6	6	30
VT-242 Westfield	0	0	0	6	5	11
VT-279 Bennington	0	0	6	6	6	18
VT-302 Topsham	0	0	6	6	6	18
US-4 Fair Haven	0	0	6	6	6	18
US-4 Mendon	0	5	6	6	6	23
US-4 Mendon Mtn	0	6	6	6	6	24
VT-5A Westmore	0	0	6	6	6	18
US-7 Brandon	0	5	6	6	6	23
US-7 Clarendon	6	6	6	6	6	30
VT-78 Alburgh	6	6	6	6	6	30
VT-9 Woodford	5	6	0	6	6	23
US-2 Cabot	5	6	6	6	6	29
VT-102 Maidstone	0	0	0	0	6	6
VT-114 Canaan	0	0	0	0	6	6
VT-9 Searsburg	0	0	0	0	6	6
Total	**111**	**185**	**219**	**237**	**259**	**1011**

4 Calculation of AWSSI Weather Severity Measures

The AWSSI is calculated using a daily scoring system, summarized in Table 2, which assigns points based on the high and low temperatures for the day as well as the snowfall and snow depth on that day.

Table 2 AWSSI Scoring System

Points	Daily High Temperature Range		Daily Low Temperature Range		Daily Snowfall Range		Current Snow Depth Range	
	From	To	From	To	From	To	From	To
0	33 and above		33 and above		0	0.1	0	1
1	25	33	25	33	0.1	1	1	2
2	20	25	20	25	1	2	2	3
3	15	20	15	20	2	3	3	4
4	10	15	10	15	3	4	4	6
5	5	10	5	10			6	9
6	0	5	0	5	4	5	9	12
7	-5	0	-5	0	5	6	12	15
8	-10	-5	-10	-5			15	18
9	-15	-10	-15	-10	6	7	18	24
10	-20	-15	-20	-15	7	8	24	36
11			-25	-20				
12					8	9		
13					9	10		
14					10	12		
15	-20 and below		-35	-25			36	
18					12	15		
20			-35 and below					
22					15	18		
26					18	24		
36					24	30		
45					30			

As an illustrative example, a day with a high temperature of 30°F (1 point), a low temperature of 18°F (3 points), 2.5 inches of snowfall (3 points), and 4.5 inches of snow depth (4 points) would have a daily score of 11 points. The pAWSSI differs from the AWSSI in that it uses a snowfall equivalent calculated using liquid precipitation rather than a direct measurement of snowfall. As a result, it captures at least some of the impact of freezing rain which is not well captured by the original AWSSI. Once precipitation-based snowfall and snow depth values are calculated, it uses the same point system as the AWSSI. For the rAWSSI, points are only scored on days with active snowfall, and the snow depth points are omitted from the scoring calculation. This variant is intended to be more closely correlated with SIC control activities since it eliminates the impact of cold days with existing snow depth that generally do not require SIC but which otherwise increase the AWSSI. The AWSSI, pAWSSI, or rAWSSI on any given day is the cumulative sum of daily scores up to that day in the current winter season. The final seasonal scores for the AWSSI, pAWSSI, and rAWSSI, then, are the sum of all daily scores across the entire winter season. These measures are intended to represent the cumulative effects of the winter precipitation since snow and ice events become more challenging as storm events accumulate through the winter.

To support the calculation of the pAWSSI, precipitation-based snowfall and snow depth values were calculated for all records in the NOAA dataset using the formulas provided in Boustead et. al (2015). Thereafter, the appropriate point values were assigned for high and low temperatures, snowfall, and snow depth. Daily scores for the three AWSSI severity measures are then calculated by summing the appropriate point values for each variable. Individual daily scores (rather than accumulated scores) are used in this study. A sample of the daily dataset is shown in Table 3 at the end of this section.

As shown in Figure 2, the three AWSSI variants provide relatively stable winter severity rankings but they do vary in some instances.

