



A Report from the University of Vermont Transportation Research Center

**Snow and Ice Control Performance
Measurement: Comparing “Grip,” Traffic
Speed Distributions and Safety Outcomes
During Winter Storms**

Final Report

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16. Abstract Effective performance measurement provides benchmarking for transportation agencies to promote transparency, accountability, cost-effectiveness, and process improvement. Vaisala's proprietary "Grip" measure provides an imputed measure of the condition of the road surface (Jensen et al., 2014). VTrans' Average Distribution Deviation (ADD) measures changes in the distribution of vehicle speeds during and after winter weather events (Sullivan et al., 2016). The algorithm for the calculation of Grip was reverse-engineered from Road Weather Information System (RWIS) data over the winters of 2016-2017 and 2017-2018. The resulting algorithm is consistent with research connecting snow, water and ice layer thicknesses to skidding friction. ADD and Grip were found to be relatively poorly correlated, indicating that each measure is independently useful and one cannot be used as a proxy for the other. In fact, the exploration revealed that instances when ADD and Grip diverge maybe especially useful for signaling high-risk situations, or situations when the traveling public is not correctly perceiving the road surface conditions. Finally, a review of winter storm and season severity indices concluded that the precipitation-based Accumulated Winter Season Severity Index was appropriate for use in Vermont because it was well calibrated, captured key factors influencing winter maintenance activities and calculated from data that are readily available across the state.			
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Executive Summary

Effective performance measurement provides benchmarking for transportation agencies to promote transparency, accountability, cost-effectiveness, and process improvement. Road surface conditions and vehicle speeds capture important factors that influence mobility and traveler safety during and after a winter storm event. Vaisala's proprietary "Grip" measure provides an imputed measure of the condition of the road surface (Jensen et al., 2014). VTrans' Average Distribution Deviation (ADD) measures changes in the distribution of vehicle speeds during and after winter weather events, capturing the traveling public's response to their perception of road surface conditions (Sullivan et al., 2016). The objectives of this project were to gain a better understanding of the derivation of the Grip metric, the correlation between Grip and traffic speeds under different winter weather conditions, and the relationship among Grip, speed and crashes. The goal is to further advance a comprehensive performance measurement system that is consistent with the state's Snow and Ice Control Plan target of providing "safe roads at safe speeds."

Review of Winter Severity Indices

RSIC performance measures should reflect storm and winter severity. More time and resources are required to recover from a severe storm than from a mild one and this needs to be reflected in RSIC performance measurement. This is best accomplished by normalizing performance measures using a storm or seasonal severity index. An ideal severity index would well calibrated, capture key factors influencing RSIC activities – such as storm duration, temperature and precipitation dynamics – and use data that are readily available across the state.

The Accumulated Winter Season Severity Index (AWSSI) and a variant of this index that corrects for common snowfall measurement errors, known as the precipitation-based AWSSI (pAWSSI), perform well on all three of these criteria. The AWSSI was developed to address the lack of a daily/seasonal measurement of winter severity that uses widely available climatological data and that can be scaled for objective comparisons between geographies and over time (Boustead et al., 2015). The data that are required to calculate the both the AWSSI and the pAWSSI – temperature, precipitation, snowfall and accumulated snow depth on the ground – are widely available at NOAA weather stations. The AWSSI/pAWSSI scoring system is capable of characterizing daily weather event as well as accumulating these daily

measurements throughout the winter, resulting in a seasonal rating at the end of the winter. Currently, the pAWSSI can be calculated at 27 weather stations throughout Vermont. Figure E-1 charts the season-long accumulation of the pAWSSI for each of these 27 stations for the 2017-2018 winter season.

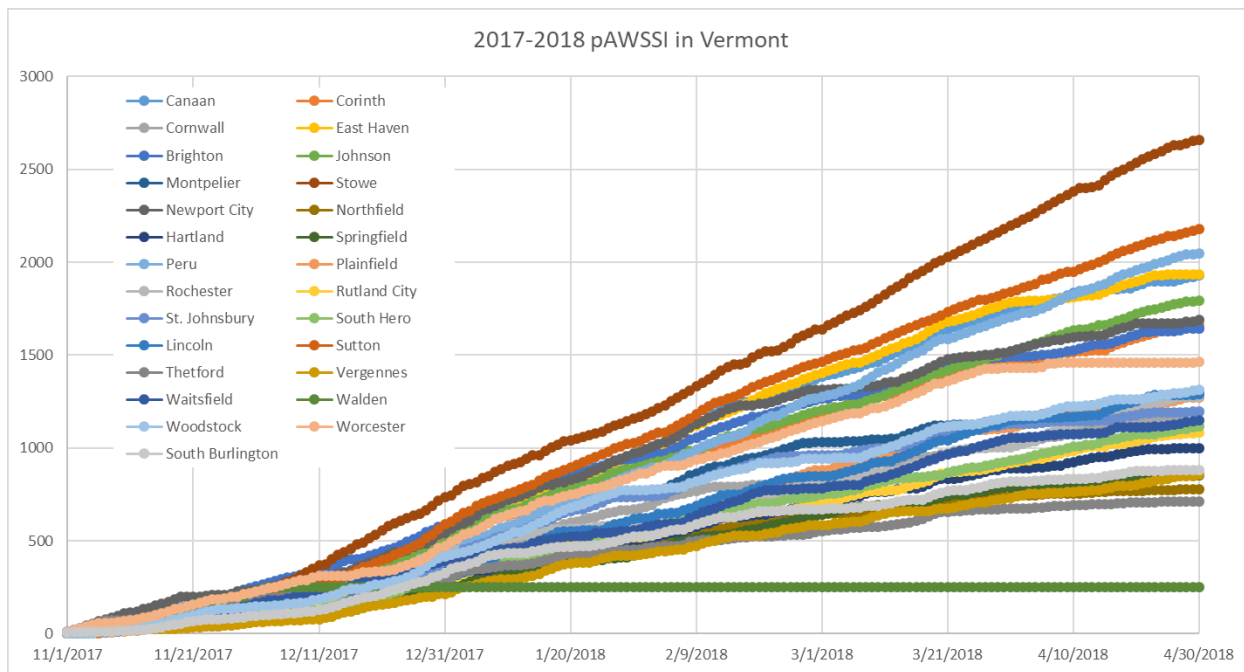


Figure E-1 Winter Severity as Measured by pAWSSI

Several other severity indices created by Vaisala (Jensen et al, 2013), Meridian Environmental Technology (Mewes, 2012), researchers at the University of Iowa (Nixon and Qiu, 2005), and the National Weather Service were also examined. Ultimately these indices were found to either exclude key storm parameters, exhibit calibration issues, or to be too data intensive for use across the state.

Analysis of Grip

Vaisala’s “Grip” measure is a proxy for friction that is imputed based on weather and road surface variables collected at RWIS station. The calculation method for Grip is proprietary. To better understand Grip and establish a level of confidence in this measure, the research team conduct a literature review on the development of Grip and used two winters of RWIS data to reverse-engineer the formulas and steps used to calculate Grip.

This process resulted in a series of conditional formulas for Grip that depend on the surface temperature, and layer thickness of water, snow and ice. A final algorithm with 4 decision points and 3 separate sub-models was deduced with a fit (R-squared) to the real Grip loss data for 2016-2017 of 0.96. The same algorithm and functions were then applied to the 2017-2018 data and the resulting R-squared was again 0.96.

Coefficients for each of the 3 sub-models were optimized to minimize the sum of the squared differences between the model Grip loss and the real Grip loss data. The Grip calculation decision process is shown in Figure E-2 and the corresponding sub-model formulas in Table E-1.

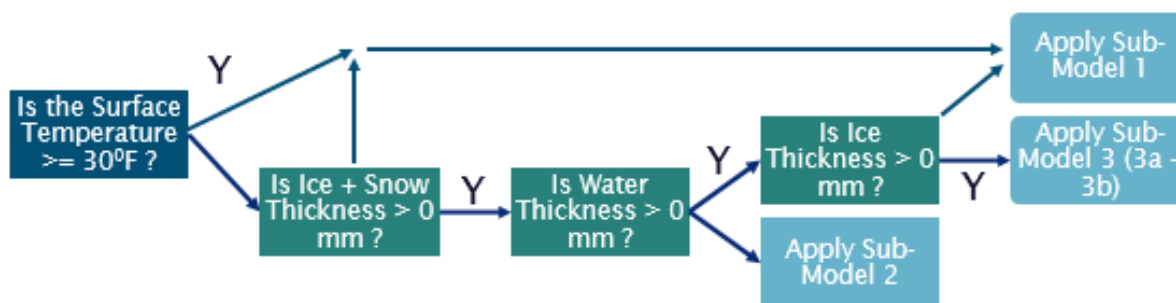


Figure E-2 Reverse-Engineered Algorithm for Calculation of Grip Loss

Table E-1 Reverse-Engineered Grip Loss Calculation Formulas

	Functional Form	a	b	x (in mm)
Sub-Model 1	ax^b	0.15	0.44	water
Sub-Model 2	$a\ln(x) + b$	0.11	0.64	snow + ice
Sub-Model 3a	ax^b	0.58	0.20	ice
Sub-Model 3b	$a\ln(x) + b$	0.05	0.22	water

Grip Threshold Validation

The performance measurement procedure developed by the Idaho Transportation Department (ITD) and Vaisala uses a Grip value of 0.6 as a threshold to indicate whether or not road conditions are compromised. In order to assess whether or not this threshold was appropriate for use in Vermont, the research team created a simple survey App to facilitate a comparison between measured Grip values and assessments of road conditions conducted by VTrans supervisors.

There was a moderate positive correlation (0.67) between Grip and supervisor-assessed road conditions. In all cases where Grip was below 0.6, the supervisors assessed that additional snow and ice control was required, consistent with the ITD/Vaisala threshold. However, the supervisors also determined that additional RSIC activities were required in 10 instances where Grip was greater than or equal to 0.6. In most instance, the apparent discrepancy between the level Grip threshold, which indicated adequate road conditions relative to a threshold of 0.6, and the assessed need for additional RSIC operations reflected supervisors' knowledge of forecasted weather conditions. Grip does not provide the comprehensive view of road and storm conditions that VTrans personnel utilize to make RSIC decisions but provides a snap-shot of road surface conditions at a particular point in time. Given this, it is likely that for many of these instances the Grip readings correctly indicated that road friction was adequate at that point in time. More extensive data collection would help to reinforce the validity of the 0.6 Grip threshold.

Comparison of Grip, Speed, and Crashes

During winter weather events, drivers are expected to reduce their travel speeds in response to adverse driving conditions. If drivers reliably reduced their speeds in slick conditions, there would be a very high correlation between ADD and loss of Grip, potentially indicating that Grip and ADD could be used interchangeably for performance measurement. The overall correlation between Grip and ADD is relatively modest, however, indicating that the ADD does not accurately capture road surface conditions. When Grip is very compromised, the ADD is generally large but there are a number of observed cases where the ADD is within the normal range when Grip is low, showing that driving speeds have not changed substantially even though the roads are very slick.