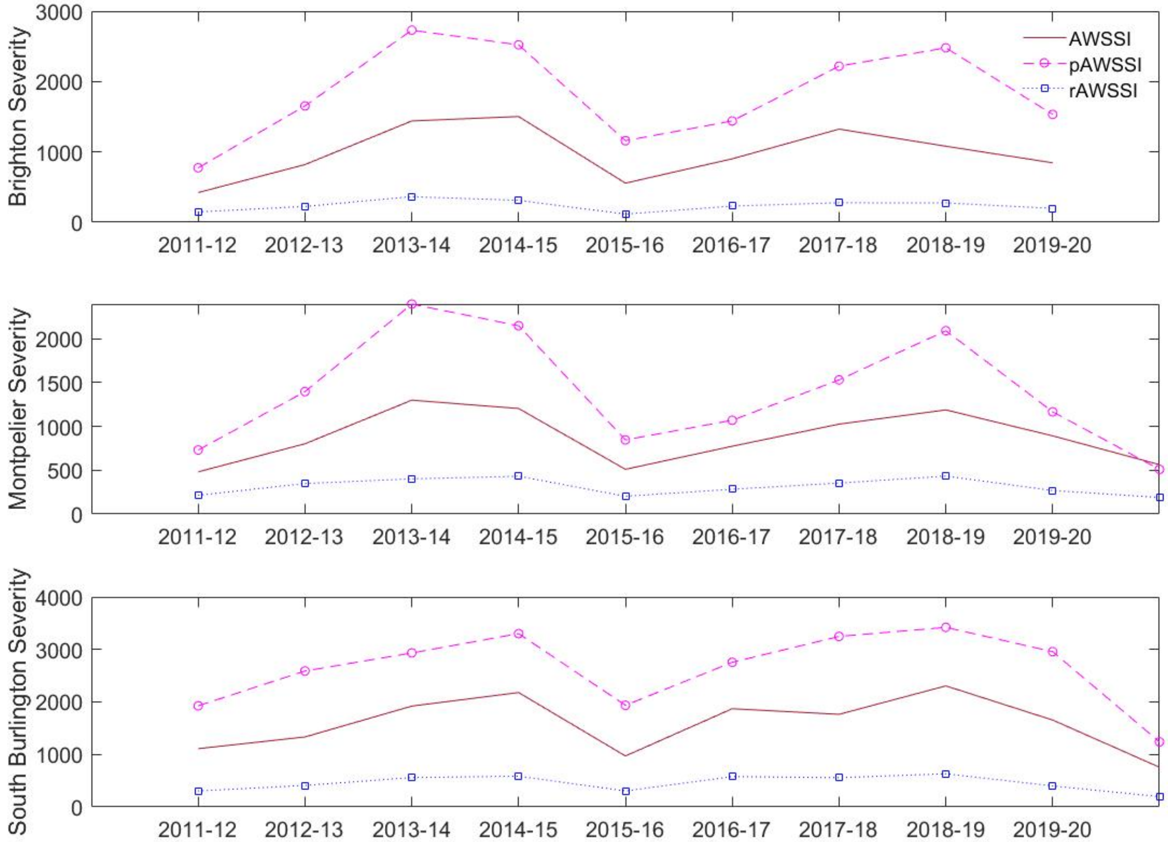

Figure 2 Illustration of AWSSI, pAWSSI, and rAWSSI at three sites

In Brighton, for example, the AWSSI score for the 2014-15 season is higher than that for 2013-14 while the opposite is true for both the pAWSSI and rAWSSI. In Montpelier, the AWSSI and rAWSSI both rank 2016-2017 as more severe than 2017-2018 while the pAWSSI ranks 2017-2018 as more severe. As expected, the rAWSSI is always lower than the AWSSI and pAWSSI because rAWSSI points only accumulated on days with active snowfall whereas AWSSI and pAWSSI points will still accumulate based on daily temperature and snow depth variables even when there is no new snowfall. Because the final winter severity dataset includes all three AWSSI variants, correlation testing was conducted for each of these severity measures.

Table 3 Weather severity calculations for South Lincoln* VT Jan. 14-28, 2012

Day	NOAA Weather Data					Precipitation-Based…		Severity Measure Score Points						Daily Score to Support the…		
	Prcp	Snw	Dpth	TMax	TMin	pSnw	pDpth	Snw	Dpth	TMax	TMin	pSnw	pDpth	AWSSI	pAWSSI	rAWSSI
1/14	0.33	6.8	7	41	14	4.68	5.47	9	5	0	4	6	4	18	14	13
1/15	0	0.1	7	14	0	0.00	9.97	1	5	4	6	0	6	16	16	11
1/16	0	0	7	8	-7	0.00	15.59	0	5	5	8	0	8	18	21	0
1/17	0.01	0.1	6	30	-6	0.19	18.53	1	5	1	8	1	9	15	19	10
1/18	0.21	0	2	44	25	0.48	16.11	0	2	0	1	1	8	3	10	0
1/19	0	0	2	25	3	0.00	18.36	0	2	1	6	0	9	9	16	0
1/20	0.03	1.2	3	26	3	0.48	20.95	2	3	1	6	1	9	12	17	9
1/21	0	0	3	22	5	0.00	23.33	0	3	2	5	0	9	10	16	0
1/22	0.06	0.7	4	19	0	0.98	27.64	1	4	3	6	1	10	14	20	10
1/23	0	0	4	36	1	0.00	28.77	0	4	0	6	0	10	10	16	0
1/24	0.16	0	0	49	36	-0.17	23.73	0	0	0	0	0	9	0	9	0
1/25	0	0	0	42	30	0.00	20.48	0	0	0	1	0	9	1	10	0
1/26	0	0	0	30	25	0.00	19.35	0	0	1	1	0	9	2	11	0
1/27	0.2	0.6	0	37	25	1.28	18.59	1	0	0	1	2	9	2	12	2
1/28	0.64	0	0	48	31	1.64	16.04	0	0	0	1	2	8	1	11	0

*NOAA Station USC00473612

5 Calculation of SIC Performance Measures

Grip measurements provide an objective assessment of road surface conditions that can be used in the calculation of SIC performance measurements. To assess SIC performance, an important first step is to normalize the base measurement to reflect the varying conditions. Creating a severity-adjusted performance measure from Grip requires two steps – aggregating the instantaneous Grip measure over time to create an aggregated Grip loss and then adjusting this aggregated performance measure by the storm severity over the aggregation period.

To aggregate Grip loss readings in their performance measure, Idaho DOT calculates the number of hours with Grip below 0.60, effectively creating a binary compromised/uncompromised road condition variable that varies only in duration. While this provides some insight into the effectiveness of SIC activities, failing to differentiate among degrees of Grip loss reduces the information conveyed by the performance measure. SIC activities that manage to maintain Grip at 0.50 for 2 hours, for example, are not distinguished from those that allow Grip to fall to 0.20 for 2 hours. For this project, the research team calculated a weighted-Grip loss (WGL) that combines an indication of the amount of time Grip was compromised with the extent to which it was compromised.

The calculation of the WGL was initiated whenever Grip values fell below 0.60, the threshold for compromised road conditions suggested by Idaho DOT and Vaisala in Jensen et al. (2014). To calculate WGL, Grip was first converted to Grip loss by subtracting the Grip reading from the 0.60 threshold. This raw Grip loss was then scaled from 0 to 1 and multiplied (weighted) by the continuous duration of the Grip loss reading. The individual WGL values calculated from each Grip reading were then summed into a total WGL for each storm event. This calculation combines an indication of the amount of time Grip was compromised with the extent to which it was compromised. WGL was calculated at the 44 RWIS locations shown in Figure 1. WGL provides an unadjusted performance measure that does not consider storm severity while the ratio of WGL to storm severity provides a severity-adjusted SIC performance measure.

6 SIC Cost and Winter Severity Relationship

Analysis of the cost-severity relationship focused on identifying the spatial and temporal scales that produced the strongest correlation between historical winter severity and SIC cost data. With the optimal spatial and temporal scale, cost models could be developed for use in the SIC cost estimation tool. As outlined above, severity was measured using the AWSSI, the pAWSSI, and the rAWSSI. The correlation between cost and severity was modeled for each of the severity measures at multiple spatial and temporal scales. The research team also explored whether controlling for differences in SIC performance improved the ability to predict SIC cost but ultimately determined that it did not.

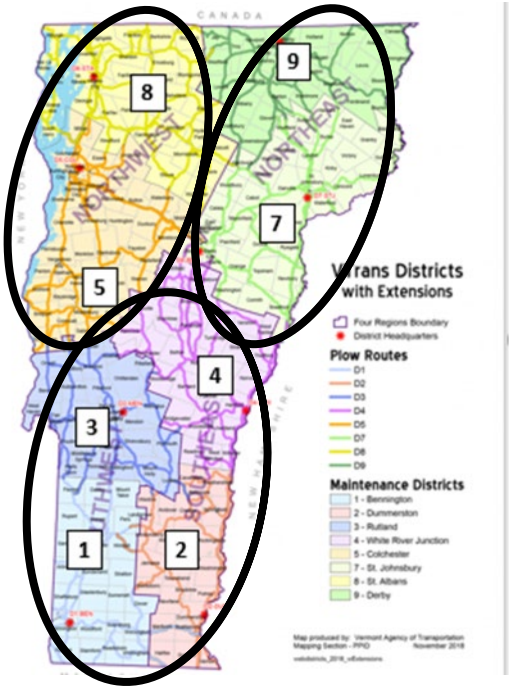

Figure 3 VTrans Maintenance Districts with Snow Regions Circled

To account for varying spatial scales, the team modeled the relationship between SIC cost and winter severity on the individual garage-level and the district level, then aggregated the models to one of three new "snow regions", defined by Districts 5 and 8 (Northwest), 7 and 9 (Northeast), and 1 through 4 (South) (Figure 3) [2]. The snow regions are geographically isolated from one another by natural features in the landscape. These snow regions turned out to be similar to typical climatological zones in Vermont defined for other purposes, like Plant Hardiness (Figure 4).

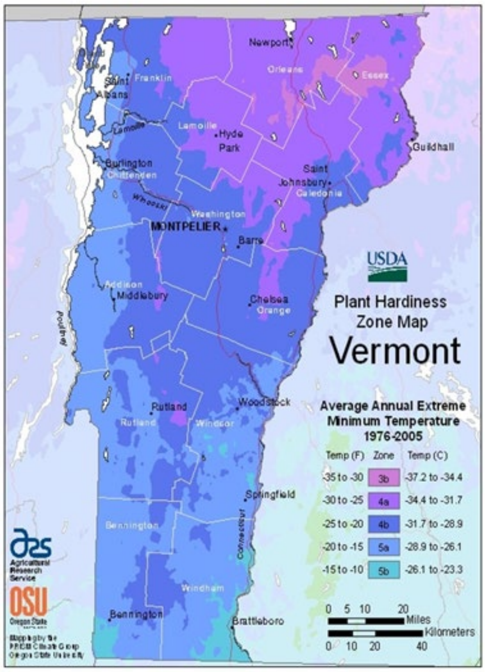

Figure 4 Vermont Plant Hardiness Zones

Consistent with the expectation that SIC is costlier when winter weather is more severe, the team found a positive correlation between SIC cost and all three of the AWSSI-related severity measures through linear modeling. The strength

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[2] Note that the district boundaries used in this analysis are those documented the VTrans 2020 Fact Book and Annual Report, rather than the revised boundaries that include a separate service territory for District 6.

of the linear models was assessed at multiple temporal (seasonally, daily, and by "storm event") and spatial (state-level, by maintenance garage, by district, and by snow region) resolutions using the models R-squared values.

Across these different temporal and spatial resolutions, the original AWSSI consistently showed the strongest model fit. This finding was somewhat surprising since pAWSSI is intended to capture some of the impacts of freezing rain and the rAWSSI was developed specifically to better measure the winter severity experienced by SIC providers by discounting daily severity scores for days with no measurable precipitation. So, the team expected these improved measures of severity to more strongly correlate to SIC costs.

Discussions with a member of the development team behind the pAWSSI from the Midwest Regional Climate Center (MRCC) suggested that regional calibration of the pAWSSI was important to its accuracy and that the published equations for the pAWSSI might not be well suited to Vermont. If the pAWSSI were calibrated specifically for Vermont, it might outperform that AWSSI as a predictor of SIC costs. The "storm-event" temporal scale used in the final analysis with the AWSSI provides a direct means of filtering out daily severity scores that are unrelated to SIC so this approach eliminates the need for the adjustment made by the rAWSSI. This explains why the rAWSSI was not found to correlate more strongly than the AWSSI in the linear modeling. Therefore, the AWSSI was used in all further linear modeling due to its superior correlation with SIC costs.

The team initially considered an inverse exponential model in our analysis because it fit our hypothesized relationship between SIC costs and severity. The team anticipated that SIC cost would rise somewhat linearly with increasing severity but then plateau, once SIC resources were fully deployed, and increasing SIC resource utilization further was not possible. The inverse exponential function provides the "plateau" the team expected to exist after an initial linear relationship (Figure 5).