Since the response of the traveling public is not always consistent with Vermont's "safe roads and safe speeds" policy, circumstance where speeds are not reduced (or not sufficiently reduced) in response to road conditions, can create increased accident risk. Therefore, situations in which the traffic stream is not reacting to the road surface conditions (as indicated by Grip loss) as expected may be indications of increased risk to drivers. An increased occurrence of adverse safety outcome in these circumstances would confirm that this increased risk is present.

To assess whether or not disparities between ADD and Grip do in fact capture periods of greater risk for the traveling public, the frequency of

adverse safety outcomes was compared for days which included a disparity between these two measures and for days that without such a disparity. Adverse safety outcomes were measured using crashes and state police dispatches associated with snow and ice. For RWIS stations with Grip and traffic data, the research team identified instances where Grip fell below 0.6 but the ADD remained within normal levels. Days during which this occurred were termed disparity-days (Ddays). To determine if these adverse safety outcomes were over-represented on Ddays, the two data sets were overlaid geographically to identify crashes and incidents that were near an RWIS site with a Dday. “Nearness” was considered to be within a mile of the RWIS site on the same roadway where the RWIS station was measuring road conditions. Then, this proximate set of crashes and incidents were combed to determine which, if any, occurred on the same date as the Dday. If both of these conditions were satisfied, then the Dday was determined to have had an adverse safety outcome. The difference between the percent of Ddays with an adverse safety outcome and the percent of non-Ddays with an adverse safety outcome might be an indicator that Ddays have some predictive power for adverse safety outcomes.

A second way of identifying the predictive power of these Ddays is to measure the difference between Ddays with an adverse safety outcome and those without in the set of adverse safety outcomes (crashes + incidents). In the winters of 2016-2017 and 2017-2018, there were a total of 70 and 55 adverse outcomes near RWIS sites with Grip, respectively. Of these, 21% (or 15) and 49% (or 27) occurred on Ddays.

Taken together, these two measures support the tendency of adverse safety outcomes to occur on Ddays, although not supported by statistical testing. The locations in Vermont with the most frequent occurrences of Ddays were the Fair Haven, Bolton, and Brookfield RWIS sites. Locations with occurrences of Ddays which also exhibit relatively frequent adverse safety outcomes are Berlin, Bolton, Brookfield, and Hartford – all along the I-89 corridor between Burlington and the border with New Hampshire.

Conclusions

One of the primary outcomes of this research is a comprehensive evaluation of RSIC performance measures for Vermont, especially those that are reported in the Vaisala RWIS data reports. The imputed Grip measure showed great promise for use in RSIC performance measurement but the severity index currently include in the portal has significant drawback relative to other indices, especially the pAWSSI.

Two significant findings of this research support the usefulness and effectiveness of the Grip measure for RSIC performance measurement. First, the algorithm for the calculation of Grip was reverse-engineered from the RWIS data over the winters of 2016-2017 and 2017-2018. The resulting algorithm is consistent with research connecting these layer thicknesses to skidding friction. The algorithm includes consideration of thicknesses of ice, snow, and water on the road surface, as well as the surface temperature. Therefore, the Grip measure seems to be the best proxy for skidding friction, with loss of Grip exhibiting dangerous conditions on the roadway. Second, the Grip threshold of 0.6 was validated with supervisor assessment of the need for RSIC and Grip values less than 0.6 corresponded to on-going RSIC activities. Where the two diverged, a plausible explanation was always found. For example, the reports of a supervisor who is dispatching RSIC vehicles to pre-treat a roadway in advance of a storm or in advance of a temperature drop will not correlate well with the Grip readings at that time, but that does not mean that either indicator is erroneous.

Once its effectiveness had been established, the relationship between Grip and speed was explored to better understand their correlation. The team used the ADD to explore this correlation. The ADD and Grip were found to be relatively poorly correlated (0.60), indicating that each measure is independently useful and one cannot be used as a proxy for the other. In fact, the exploration revealed that instances when ADD and Grip diverge maybe especially useful for signaling high-risk situations, or situations when the traveling public is not correctly perceiving the road surface conditions. In other words, these divergences can indicate one of two situations:

1. Grip has been compromised but the traffic stream has not responded by generally decreasing speeds
2. Grip is sufficient but the traffic stream has slowed as if it has been compromised

The second scenario is unlikely to represent a safety risk and the team found that unmeasured outcomes like visibility and traffic congestion could contribute to these results. The first situation is particularly troubling, however, since it indicates potentially increased risk from adverse safety outcomes. These discrepancies between ADD and Grip, identified as “Ddays” in this research, show a strong co-occurrence with crashes and other snow and ice-related incidents, increasing the risk of one of these adverse outcomes by 3-4 times. However, this conclusion is based on a very limited set of data for the winters of 2016-2017 and 2017-2018, so more research is needed to support this conclusion.

If the ADD-Grip discrepancies can be used to predict crashes, then this finding could be extremely useful for winter traffic safety in Vermont. For

example, a programmable message board, linked to the real-time calculation of the ADD-Grip discrepancy, can be used to communicate poor Grip situations, with special urgency added when the ADD is indicating that current speeds are not safe. This research also supports the use of variable speed limits that are responsive to real-time reports of Grip and ADD.

RSIC performance measurement includes benchmarking measures of effectiveness with measures of winter storm and season severity. To that end, a series of winter storm and season severity indices were reviewed for their effectiveness and applicability to Vermont. Of these, the pAWSSI was found to be effective, based on sound research, applicable to Vermont, and relying on easily obtainable data. In addition, although the pAWSSI was developed as a seasonal measure of winter severity, its daily updating algorithm makes it an effective indicator of storm-specific conditions. The MRCC currently calculates the AWSSI for two locations in Vermont. However, these locations are not sufficient to capture the significant local variation in winter storm trends across Vermont. Therefore, the research team recommends the use and expansion of the pAWSSI in Vermont.

Future research should include the development of a web-based tool, similar to the one developed by MRCC, to calculate the pAWSSI at all 27 locations in Vermont on a daily basis, with real-time updates. This step would allow supervisors and decision-makers to benchmark RSIC performance in real-time, evaluating storm-specific performance as well as seasonal performance.

Summary of Recommendations

- The pAWSSI can become an effective tool for real-time (daily) reporting of winter severity statewide (27 locations) with a web-based calculator
- Grip seems to be a useful proxy for road surface friction, exhibiting a strong tendency to indicate dangerous conditions on the roadway
- Grip and ADD are correlated but not highly enough to be used as direct proxies for one another
- In fact, discrepancies between ADD and Grip co-occur with crashes, but more study is needed to support this conclusion, due to the limited amount of data available
- These ADD-Grip discrepancies may be capable of predicting high-risk winter weather conditions in real time, and could be a trigger for some type of response, and/or coordinated with a message board to communicate to drivers
- Consequently, this research supports the use of variable speed limit signs that are responsive to Grip and ADD

1 Introduction

Effective performance measurement provides benchmarking for transportation agencies to promote transparency, accountability, cost-effectiveness, and process improvement. The Maintenance Bureau at the Vermont Agency of Transportation (VTrans) is working to implement objective performance measures to evaluate and improve its winter maintenance activities. As of the winter of 2016 – 2017, the Bureau has explored both speed-based and road-surface-based performance measures to measure progress of roadway snow and ice control (RSIC) activities.

As part of this effort, VTrans obtains performance measures originally developed by the Idaho Transportation Department (ITD) and implemented in partnership with Vaisala at its RWIS stations (Jensen, 2013). These measures include the proprietary “Grip” measure calculated from the thickness of ice, water and snow on the road every 15 minutes. They also include a Severity Index (SI) calculated from wind speed, precipitation accumulation, and road surface temperature, a Winter Performance Index, and a Mobility Index calculated for continuous sequences of 15-minute data (see Figure 1).

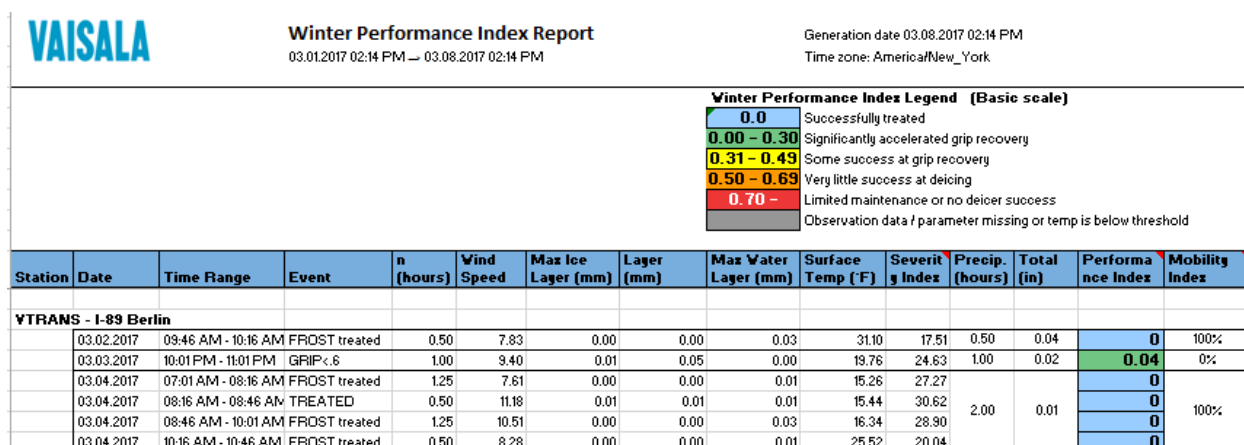


Figure 1 Vaisala Winter Performance Index Report

The ITD/Vaisala performance measures are promising because they rely on measured weather and road surface condition variables that are directly related to the need for RSIC activities. Additional validation of these methods in the Vermont would increase confidence in these measures and lead to methodological improvements for application in Vermont.

Potential issues with the ITD/Vaisala methods include the black-box imputation of measures like Grip, which makes validation difficult. In

addition, the following relationships between Grip and road conditions were observed in Idaho (Jensen et al., 2014):

- >0.6 usually dry (or wet) surface
- 0.5 to 0.6 slush or ice forming
- 0.4 to 0.5 snow pack or icy
- 0.3 to 0.4 icy - vehicles may start sliding off
- <0.3 icy - multiple vehicle slide offs possible; mobility greatly affected

Validation of these thresholds, and especially of the impact on roadway safety, is needed to relate Grip to VTrans' "safe roads at safe speeds" goal. Finally, the Vaisala SSI may not be suitable for all storm conditions. The surface temperature component of the SI is so heavily weighted in the formula that VTrans personnel report it overstates the severity of low-temperature storms. It includes surface precipitation accumulation, a variable which is directly affected by RSIC treatment, so the SI value for a given storm would likely change once the route was serviced. A better severity index would reflect storm conditions independently of the conditions on the road at the RWIS station.

In previous research, VTrans explored the use of measured speed distributions before, during, and after a winter storm to measure RSIC performance (Figure 2). The Average Distribution Deviation (ADD) measure changes in the distribution of vehicle speeds during and after winter weather events. ADD can be used as the basis for a speed-based performance measure that calculates the time it takes from the onset of a winter storm to return vehicle speeds to pre-storm "normal" conditions. This measure relies on the distribution of speeds in the traffic stream as an indicator of the road surface conditions.

Grip and ADD each capture important factors that influence

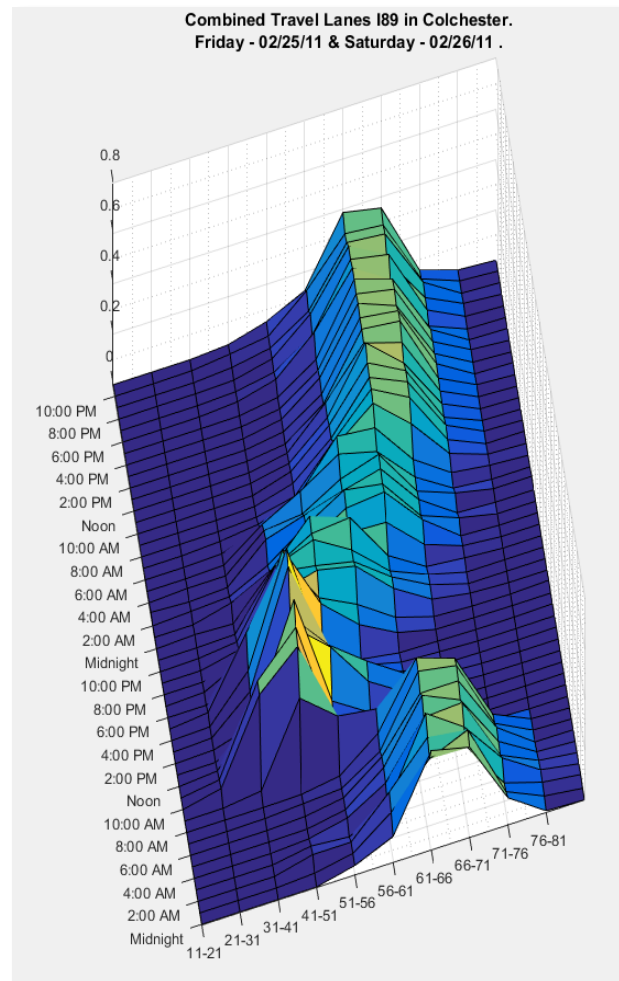


Figure 2 Speed disruption and recovery during and after a 2011 winter storm event

mobility and traveler safety during and after a winter storm event. Grip provides an imputed measure of the condition of the road surface while ADD measures the traveling public's response to perceived conditions of the road surface. The objectives of this project were to gain a better understanding of the derivation of the Grip metric, the correlation between Grip and traffic speeds under different winter weather conditions, and the relationship between Grip, speed and crashes. The goal is to further advance a comprehensive performance measurement system that is consistent with the state's Snow and Ice Control Plan target of providing "safe roads at safe speeds."

This report was prepared under project VTRC017-001 entitled "Snow and Ice Control (SIC) Performance Measurement: Comparing "Grip," Traffic Speed Distributions and Safety Outcomes During Winter Storms" for VTrans. The project scope consisted of the following tasks:

1. Collect winter 2016 – 2017 data
2. Reverse-engineer Grip formula
3. Grip validation literature review
4. Compare Grip to ADD
5. Grip/ADD/crash analysis
6. Winter 2017-18 data collection/analysis
7. Review storm/seasonal severity indices

The Technical Advisory Committee members for this project were Emily Parkany, Ian Anderson, Todd Law, Robert White, Ken Valentine, Josh Schultz, Alec Portalupi, and Ernie Patnoe. The completion of these project tasks is documented in the remaining Sections 2 through 4 of this report. Section 2 includes the review of existing winter severity indices. These includes measures of winter *storm* severity, as well as measures of winter *season* severity. Section 3 describes the analysis of Vaisala's proprietary "Grip" measure in Vermont. Section 4 describes the use of RWIS data in Vermont from the winter seasons in 2017 and 2018 to compare "Grip", the ADD in speed of the traffic stream, and safety outcomes. Finally, Section 5 summarizes the conclusions and recommendations of the overall research included in this project.

2 Data Used in this Project

Data on roadside weather, regional weather, traffic flow, and safety outcomes was obtained for analysis in this project. All data obtained to support the analyses conducted in this project is described below.

2.1.1 Road Surface Conditions, Roadside Weather, and Traffic Flow Data

VTrans currently has 38 road weather information stations (RWIS) in operation across the state. These stations are equipped with a variety of devices to record and log data related to ambient roadside weather, road surface conditions, and traffic flow. Ambient weather data collected includes one or more of the parameter shown in Table 1.

Table 1 Ambient Weather Data at RWIS Stations in Vermont

Ambient Weather Parameter	Number of Stations
Air Temp (°F)	35
Dew Temp (°F)	35
Relative Humidity (%)	35
Rain Intensity (in/h)	29
Wind Speed Ave (mph)	34
Wind Speed Max (mph)	33
Wind Direction	34
Visibility (ft)	29
Precipitation, Rolling Average, past 1 hour (in)	30
Precipitation, Rolling Average, past 3 hours (in)	30
Precipitation, Rolling Average, past 6 hours (in)	30
Precipitation, Rolling Average, past 12 hours (in)	30
Precipitation, Rolling Average, past 24 hours (in)	30

When the data is logged (typically in 10-minute intervals), two more variables are imputed. Rain On/Off is imputed for 26 RWIS stations and Rain State is imputed at 30 RWIS stations). Rain State has the following possible values:

- none
- light
- medium
- heavy
- h.snow
- m.snow
- l.snow

Road surface condition data collected includes the parameters shown in Table 2.

Table 2 Road Surface Condition Data at RWIS Stations in Vermont

Road Surface Condition Parameter	Number of Stations
Water Layer (mm)	27
Ice Layer (mm)	27
Snow layer (water equivalent) (mm)	27
Sub Surface Temp (°F)	8
Surface Temp (°F)	34
Water Thickness (in)	18

Once this data is logged, two additional variables are imputed. Level of Grip, a value that varies from 0.00 to 0.82 and represents the friction loss on the road surface, is imputed at 27 stations and Surface State is imputed at 7 stations. Surface State has the following possible values:

- dry
- wet
- moist
- icy
- slushy
- snowy
- iceWarn
- iceWatch
- unknown

Traffic flow data collected includes the following parameters each lane of observation:

- Headway (5-minute average, sec)
- Occupancy (5-minute average, %)
- Vehicle Speed (5-min average, mph)
- Vehicle Speed (85th percentile, mph)
- Gap between vehicles (yd)
- Volume (count)
 - Vehicle Classification, as a count of vehicles under 10, 19, 24, 54, 109, and 256 feet long
 - Vehicle Speed, as a count of vehicles above 0, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, and 95 mph

These data are logged in 10-minute intervals.

23 of the RWIS are located on interstates, 6 are located on US highways and 9 are located on state highways. In the winter of 2016-17, 21 of the RWIS stations were configured to record Level of Grip, but two of these devices

experienced equipment problems in the 2016-17 winter season and did not successfully record it.

2.1.2 Vermont NOAA Precipitation Data

Daily snowfall, accumulated snow depth, daily maximum and minimum temperature and daily precipitation were obtained from the NOAA's GHCND (Global Historical Climatology Network-Daily) Program for calculation of the AWSSI in Vermont. The GHCND is an integrated database of daily climate summaries from land surface stations across the globe, comprised of daily climate records subjected to a common suite of quality assurance reviews. The GHCND contains records from over 100,000 stations in 180 countries and territories, including maximum and minimum temperature, total daily precipitation, snowfall, and snow depth. For this project, GHCND data was obtained for every day of December, January, February, March, and April of 2016-2017 and 2017-2018 for 132 GHCND stations in Vermont. Of these, there were 27 which had all of the required data elements for the time periods required.

2.1.3 Vermont Crash Data

Crash data in Vermont for the winter seasons of 2016-2017 and 2017-2018 were obtained for use in this study. Data were queried and downloaded from the VTrans Public Crash Data Query Tool - <http://apps.vtrans.vermont.gov/CrashPublicQueryTool/>. The tool provides the public with access to statewide law-enforcement-reported motor vehicle crash data for the years 2010 to the present. The database does not include the crash report narrative or any crash diagrams, it only includes the following data fields

- Crash Date
- City/Town
- Address
- Route ID
- Crash Type
- Collision Direction
- Weather
- Road Group
- Report Number
- Reporting Agency Road Group
- Milepoint
- Animal
- Time of Day
- Intersection With Impairment
- Involving
- Local ID
- Non Reportable Address
- Reporting Agency ID
- Road Characteristics
- Road Condition
- Street Address
- Surface Condition
- Route ID
- Coordinates

Fatal crash reports are submitted to the database as soon as sufficient information is available. Due to the complexity of a fatal crash investigation, it may take 90 days or more to receive all data related to a crash. Figure 3 contains a map displaying the locations of all crashes obtained for this project.

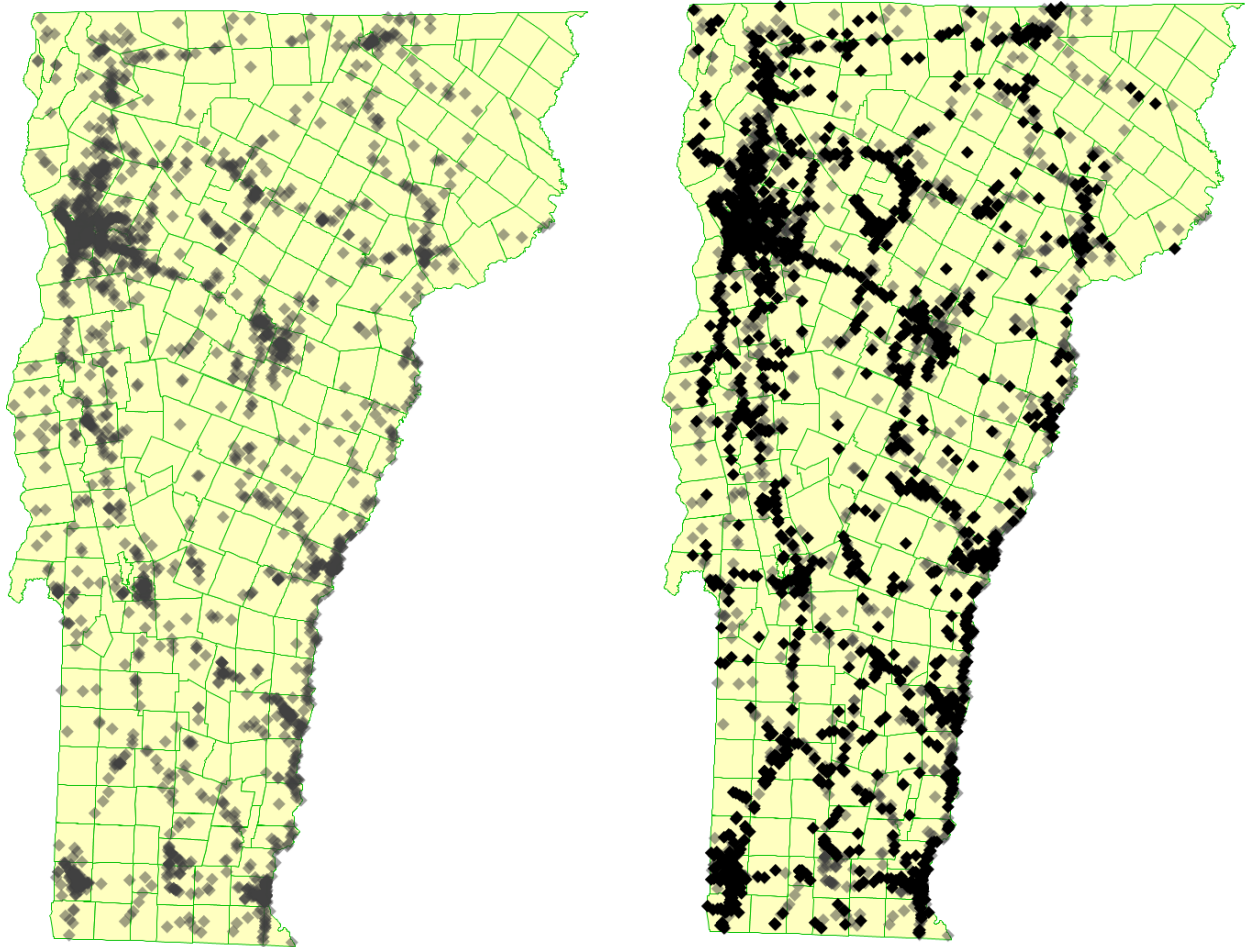


Figure 3 2017 (left, grey markers) and 2018 (right, in black) winter crash data in Vermont