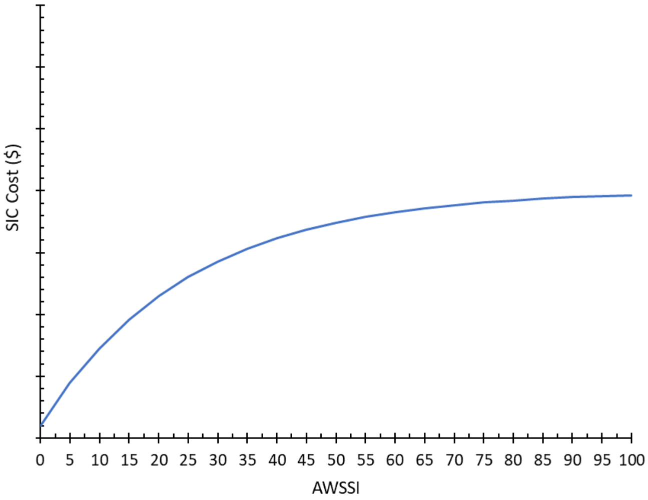

Figure 5 Expected model of the relationship between AWSSI and SIC Cost

However, when this functional form was fit to the data, the best-fit parameters continually stretched the function back to a linear model. Every attempt to fit an inverse exponential fell short of the fit quality that was revealed by a simple linear model. In retrospect, this can be expected from the fact that our theory is that the right edge of the curve would form a plateau because each garage or district has a limited amount of resources to put into action, so there is a theoretical "cap" to SIC costs, beyond which increasing AWSSI would not correspond to increased SIC costs. Before that point, we expected that a linear relationship is likely. However, the theoretical "plateau" on the right edge of the curve represents an extreme condition that may only rarely be experienced by a garage or district. Therefore, our data sets did not include enough points in this theoretical "plateau" for the inverse exponential to fit. Therefore, the best functional form for this analysis continued to be the linear model, since the domain of this analysis is confined to the more linear portion of the theoretical curve, toward the left in Figure 5. Therefore, the team used linear models exclusively in this analysis.

6.1 Temporal Scale Analysis

The correlation between severity and SIC costs was initially analyzed at the seasonal and daily levels. The seasonal analysis included cost and severity measurements for 40 VTrans "parent" garages for the 10 winter seasons from 2011-2012 through 2020-2021. These 400 data points are shown in Figure 6, color-coded by winter season.

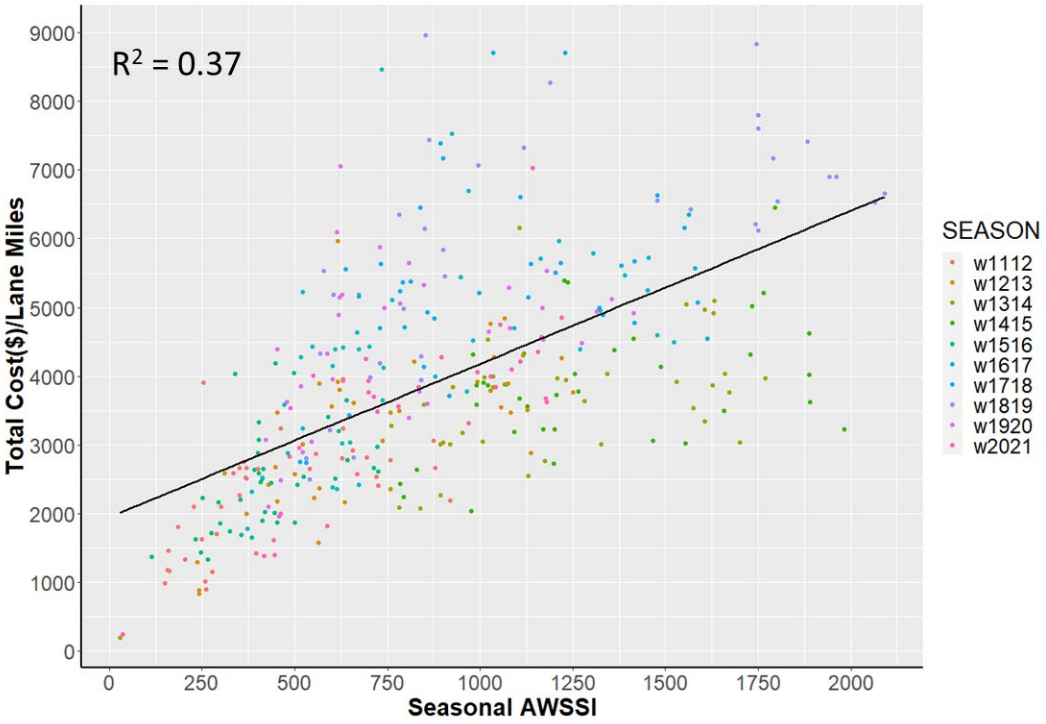

Figure 6 State-level linear model for seasonal SIC cost and severity

The daily analysis included 181 costs and severity measurements for each winter season (representing every day from November 1 through April 30) for the same 40 VTrans garages, for a total of approximately 72,000 data points. Both the seasonal and daily models showed a positive correlation between cost and severity but these correlations were relatively weak. The R^2 for the seasonal analysis was 0.37 (see Figure 4) while the R^2 for the daily analysis was just 0.09.

The correlation between cost and severity is reduced at both of these temporal levels due to the accrual of AWSSI scores related to temperature and existing snow depth on days with no precipitation. As a result, many days have an AWSSI score that is greater than zero but do not have any SIC costs (or snowfall). The daily correlation is further reduced by the inconsistency between the discrete, daily severity scoring and the continuous nature of SIC activities, which are responsive to current and forecasted weather conditions rather than the time of day. For example, pre-treatment incurs costs before a storm begins and potentially on a different day than the one when the majority of the AWSSI score for that storm is accrued. Additionally, moving salt or restaging equipment between garages can take place on days with minimal or no severity score. To address these issues the research team converted both cost and severity data from daily values to aggregated values over multi-day "storm events."

For this analysis, storm events were defined as consecutive days with SIC material application costs in the MATS database.[3] Once storm events had been identified from the MATS data, daily SIC costs and daily AWSSI scores were summed for each storm event to create an aggregated cost and severity for that event. The dataset of aggregated storm events across the 40 VTrans garages consisted of approximately 9,300 points.