2.1.4 Vermont State Police Incident Data

In order to consider the effect of weather on non-reportable safety outcomes, non-reportable incident data from the Vermont State Police was also obtained and geo-coded for use in this study. This data pertains to instances when state police were dispatched to a roadway locations for a reason other than a reportable crash. The data includes a field that identifies “snow/ice” as a contributing factor in the dispatch. In addition, the date-time, address

and town are provided, along with the nature of the dispatch which includes the following valid entries:

- Abandoned Vehicle
- Accident
- Agency Assist
- Citizen Assist
- DUI
- Motor Vehicle Complaint
- Property Damage
- Suspicious
- Theft-Automobile
- Traffic Hazard

The data pertaining to dispatches for “Accident” were discarded, since they are likely duplicates of the crash data. All other types of incidents were counted as potential safety outcomes pertaining road weather. Figure 4 shows the locations of these data for both winter seasons in this study, overlaid on the crash data shown in Figure 3.

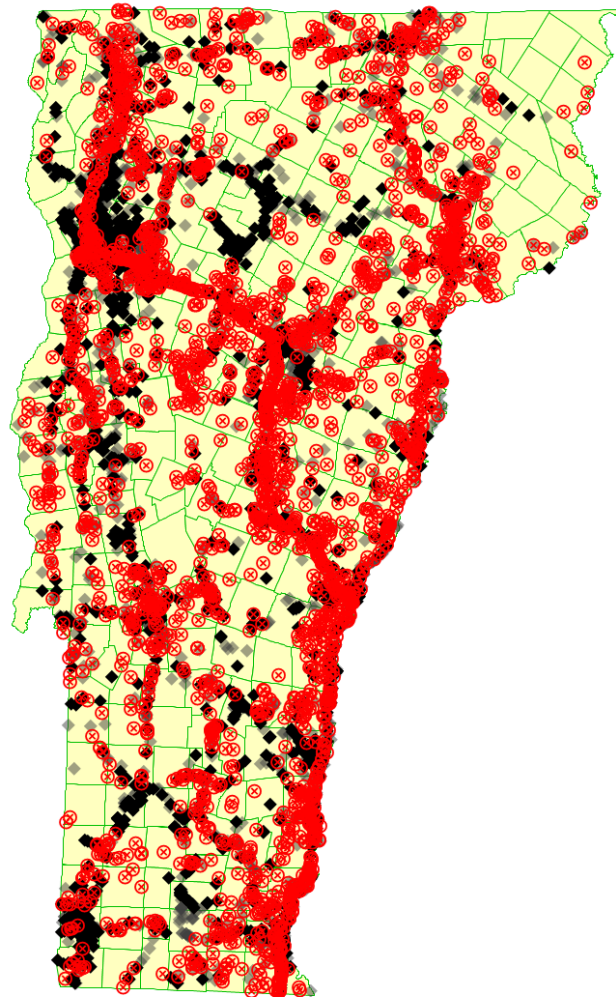


Figure 4 Vermont State Police incident data (red), winters of 2017 and 2018

3 Review of Winter Severity Indices

Effective RSIC performance measures should be normalized in relation to winter severity. Road conditions during and after a severe winter storm will be significantly different than during and after a brief, overnight snowfall. A variety of measures of precipitation, wind, and temperature will influence RSIC recovery time. A high number of total storms in a season or multiple storms in rapid succession can be expected to negatively impact recovery times since personnel, equipment, and materials are relatively fixed and can be stretched thin.

Severity indices can also be used to normalize the Agency’s performance across the entire winter season. In this case, a seasonal severity index will be required to capture the cumulative effects of the individual storms experienced throughout. In this case, it becomes critical to also understand when the season begins and ends.

3.1 The Severity Index from Vaisala and the Idaho Transportation Department

A series of severity indices and performance measures were developed by the Idaho Transportation Department (ITD) in collaboration with Vaisala for use in the road weather information stations (RWIS) data managed by Vaisala (Jensen et al, 2013). These measures combine Vaisala’s proprietary “Grip” metric and a severity index (SI). The SI is calculated for each event based on the wind speed, layer thickness surface temperature experienced during and event:

$$SeverityIndex = MaxWindSpeed(mph) + MaxLayerThickness(mm) + \left(\frac{300}{MinSurfaceTemp(^{\circ}F)} \right)$$

MaxLayerThickness is the thickest of the ice, water, and snow layers at the time.

This SI may not be suitable for all storm conditions. For the period of January – March 2017 in Vermont, it was successfully computed for 1,421 events across 16 sites in Vermont. A histogram of the SIs is shown in Figure

5. The minimum value was 9.5 and the mean was 26.7 across this period, but the maximum (not shown) was 2,170. Other extremely high values were recorded at the Jay and Buels Gore RWIS stations. These extreme values adversely affect the resulting calculations of the Performance Index for an event.

These extreme values are the result of the non-linear relationship between surface temperature and the SI. Table 3 provides an indication of how different surface temperatures affect the SI.

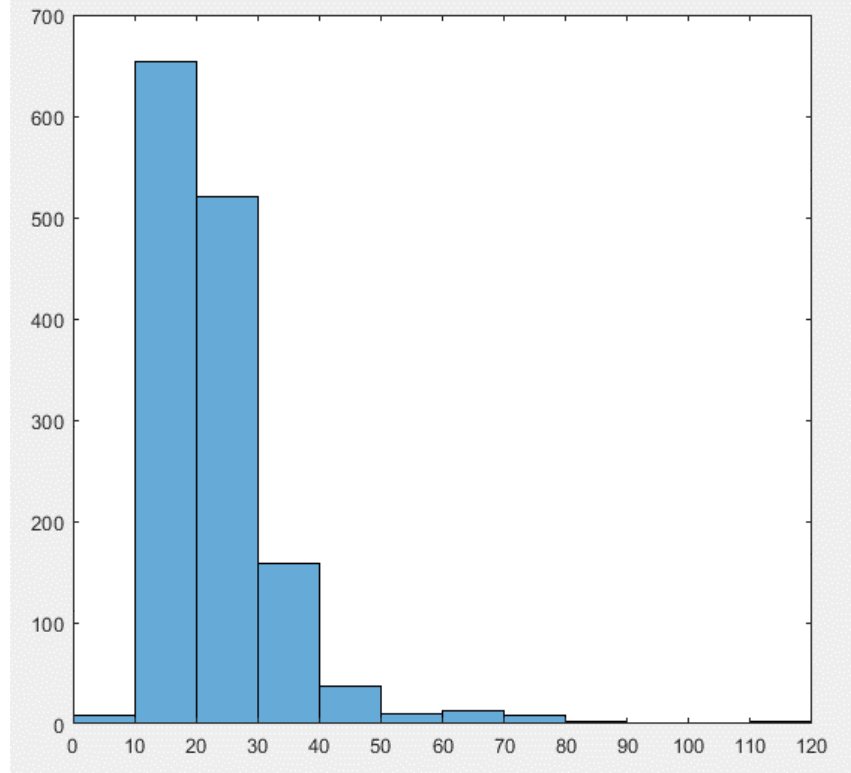


Figure 5 Histogram of SIs in Vermont in 2017

Table 3 Relationship between road surface temperature and SI

Road Surface Temperature	Contribution to SI
30.0	10
25.0	12
20.0	15
15.0	20
10.0	30
5.0	60
4.0	75
3.0	100
2.0	150
1.0	300
0.1	3,000

Another issue with this SI is that the formula breaks down at sub-zero temperatures since the temperature component flips sign and reduces, rather than increases, the SI. While this is not a frequent occurrence, it does happen in Vermont. Two event with identical wind speeds and maximum layer thicknesses but with minimum surface temperatures of 1° and -1° would have SIs that

differed by 600. For this reason, the RWIS does not calculate SI when the surface temperature is below 0°, as seen in this Buels Gore example from last January (Figure 6).

Station	Date	Time Range	Event	Duration (hours)	Max Wind Speed (mph)	Max Ice Layer (mm)	Max Snow Layer (mm)	Max Water Layer (mm)	Min Surface Temp (°F)	Severity Index	Precip. (hours)	Precip. Total (in)	Performance Index	Mobility Index	Comments
VTRANS - Rt 17 Buels Gore															
	01.01.2017	12:01 AM - 03	TREATED	3.75	9.62	0.08	0.06	0.22	-15.34						Temp is below the index calculation threshold
	01.01.2017	03:46 AM - 08	GRIP<6	4.25	16.78	0.22	0.85	0.04	-15.88		6.50	0.02		70%	Temp is below the index calculation threshold
	01.01.2017	09:16 AM - 12	TREATED	3.25	9.17	0.00	0.00	0.35	-12.28						Temp is below the index calculation threshold
	01.01.2017	12:31 PM - 02	FROST treated	1.75	9.40	0.00	0.00	0.02	-7.60						Temp is below the index calculation threshold

Figure 6 Buels Gore, Vermont Winter Performance Index Report for January 2018

The SI also lacks a time component, to reflect the differing severity of two storms with different durations but the same total snow/ice accumulations. Without recognition of the impact of storm duration, the SI would provide equivalent measures of severity for storms that were 2 hours and 8 hours long, if their overall maximum layer thickness on the roadway was the same.

3.2 Winter Severity by Meridian Environmental Technology

A project completed for the Clear Roads Pooled Fund in 2012 by Meridian Environmental Technology was focused on mapping winter severity (WS) across the U.S. The primary focus of this project was the selection and mapping of the best indicators of winter weather severity. The final list of weather severity parameters selected consisted of snowfall duration and accumulation, duration of freezing rain, and duration of blowing/drifting snow. Maps of these individual parameters were created and an overall winter severity measure, which was a combination of these parameters, was also developed and mapped:

$$\begin{aligned}
 \text{Winter Severity} = & 0.50 * (\text{average annual snowfall, in inches}) + \\
 & 0.05 * (\text{annual duration of snowfall, in hours}) + \\
 & 0.05 * (\text{annual duration of blowing snow, in hours}) + \\
 & 0.10 * (\text{annual duration of freezing rain, in hours})
 \end{aligned}$$

This formula was based on the qualitative “look” of the index and the need to avoid certain problems with other indices (Mewes, 2012). This index is not limited to the roadway weather characteristics, so it capitalizes on the availability of more general weather parameters to estimate the severity of a winter season. Note that this index is not storm-specific. It also includes a time component, in the durations of snowfall, blowing snow, and freezing rain. However, it lacks a temperature component, which can be a primary contributor to winter season severity. It also utilizes a fairly arbitrary set of

weighting parameters, and it is not clear if the index has been calibrated or provided with an empirical basis. In fact, the author asserts that particular index values have no specific interpretation, and are provided only for the sake of relative comparisons of winter severity (from a winter maintenance perspective) between differing locations across the country. So the index does not appear to be designed for measuring winter performance, but rather for effective regional mapping.

3.3 The Storm Severity Index by the University of Iowa

Nixon and Qiu extended their earlier work on characterizing winter storm events to create a comprehensive storm severity index (SSI) focused on roadway maintenance (Nixon and Qiu, 2005). Using a thorough process of multivariate regression, normalization, and calibration with experts' input, an SSI was developed that is based on the following storm characteristics:

- storm type (heavy snow, medium snow, light snow, freezing rain)
- in-storm road surface temperature (> 32 F, 25-32 F, < 25 F)
- in-storm wind condition (< 15 mph, > 15 mph)
- early storm behavior (starts as snow, starts as rain)
- post-storm temperature (same as storm, warming, cooling)
- post-storm wind condition (< 15 mph, > 15 mph)

The event characterization for these parameters creates a score which is plugged into the following equation:

$$SSI = \left[\frac{1}{b} [(ST * T_i * W_i) + B_i + T_p + W_p - a] \right]^{0.5}$$

Where ST is storm type, T_i is in-storm road surface temperature, W_i is in-storm wind condition, B_i is early storm behavior, T_p is post-storm temperature and W_p is post-storm wind condition. a and b are used to normalize the SSI so that it is between 0 and 1. Expert input was used to rank 10 real storms in order of severity, and this ranking was compared to the ranking that would result from the SSI calculation for each storm. The scores applied to each storm characteristic were adjusted so that the two sets of ranking aligned. An example of the way the SSI measures storm severity based on these characteristics is provided in Table 4.

Table 4 University of Iowa SSI for a variety of storm conditions

Storm Type	Storm Temp	Early Storm Behavior	Wind Condition in Storm	Post-storm Temp	Post-storm Wind Condition	SSI
Heavy snow	Cold	Starts as rain	Strong	Cooling	Strong	1.000
Freezing rain	Cold	Starts as rain	Light	Same	Light	0.695
Heavy snow	Warm	Starts as rain	Light	Cooling	Strong	0.664
Heavy snow	Warm	Starts as snow	Light	Cooling	Strong	0.618
Heavy snow	Mid	Starts as snow	Strong	Cooling	Light	0.609
Medium snow	Mid	Starts as snow	Light	Warming	Strong	0.467
Freezing rain	Warm	Starts as rain	Strong	Warming	Light	0.367
Medium snow	Mid	Starts as snow	Light	Same	Light	0.350
Light snow	Mid	Starts as rain	Light	Warming	Light	0.300
Light snow	Warm	Starts as snow	Light	Warming	Light	0.000

The development of the SSI relied on very effective research, with comprehensive modeling and validation. Therefore, it is a very effective tool for measuring the severity of a winter storm. However, its focus on wind conditions and its need for wind strength data make it less applicable to Vermont, where blowing snow is not as big a threat as it may be in the Snowbelt Great Plains' states.

3.4 The Accumulated Winter Season Severity Index by the Midwestern Regional Climate Center

The accumulated winter season severity index (AWSSI) was developed to address the lack of a daily/seasonal measurement of winter severity that uses widely available climatological data and that can be scaled for objective comparisons between geographies and over time (Boustead et al., 2015). The AWSSI includes both a temperature component and a snow component, making it more comprehensive than those that consider precipitation only. The snow component uses daily snowfall, but also accumulated snow depth to account for the accumulated impacts of snow remaining on the ground, independently of temperature. This inclusion also accounts for the effect of repeated storms, which is a factor that is directly relevant to RSIC.

The authors note that snowfall measurements commonly contain errors—gauge undercatch of snowfall is a known concern – and that snowfall data is not as widely collected as precipitation data. To address periods with no or unreliable snow data, a variant of the AWSSI known as the precipitation-based AWSSI or pAWSSI was also created. The pAWSSI estimates snowfall on the basis of temperature and precipitation data using an algorithm described in (Boustead et al., 2015). The AWSSI and pAWSSI generally perform similarly in locations that receive little mixed precipitation, while the pAWSSI may produce higher severity values than the AWSSI in areas that include mixed snow and ice phases.

The effectiveness of the AWSSI lies in the fact that the data required is widely available at NOAA weather stations – temperature, precipitation, snowfall and accumulated snow depth on the ground. A scoring system, similar to the one used by the University of Iowa researchers (Nixon and Qiu, 2005) is used to characterize each daily weather event (see Figure 7), so a storm-specific rating is available, but the daily measure also accumulates throughout the winter, resulting in a seasonal rating at the end of the winter.

AWSSI Point Thresholds				
Points	Temperature (°F)		Snow (in)	
	Max	Min	Fall	Depth
1	25 to 32	25 to 32	0.1 to 0.9	1
2	20 to 24	20 to 24	1.0 to 1.9	2
3	15 to 19	15 to 19	2.0 to 2.9	3
4	10 to 14	10 to 14	3.0 to 3.9	4 to 5
5	5 to 9	5 to 9	-	6 to 8
6	0 to 4	0 to 4	4.0 to 4.9	9 to 11
7	-1 to -5	-1 to -5	5.0 to 5.9	12 to 14
8	-6 to -10	-6 to -10	-	15 to 17
9	-11 to -15	-11 to -15	6.0 to 6.9	18 to 23
10	-16 to -20	-16 to -20	7.0 to 7.9	24 to 35
11	-	-21 to -25	-	-
12	-	-	8.0 to 8.9	-
13	-	-	9.0 to 9.9	-
14	-	-	10.0 to 11.9	-
15	<-20	-26 to -35	-	36+
18	-	-	12.0 to 14.9	-
20	-	<-35	-	-
22	-	-	15.0 to 17.9	-
26	-	-	18.0 to 23.9	-
36	-	-	24.0 to 29.9	-
45	-	-	>=30.0	-

Figure 7 AWSSI Scoring System (Boustead et al., 2015)

The AWSSI is calculated and tracked for a limited set of weather stations in the U.S. by the Midwestern Regional Climate Center:

<http://mrcc.isws.illinois.edu/research/awssi/indexAwssi.jsp#manual>.

The AWSSI can also be used to index individual storms, with each 24-hour period as the basis for measurement. This is a convenient time component because it coincides with the constraints on dispatch scheduling for RSIC crews and the need to respond to daily commuting schedules. For individual storms, the AWSSI also takes advantage of the effect of the preceding storms in the season, making it especially effective at measuring the effects of depleted resources on RSIC.

3.5 The Winter Storm Severity Index by the National Weather Service

The National Weather Service (NWS) is developing a prototype winter-storm severity index (WSSI) to provide a classification of the overall expected severity of winter weather (<https://www.weather.gov/bgm/winterseverity>).

The following datasets are used or derived as part of calculating the prototype WSSI:

- 6-hour snow accumulation
- 6-hour ice accumulation
- 6-hour precipitation accumulation
- Wind gust (hourly time steps)
- Temperature (hourly time steps)
- Total snowfall
- Total ice accumulation
- Maximum wind gust within each 6 hour period
- 6-hourly snowfall accumulation rate
- 6-hourly snow-liquid ratio
- Average snow-liquid ratio
- Snow depth
- Snowpack temperature
- Snow water equivalent
- Urban area designation
- Land-use designations

The prototype WSSI is actually a series of component algorithms, each of which use meteorological and non-meteorological data to model predicted severity of specific characteristics of winter weather. This WSSI is intended to be extremely comprehensive, to assist with assessing impacts to a variety of infrastructure, including impacts associated with snow load (e.g., downed

trees/power lines), snow amount (normalizes for climatology, such that regions of the country that experience, on average, less snowfall will show a higher level of severity for the same amount of snow), ice accumulation (e.g., downed trees/power lines, roads/bridges), blowing snow, flash freeze (temperatures starting above freezing and quickly dropping below freezing), and ground blizzard (strong winds interacting with pre-existing snow cover).

Each of the components produce a 1 to 5 output score to indicate the severity based of winter weather hazards expected. The final WSSI value is the maximum value from all the sub-components. The 5 levels are given the following descriptors: Limited, Minor, Moderate, Major, and Extreme.

3.6 Expanding the pAWSSI in Vermont

There is a tradeoff between data specificity and geographic granularity. The NWS WSSI contains a high level of data specificity, but it is still under development, so it is not clear how many weather stations will provide enough data to calculate it. An index that has more geographic granularity and requires less data is more useful, particularly for Snowbelt states, which require considerations that a nationally-applicable index may not provide.

The pAWSSI was chosen for expansion in Vermont because it breaks down the categories explored in the University of Iowa research (Nixon and Qiu, 2005) even further, and includes snow accumulation, making it good for measuring the severity of a particular storm but also effective as a seasonal index. It also uses readily available data that is particularly important for Snowbelt states and relevant to RSIC, allowing Vermont to compare its storms to those in other states. Clear Roads project 16-02 “AWSSI Enhancements in Support of Winter Road Maintenance” is focused on expanding the AWSSI to be calculated at more stations nationally. For this project, the research team expanded its coverage throughout Vermont, to the extent permitted by available data. In the NOAA GHCND Program, there are 132 weather data stations in Vermont. Only 27 of these collect daily snowfall, snow depth, minimum temperature and maximum temperature, making the calculation of the AWSSI feasible. As an example, the AWSSI was calculated for every day in the winter of 2017-2018 at each of these 27 stations. The AWSSI and pAWSSI at the end of the winter at each of these stations is provided in Table 5.