Grouping the severity and cost data into storm events was expected to increase the correlation between these variables for several reasons. First, this approach eliminates days without SIC activity from the dataset. This is desirable since daily AWSSI scores can be relatively high on these days because of existing snow depth or extreme cold, even when these factors are not affecting the SIC that is required on that day. In this respect, the aggregation of the data to the storm event increases the similarity between the AWSSI and rAWSSI. Second, while the daily AWSSI score is a discrete, 24-hour measure, the calendar day is not a meaningful division for winter weather. The SIC response to winter weather follows the weather patterns more than it follows calendar days. For example, a storm that begins late on a Monday night and continues into the early hours of Tuesday may accrue

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[3] In some cases, this approach may group small, independent storm events that occur on consecutive days into a single, larger storm event. Give the strong linear relationship between cost and severity, this occurrence is unlikely to meaningfully skew the relationship be cost and severity at the storm event level.

AWSSI points primarily on Monday but SIC costs may accrue primarily on Tuesday. In this case, aggregating the storm event to include both Monday and Tuesday would produce a more accurate relationship between the storm and its attendant SIC response. Third, SIC can include pre-treatment, general support, and clean-up activities that do not necessarily occur on the same day as the majority of the snowfall, creating a misalignment between cost and severity on the daily level. Finally, multi-day storms may also have higher costs because of overtime and other factors.

For these reasons, the storm-event grouping was expected to better align SIC costs with the winter weather causing them. At the level of the storm event, the R^2 between SIC costs and severity jumped to 0.74, as shown in Figure 7.

Figure 7 State-level linear model for storm-event SIC cost and severity

Figure 7 also illustrates the suitability of the linear model to this analysis. We anticipated that the full relationship between SIC cost and AWSSI would include a plateau at higher AWSSI scores (above 400). However, the figure illustrates well how few points we have in the region where we would expect this plateau to exist. This lack of observations in the plateau region means that the best fit function to the data is always going to be linear, reflecting the preponderance of observations to the left on the plot, where relatively frequent but minor storms incur correspondingly low SIC costs.

6.2 Spatial Scale Analysis

All spatial-resolution analyses were conducted at the temporal level of the storm event. The state-level analysis used in the initial modeling showed a positive correlation between SIC costs and winter severity (Figure 7). However, regional differences in winter weather patterns across the state suggest that the relationship between cost and severity is likely to vary across the state. For example, cost-severity relationships in Rochester, Mendon, and Ludlow tended to fall above the linear model shown in Figure 7, whereas these relationships in Lyndon, Barton, and Brighton tended to fall below the linear model. Consequently, developing models at higher resolutions stood to improve the correlation between cost and severity and to facilitate SIC cost projections that capture regional variations in winter severity. For the spatial-resolution analyses, the relationship between cost and severity was examined at the garage level, the maintenance district level, and the level of the newly developed snow regions. These substate-level analyses can discern differences in the cost-effectiveness of SIC performance.

Garage-level analysis continued to show strong linear relationships between storm-event cost and severity, with R² values ranging from 0.50 to 0.91 (Figure 8).

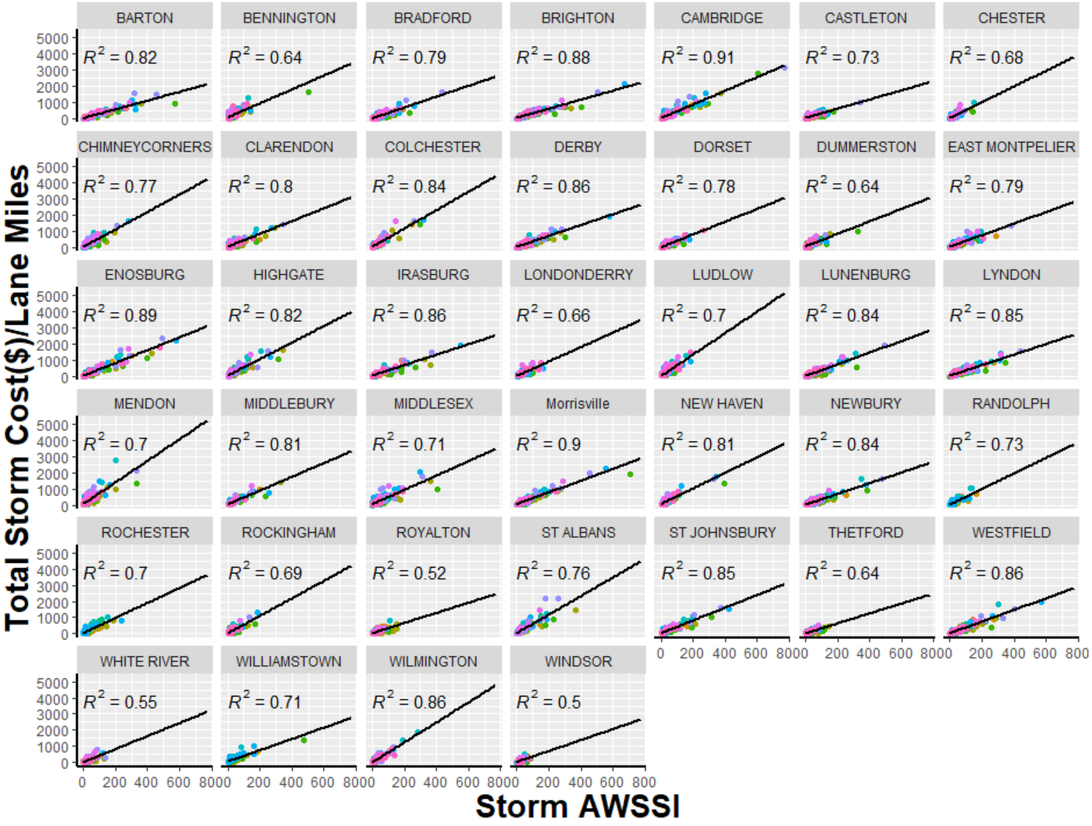

Figure 8 Garage-level linear models for storm-event cost and severity

The slopes of the linear models for each garage were considered to be potential indicators of performance. SIC costs at garages with higher slopes increase more rapidly as severity worsens than at garages with lower slopes. A lower slope would indicate that increasing storm severities were being managed with smaller cost increases and would be preferable, assuming that VTrans SIC standards are being met in all cases. Visually, it can be seen in Figure 8 that slopes differed from garage to garage, with higher slopes in the northwest part of the state (e.g., Colchester, Chimney Corners), and lower slopes in the northeast (e.g., Brighton, Bradford, Newbury).