Table 5 pAWSSI and AWSSI in Vermont for Winter 2017-2018

NOAA GHCND ID	Town	2017-2018 pAWSSI	2017-2018 AWSSI	pAWSSI Rank	AWSSI Rank
USC00435416	Stowe	2657	2308	1	1
USC00430193	Canaan	1928	1540	5	2
USC00432314	East Haven	1934	1429	4	3
USC00438169	Sutton	2180	1427	2	4
USC00431565	Corinth	1662	1228	8	5
USC00436335	Peru	2045	1198	3	6
USC00434120	Brighton	1644	1102	9	7
USC00434290	Johnson	1791	1076	6	8
USC00435542	Newport City	1689	984	7	9
USC00437612	Lincoln	1289	926	13	10
USC00436391	Plainfield	1273	867	15	11
USC00438640	Waitsfield	1147	861	18	12
USC00436893	Rochester	1278	826	14	13
USC00436995	Rutland City	1085	820	20	14
USC00439984	Woodstock	1314	785	11	15
USC00435768	Hartland	996	781	21	16
USC00435982	Springfield	853	780	24	17
USC00439988	Worcester	1464	766	10	18
USC00437054	St. Johnsbury	1196	760	17	19
USC00431580	Cornwall	1198	687	16	20
USC00435733	Northfield	778	659	25	21
USC00435273	Montpelier	1299	641	12	22
USC00438556	Thetford	713	641	26	22
USW00014742	S. Burlington	883	611	22	24
USC00437607	South Hero	1116	584	19	25
USC00438597	Vergennes	859	559	23	26
USC00438652	Walden	253	121	27	27

The effectiveness of this enhanced breakdown of the AWSSI throughout the state is evidenced by the relative position of the Rutland and South Burlington stations in this list. These are the two stations whose AWSSI are automatically calculated by MRCC each day and published on their website. However, these stations are the 14th and 24th in the relative severity of stations within Vermont. Therefore, they do not represent the true severity of winter weather experienced by most of the RSIC personnel in Vermont.

A better indication of the array of winter severity experienced throughout Vermont is in the charted season-long accumulation of the pAWSSI for each of the 27 stations, as shown in Figure 8. The chart demonstrates that by late

December the separation of the winter severity in Stowe and Sutton is evident.

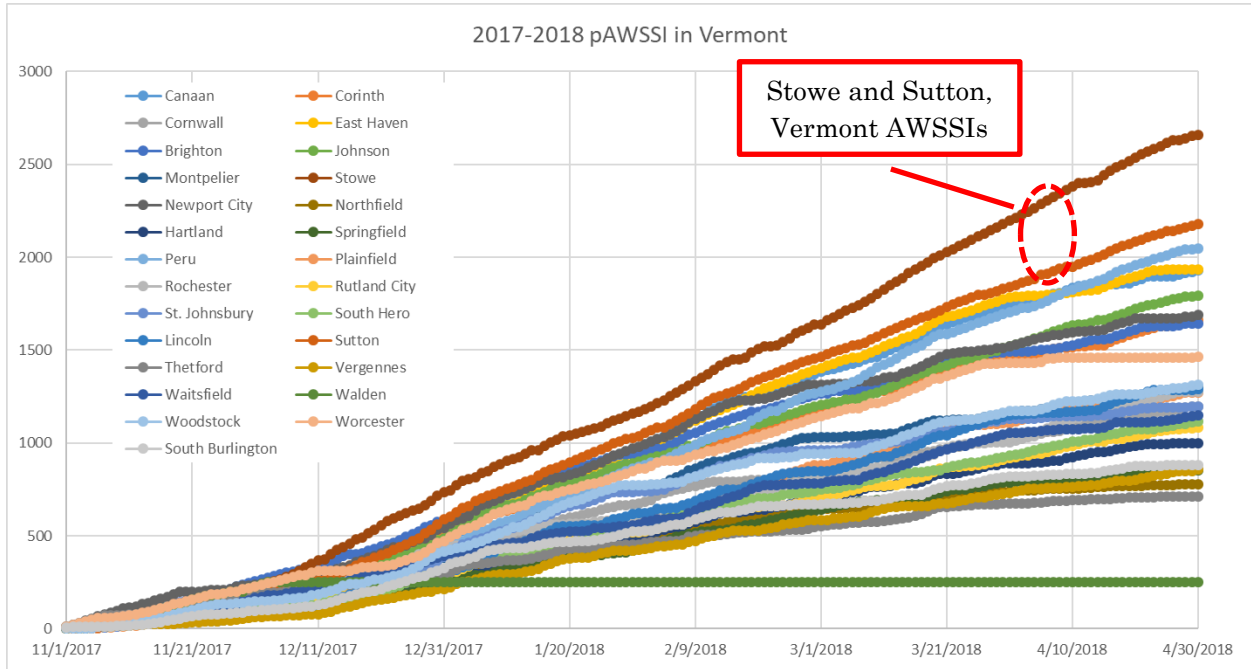


Figure 8 Accumulation of pAWSSI in Vermont throughout the Winter of 2017-2018

4 Analysis of Grip

This section describes the analysis of Vaisala’s proprietary “Grip” measure in Vermont. First, the literature related to the development of the “Grip” measure is reviewed and summarized. Next, the process by which the Grip loss was validated with supervisor input is described. Finally, the proprietary calculation of Grip is reverse-engineered to uncover the formulas and steps used to implement the algorithm.

4.1 “Grip” Literature Review

Evidence from the Vermont RWIS data and from Vaisala documentation (Bridge, 2008; Tarleton, 2015) indicate that Grip is only reported where both surface temperature and thickness of snow, ice, and water on the road surface are reported. This Grip value is suggested to be equivalent to a coefficient of friction, which ranges from 0 to 1.0. A typical dry road surface is supposed to have a Grip value of 0.82, a wet road would be around 0.7, and a snow or ice-covered road could range from 0.4 to 0.6. The Grip reading is based on active transmission of an infrared light beam on the road surface and detection of the backscattered signal at the RWIS, which provides a direct indication of the thickness of moisture or ice on the surface (Jensen et al., 2013). Absorption of water and ice occur practically independently of each other. White ice (snow or hoar frost) reflects light much better than black ice, so these can be distinguished as well. Since side friction is strongly related to the superelevation of the roadway, it is more likely that the Grip value corresponds to skid resistance, or skidding friction.

Other research was also consulted to determine the specific mathematical relationship between water, ice, and snow film thickness and coefficient of skidding friction (Al-Qadi et al., 2002; Fleege et al., 1996; Salimi, 2014; Harwood et al., 1987; Hayes and Gallaway, 1983; Henry, 2000; Horne and Buhlmann, 1983).

Fleege et al (1996) published a chart of friction and % slip for a series of roadway conditions that was particularly informative, as shown in Figure 9.

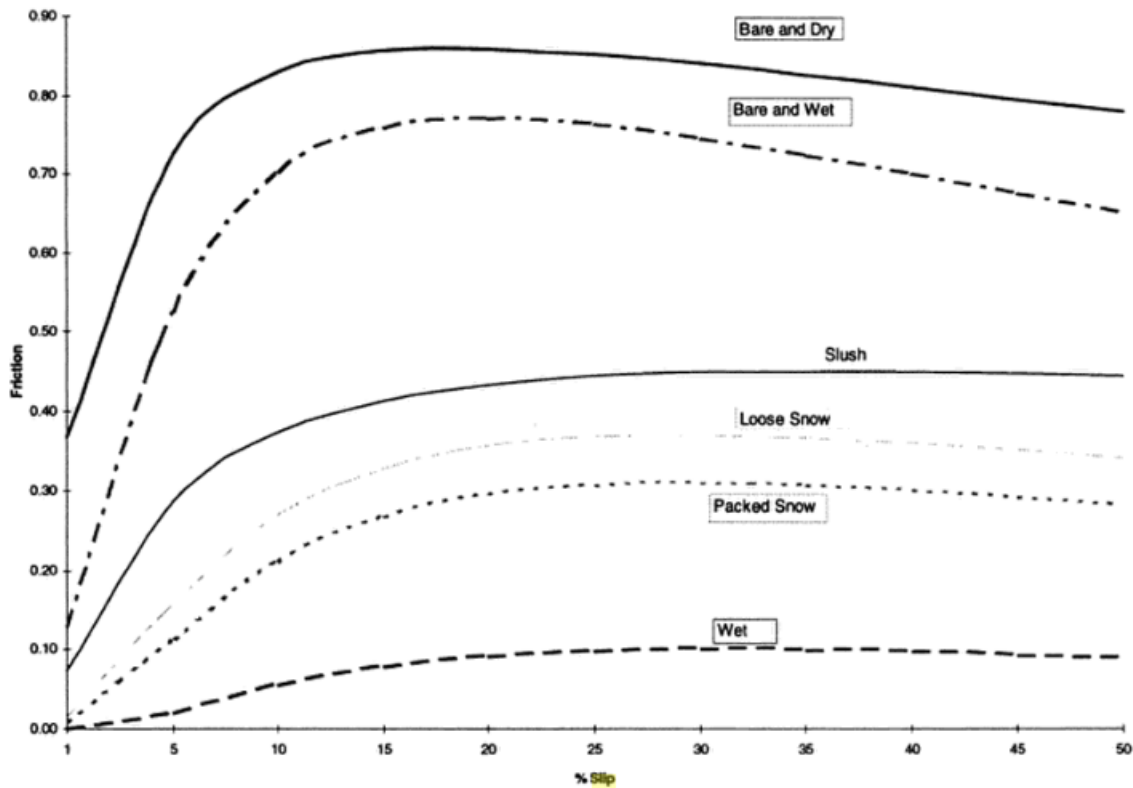


Figure 9 Friction vs. % Slip for a Variety of Road Conditions (Fleege et al., 1996)

Another resource reported that ice on the surface reduces friction by 55% and light, moderate and heavy snow reduce friction by 69%, 75%, and 81%, respectively (Salimi, 2014).

4.2 Vermont RWIS Grip Data

Of the 215,636 possible records of Grip from 20 RWIS stations reporting Grip in 2016-2017, there are 208,748 records that have a value for each of the 4 parameters believed to be in use for the calculation of (Surface Temp (oF), Water Layer (mm), Ice Layer (mm), and Snow Layer (mm water)). Table 6 provides a summary of these data records.

Table 6 Summary Statistics of Grip Records in 2016-2017

	Minimum	Maximum	Mean	Std. Dev.
Surface Temp (°F)	-39.6	108.3	35.5	16.0
Water Layer (mm)	0	60	0.070	0.375
Ice Layer (mm)	0	10	0.005	0.080
Snow Layer (mm water)	0	4.65	0.045	0.248
Level of Grip	0	0.83	0.764	0.141

Snow layer, in mm water, can be multiplied by 5-10 to get an approximate estimate of snow depth. The first step in developing a model of the calculation of Grip from these parameters was to calculate the correlation coefficients of all pairs of values (Table 7).

Table 7 Correlation Coefficients Parameters Related to Grip

	Surface Temp (°F)	Water Layer (mm)	Ice Layer (mm)	Snow Layer (mm water)
Water Layer (mm)	-0.01			
Ice Layer (mm)	-0.05	0.01		
Snow Layer (mm water)	-0.20	-0.03	0.02	
Level of Grip	0.28	-0.13	-0.17	-0.73

Generally, the loss of Grip correlates very highly with snow layer alone, but it is also clear that surface temperature has an influence. This relationship is also clear in a plot of each layer's thickness and Grip loss ($0.82 - \text{Grip}$), provided in Figure 10. The presence of snow, especially at thicknesses of more than 2 mm, is strongly associated with significant Grip loss of more than 0.6 (corresponding to a Grip of 0.22). However, the presence of water also seems to be a strong indicator of Grip loss, but only up to a Grip loss of about 0.33. Perhaps this relationship is controlled by surface temperature. Figure 11 contains the same data, along with the normalized temperature value multiplied by 10.

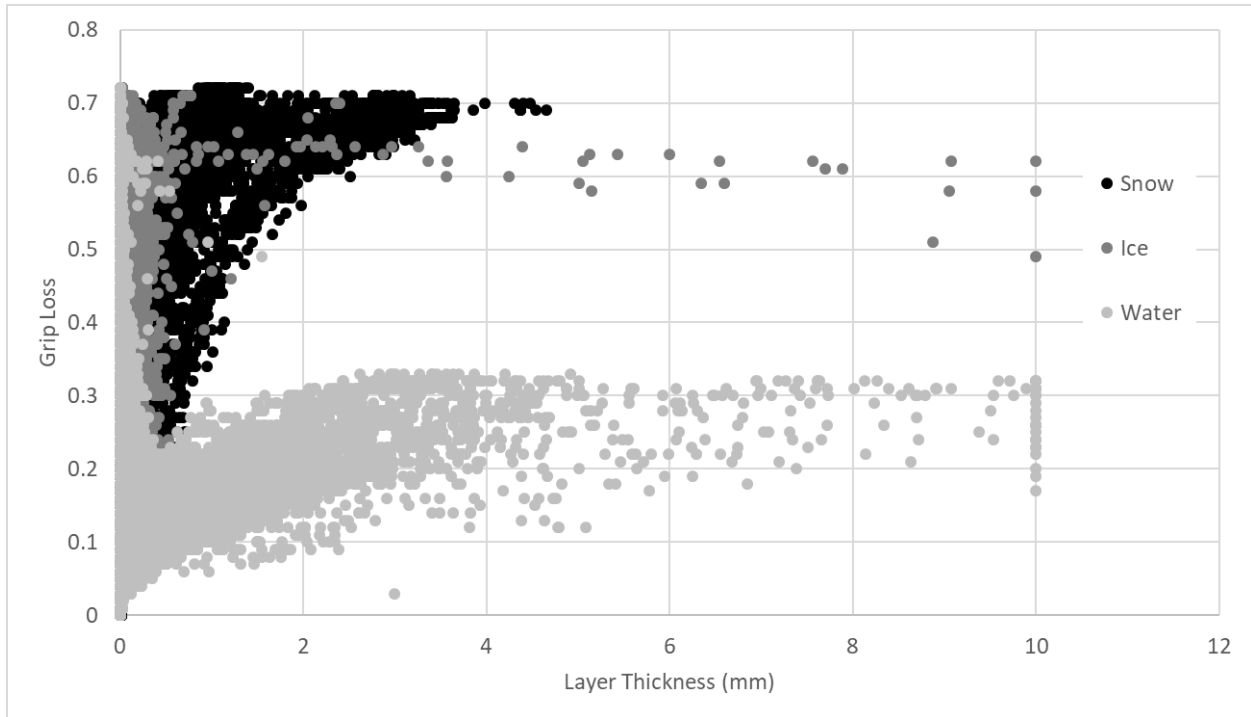


Figure 10 Grip Loss vs. Layer Thickness for the Winter of 2016-2017

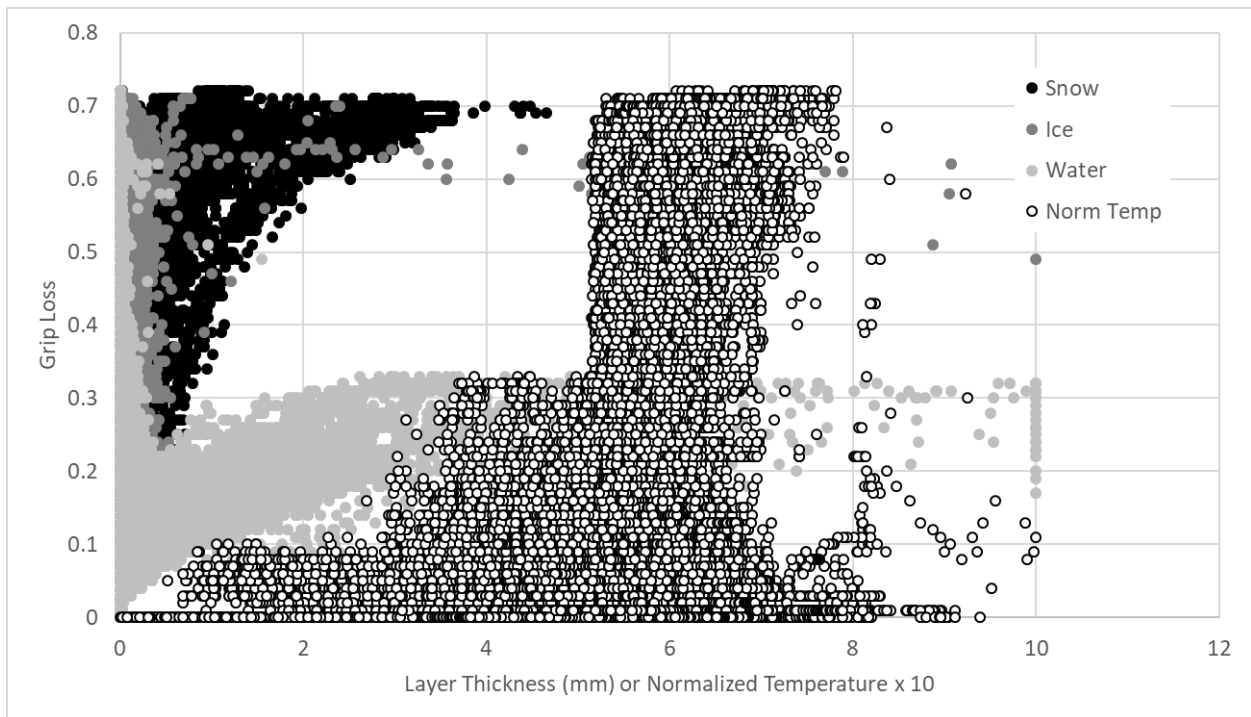


Figure 11 Grip Loss vs. Layer Thickness with Normalized Temperature x10 for Winter of 2016-17

4.3 Reverse-Engineering the Grip Algorithm

Based on this information, a series of multivariate regressions were conducted on a variety of subsets of the data using Grip loss at the dependent variable and surface temperature, water thickness, snow thickness, and ice thickness as the independent variables. Surface temperature was normalized to avoid confusion between positive and negative values. Normalized temperature values varied between 0, for the highest temperature in the data set, and 1 for the lowest. Table 8 provides a summary of these regressions.

Table 8 Summary of Grip Loss, Layer Thicknesses and Surface Temperature Regressions

Data Constraint		Water	Ice	Snow	Norm Temp ¹	Adj. R ²
Water, Snow, and Ice > 0	beta ²	0.06	0.28	0.43	0.00	0.618
	t-score ³	116.72	109.74	529.28	100.79	
Loss of Grip > 0	beta	0.05	0.25	0.4	0.14	0.684
	t-score	59.67	72.12	356.07	149.67	
Water > 0, Ice and Snow = 0	beta	0.05	0.14	1.19	0.14	0.795
	t-score	135.01	88.6	226.06	227.53	
Water > 0	beta	0.05	0.15	1.33	0.00	0.765
	t-score	133.06	91.01	239.94	195.29	
Snow > 0	beta	-1.56	0.89	0.26	0.01	0.859
	t-score	-53.24	44.05	127.84	133.51	
Ice > 0	beta	-0.11	0.13	0.59	0.01	0.883
	t-score	-21.17	29.29	169.64	118.41	
Snow > 0, Water and Ice = 0	beta	-1.14	0.51	0.16	0.65	0.925
	t-score	-67.69	33.95	91.26	219.31	

1. Norm Temp – normalized road surface temperature
2. beta – the estimated regression coefficient for the model of this data constraint
3. t-score – the t statistic is the relationship between beta coefficient and the standard error on the beta estimate; a higher t statistic indicates that the standard error is small relative to the value of the coefficient
4. In all cases, the constant was omitted under the assumption that a road surface with no water, ice or snow should have no loss of Grip

An additional set of regressions was attempted by excluding normalized temperature, and running separate regressions for subsets of the data stratified by temperature. The strongest of these models was stratified around 10 degrees Fahrenheit, with an adjusted R-squared of 0.862 for temperatures below this threshold and 0.719 for temperatures above the threshold. The conclusion drawn from that finding was that low temperatures influence the model due to the presence of ice, but not independently of it. The presence of ice ($\text{Ice} > 0$) seems to have an influence on the overall structure of the model, so one thought was that the algorithm might include a decision point based on the presence or absence of ice.

Interestingly, the influence of water on the loss of Grip reverses as the regressions improve. When the data set is limited to occurrences when snow is present or ice is present, the sign of the beta coefficient for water becomes negative, indicating that more water improves Grip. This findings also seems to indicate that the presence or absence of water may be a decision point in the algorithm, as well as a factor in the calculation of Grip loss. However, there is a continuing problem with records that show a loss of Grip but do not have any layer thicknesses on the road. In these cases, it is not clear if the algorithm is malfunctioning or some incipient temperature trend is thought to be causing dew on the road surface.

The next step in the process involved estimating more specific functional forms, because none of the plots indicate that linear relationships prevail. Therefore, each of the individual dependent data sets was fit with alternate functions, including logarithmic and exponential. The logarithmic functional form relates two variables in the following form:

$$y = a \ln(x) + b$$

a and b are the estimated coefficients. As an example, Figure 12 provides a logarithmic function fit to the Grip loss (y) and the snow layer thickness (x).

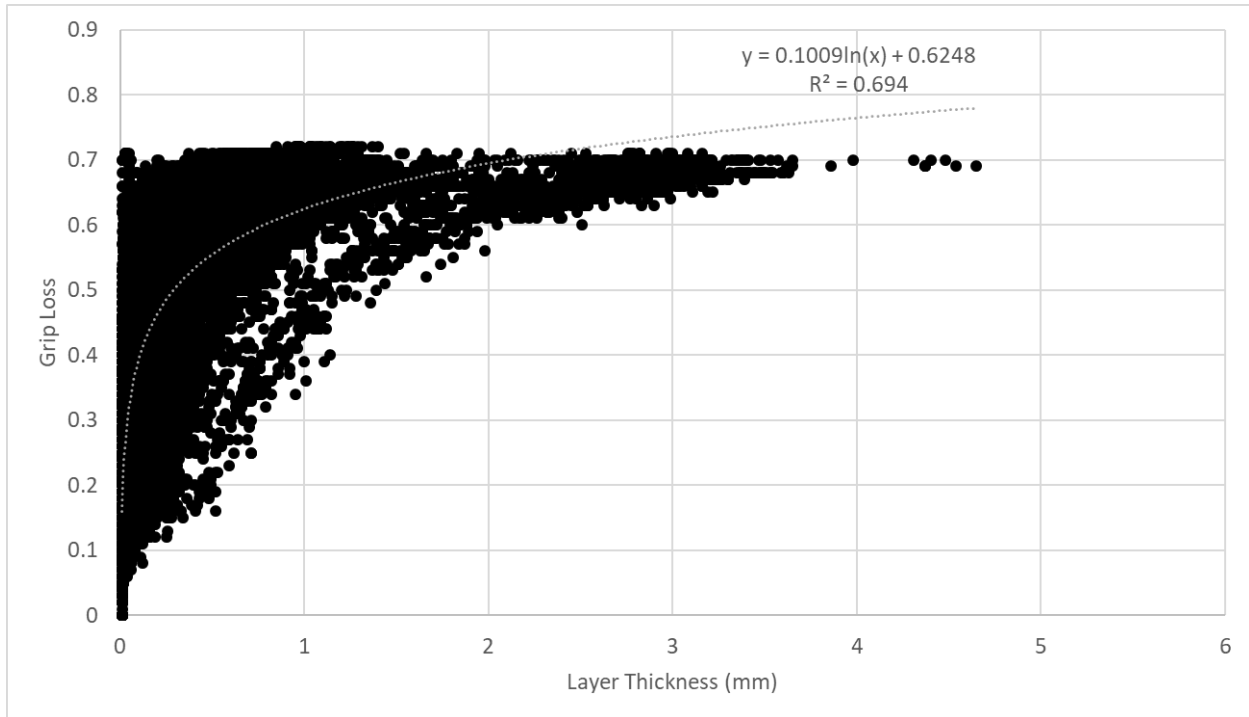


Figure 12 Grip Loss vs. Snow Layer Thickness with logarithmic curve

The exponential functional form relates two variables in the following form:

$$y = ax^b$$

A series of branching algorithms relating layer thicknesses to Grip loss was then explored. Logarithmic and exponential functional forms were tested for each of the layer types – snow, ice, and water. A final algorithm with 4 decision points and 3 separate sub-models was deduced with a fit (R-squared) to the real Grip loss data of 0.9593. Coefficients for each of the 3 sub-models were optimized to minimize the sum of the squared differences between the model Grip loss and the real Grip loss data. The algorithm is shown in Figure 13.