The strength of the model fit (indicated by the R^2) tended to be lower for garages in the southern part of the state, potentially reflecting shortcomings in the AWSSI at capturing the impacts of freezing rain on SIC costs. NOAA weather stations in Vermont are also sparser in the southern part of the state so the local weather conditions may not be captured as accurately as they are in other parts of the state (see Figure 1).

Variability in the distances between garages and NOAA stations as well as differences in SIC practices and resources among garages may result in garage-level linear models at some garages that are not representative of the underlying relationship between SIC cost and severity. To address these potential issues with the garage-level analysis, the storm-event data were grouped at the maintenance district level and re-modeled. The R^2 at the district level ranged from 0.64 to 0.88 (Figure 9).

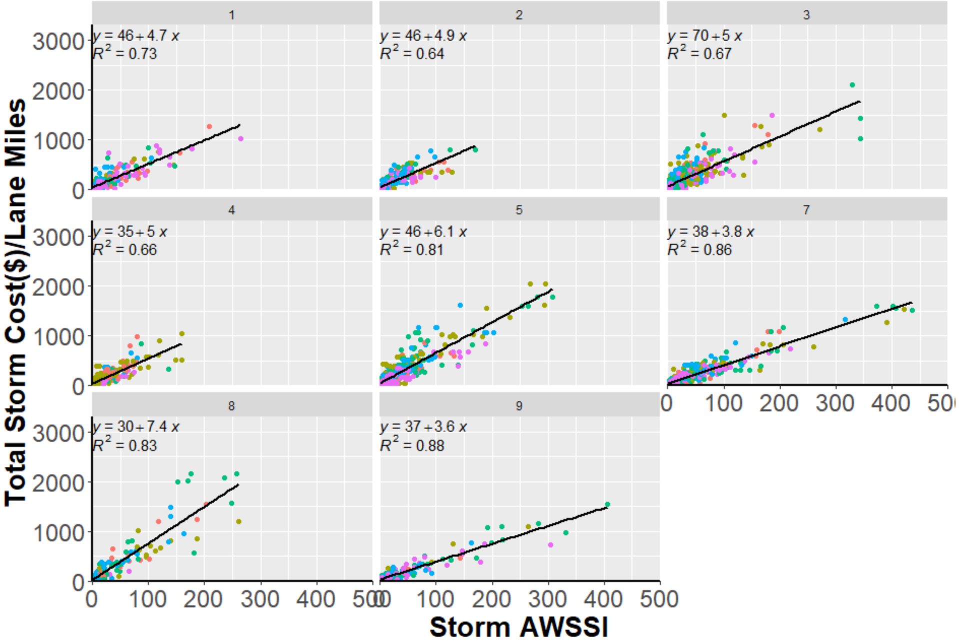

Figure 9 District-level linear models for storm-event cost and severity

The resulting slopes of the linear models were very similar for Districts 5 and 8, Districts 7 and 9, and Districts 1 through 4. The strength of these geographic differences led the team to consider the slopes of the linear models as classifiers instead of performance measures.

With this in mind, the team undertook a cluster analysis of the cost/severity ratios (a proxy for the slope of a linear model with one point) for each of the individual storm events shown in Figure 7. Clustering was conducted using the k-means methodology to group the cost/severity observations into 2, 3, and 4 clusters. For each of the cluster groupings, the cost/severity ratios tended to cluster regionally rather than by any grouping that would indicate meaningful differences in performance. Table 4 shows the average cluster assigned to the storm events in each District in the 4-cluster analysis, color-coded by their relative rank. The clustering results were consistent with the patterns observed in the district-level linear models, with apparent similarities between Districts 1 through 4, Districts 5 and 8, and Districts 7 and 9. In addition, it appeared that these geographic differences in the slopes of the linear models were due primarily to fundamental climatological differences that either (1) made SIC more or less challenging to conduct with available resources, and/or (2) made the AWSSI more or less effective as a measure of winter storm severity. On this basis, the team decided to use three "snow regions" to create the final linear models implemented in the cost estimation tool. The final linear models for the three snow regions are shown in Figure 10.

Table 4 Average cluster by district for the 4-cluster analysis

District	Avg Cluster
1	1.4
2	1.5
3	1.6
4	1.5
5	1.6
7	1.2
8	1.6
9	1.2

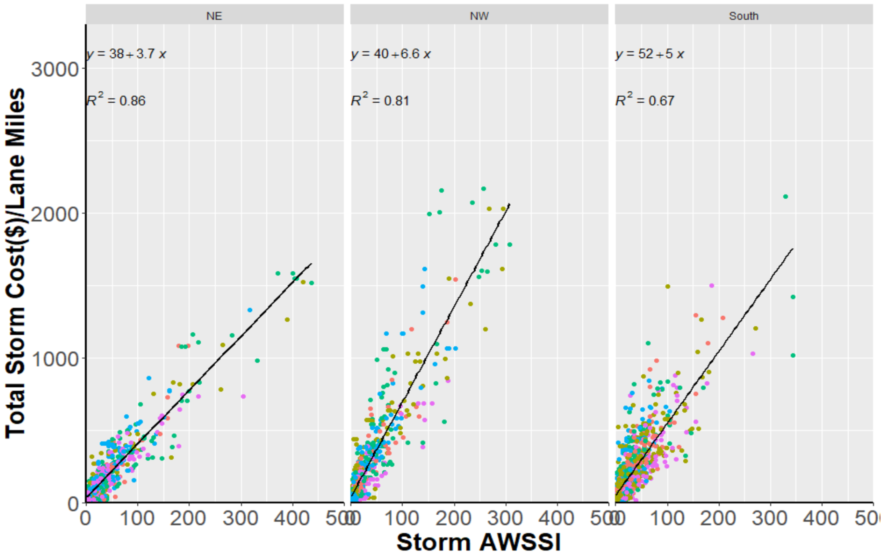

Figure 10 Regional linear models for storm-event cost and severity

6.3 Stratifying SIC Costs by SIC Performance

Once the temporal and spatial resolutions for the linear cost-severity models had been finalized, the research team examined the potential to stratify the data by SIC performance, as measured by the severity-adjusted WGL. A k-means cluster analysis was employed to group storm events into two and four clusters by their severity-adjusted SIC performance. Clusters characterized by lower WGL-severity ratios are indicative of better SIC performance since the magnitude of Grip loss is lower for any given storm severity. The highest-performing group (cluster 1) included 77% of observations in the four-cluster analysis and 95% of observations in the two-cluster analysis, indicating a consistently high level of performance.

Once the clustering process was completed, storm events were stratified by performance cluster from the 4-cluster analysis, and new linear cost-severity models were created for each cluster in each snow region. These linear cost-severity models are shown in Figure 11, with individual storm events color-coded according to their WGL-severity performance cluster.

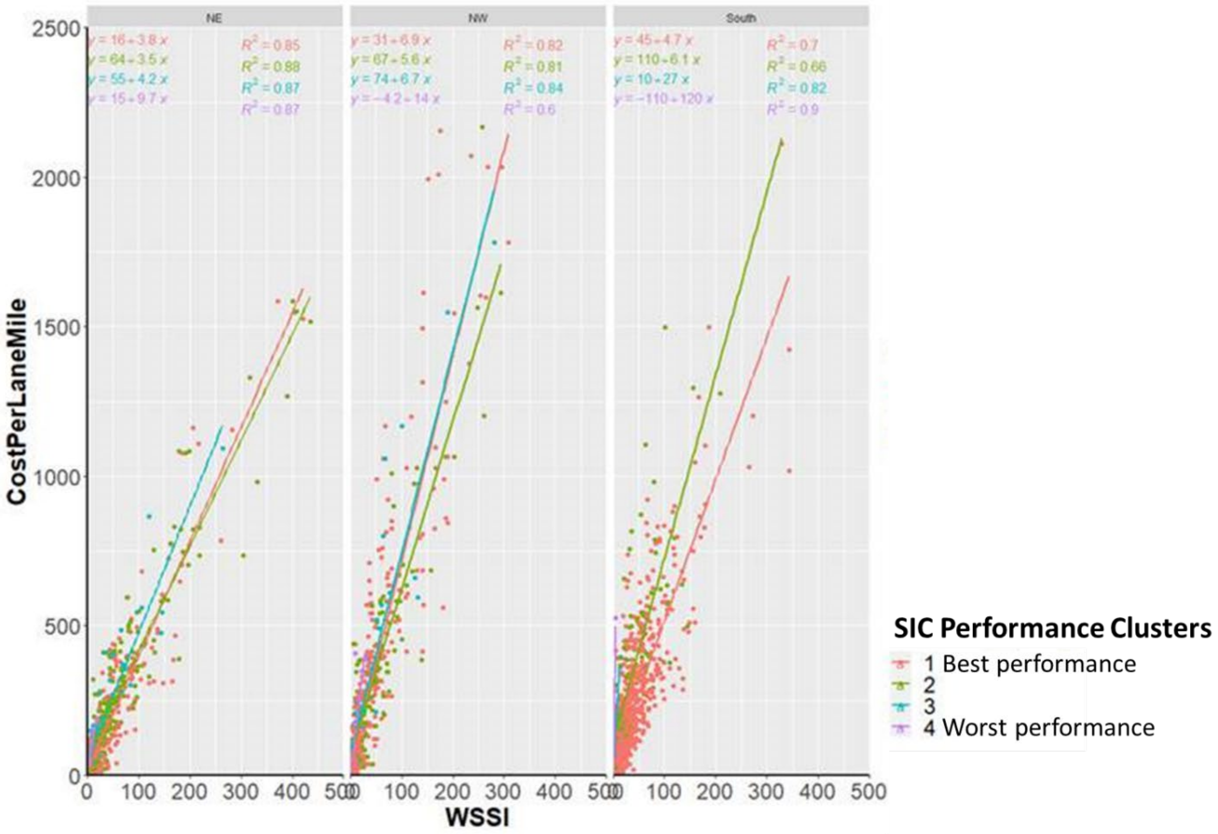

Figure 11 Regional linear models for storm-event cost and severity, grouped by SIC performance

As shown in Figure 11, some of the linear models remain very similar across clusters. The linear models for clusters 1, 2, and 3 in both the NE and NW snow regions and for clusters 1 and 2 in the S snow region are similarly aligned. This indicates that performance, as measured by the severity-adjusted WGL, does not meaningfully distinguish between different cost-severity relationships. We would expect linear models for better-performing clusters to have higher slopes than lower-performing clusters, reflecting a higher-intensity resource utilization achieving superior SIC performance. However, the linear models did not consistently show the expected relationship between cost and performance. In fact, the expected relationship was frequently reversed, with higher-performing clusters appearing also to show a lower-intensity resource utilization and therefore to be more efficient from a cost perspective as well. This lack of clear and consistent cost differentiation by the level of SIC performance likely reflects that there is only limited variability in VTrans SIC performance within the entire dataset, as indicated by the share of storm events assigned to the top-performing cluster for both the four and two cluster analyses.

This consistency across the state is likely indicative of homogeneity in the siting of current RWIS stations capable of measuring Grip, as well as the use of consistent, well-communicated performance standards by VTrans. As shown in Figure 1, most of the RWIS stations are located on Interstates, which are assigned Priority 1. SIC priority levels are established for each roadway in the VTrans Snow and Ice Control Plan (VTrans, 2020). These priorities are based on winter traffic volumes, roadway functional classification, and expected truck traffic. Priority 1 roadways are given the highest level of attention for SIC, with the goal of reaching bare pavement as soon as practical after the storm has subsided. Priority 4 roadways, on the other hand, are given the lowest level of attention, with the goal of reaching 1/3 bare pavement on the next regular working day after the storm has subsided.

Clusters with lower performance and higher cost intensity, such as cluster 3 in the NE snow region and cluster 2 in the S snow region, could be the result of inherent differences in the difficulty of maintaining certain roads, SIC practices that are simultaneously costlier and less effective, or simply limitations in the resolution of the cost and NOAA datasets in these regions. However, the sample size for these clusters is too small to differentiate among these factors. Given the limited size of the dataset and the strong regional relationships between cost and severity, stratifying by SIC performance using the adjusted WGL was not deemed to be useful for improving the ability to estimate SIC costs.

While WGL could not be incorporated into the cost estimation tool given the limitation of the current dataset, the project does provide indications that it is a meaningful SIC performance measure. The WGL-severity ratio, or the adjusted

WGL, was closely related to VTrans SIC priority levels. The relationship between WGL and storm severity by road priority level and region is shown in Figure 12. Increased storm severity is positively associated with increased WGL in all regions and for all road priority levels. But the model fit for this correlation is stronger and the slope steeper for lower priority roadways than for higher priority roadways. This pattern is consistent with the goals in VTrans winter maintenance policy and suggests that the SIC resources allocated to higher priority roadways mitigate the impact of storm severity more effectively than on lower priority roadways.

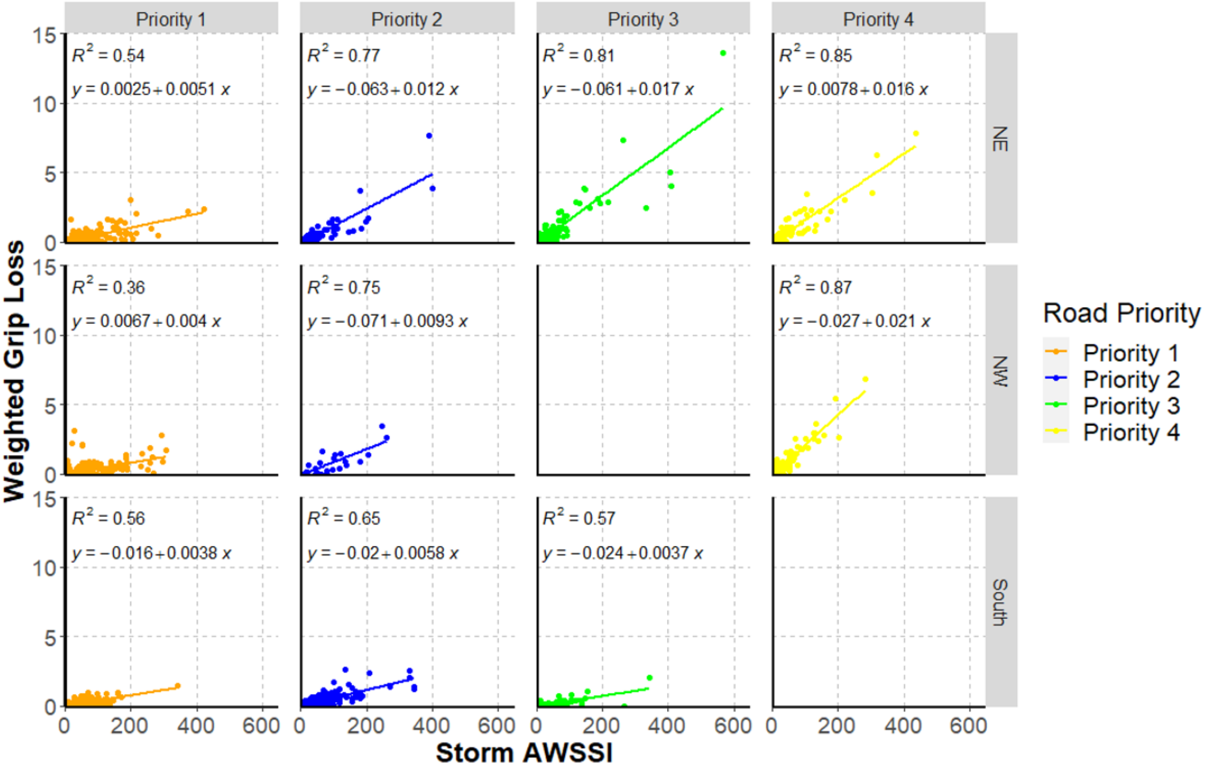

Figure 12 Weighted Grip Loss versus Storm Severity

7 Description of SIC Cost Estimation Tool

The final SIC Cost Estimation Tool was developed based on the strong linear correlations between SIC costs and AWSSI at the snow regions and is implemented in Microsoft Excel using the Visual Basic for Applications (VBA) scripting platform. The tool can be used to estimate SIC cost statewide, regionally, by maintenance district, or by individual VTrans garage with the severity-cost models yielded by the snow region analysis. Guided by historical information about the typical number and severity of winter storms for the selected geographic area of interest, the user can input information about an expected winter severity and get estimates of total and per-lane mile SIC costs for that area. To generate cost estimates, the tool simulates 10,000 winter seasons matching the user's specifications and calculates SIC costs for each simulation. The average costs across all simulations and the 25th and 75th percentile results are reported.

Cost estimates are provided in total and on a "per-lane-mile" basis. Cost estimates include an added expansion factor to capture costs that are not directly attributable to a storm severity, including staff bonuses, administrator time, and salt transfers between storms.

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