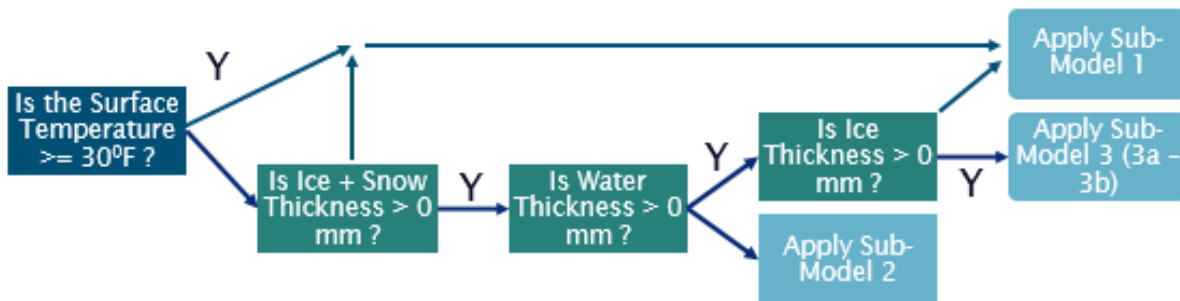


Figure 13 Reverse-Engineered Algorithm for Calculation of Grip Loss

The 3 sub-models with optimized coefficients are summarized in Table 9.

Table 9 Reverse-Engineered Sub-Models for Calculation of Grip Loss

	Functional Form	a	b	x (mm)
Sub-Model 1	ax^b	0.15	0.44	water
Sub-Model 2	$a\ln(x) + b$	0.11	0.64	snow + ice
Sub-Model 3a	ax^b	0.58	0.20	ice
Sub-Model 3b	$a\ln(x) + b$	0.05	0.22	water

The same algorithm and functions were then applied to the 2018 data and the resulting R-squared was 0.96.

4.4 Grip Threshold Validation

The performance measurement procedure developed by ITD and Vaisala uses a Grip value of 0.6 as a threshold to indicate whether or not road conditions are compromised. This threshold was established based on road conditions observed by ITD but it has not previously been validated in Vermont. In order to assess whether or not this threshold was appropriate for use in Vermont, the research team created a simple survey App to facilitate a comparison between measured Grip values and assessments of road conditions conducted by VTrans supervisors.

Supervisors using the app were requested to visit nearby RWIS sites during the course and aftermath of winter weather events and to record four pieces of information:

1. The specific RWIS station location where they were using the app,
2. Whether or not additional snow and ice control was required,
3. Their assessment of road conditions on a 0-9 scale, and
4. Their assessment of the safety of overall traffic speeds given the current road conditions.

Supervisors could also include pictures and/or general comments about the road conditions and the app automatically recorded the time that the data was entered. The interface for this app is shown in Figure 14. Timothy Hebb and Raymond Chase volunteered to participate in the data collection effort.

In total, Hebb and Chase recorded their assessment of the road conditions 27 times covering 5 winter storm events and 5 RWIS locations in March of 2018.

As shown in Figure 15, there was a moderate positive correlation (0.67) between Grip and supervisor assessed road conditions. In all cases where Grip was below 0.6, the supervisors assessed that additional snow and ice control was required, consistent with the ITD/Vaisala threshold. However, the supervisors also determined that additional RSIC activities were required in 10 instances where Grip was greater than or equal to 0.6. These instances summarized in Table 10. Frequently, it appears that the apparent discrepancy between the Grip threshold of 0.6, by which measure road conditions are adequate, and the need for additional RSIC operations reflects supervisors' knowledge of forecasted weather conditions.

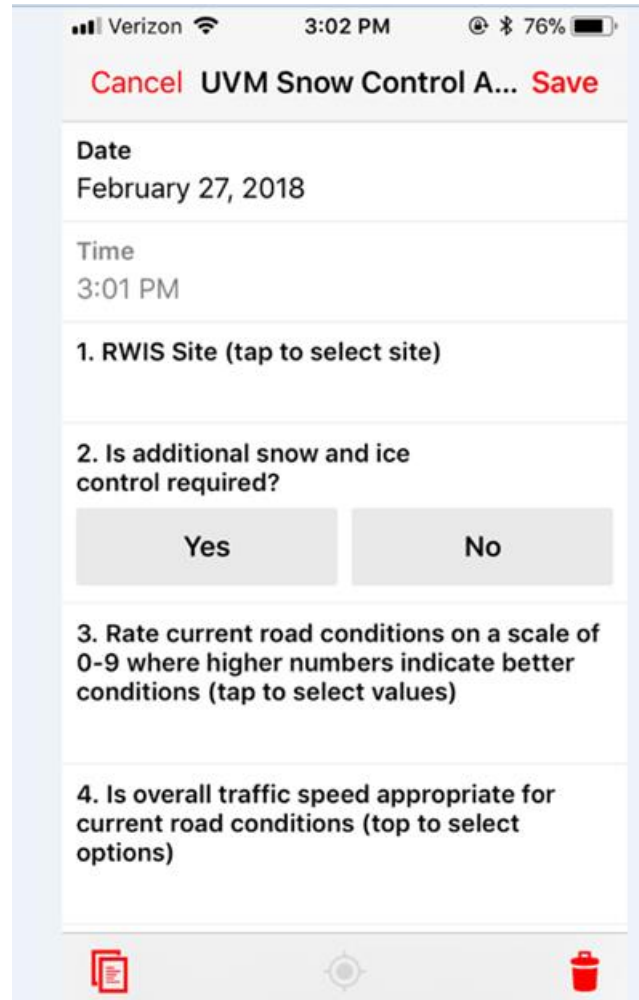


Figure 14 Snow Control Assessment App Interface

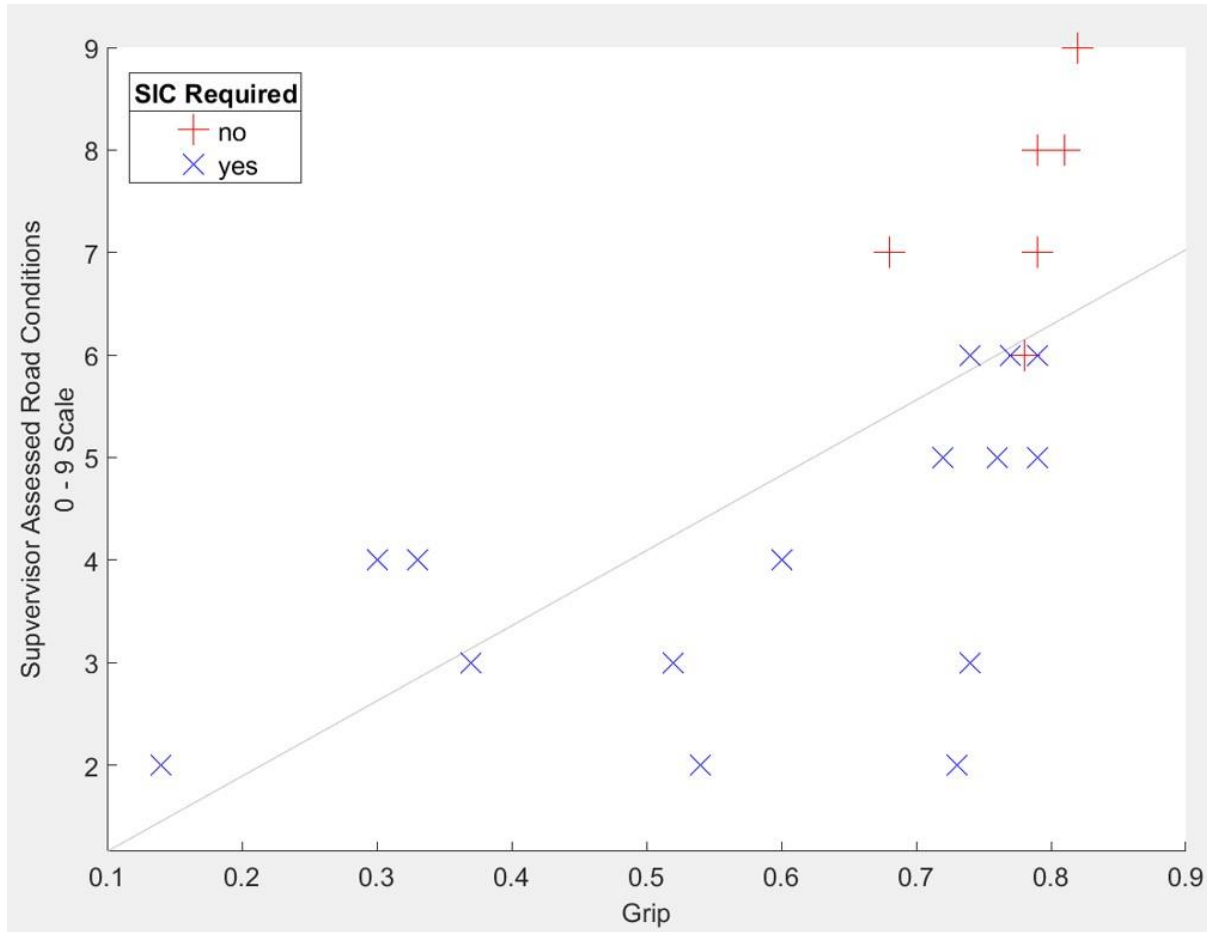


Figure 15 Grip vs Supervisor-Reported Road Conditions

As indicated in the "notes" column of Table 10, there are several instances where Grip is at or above the 0.6 threshold at the time that the supervisor assesses the road conditions but falls rapidly thereafter. This includes cases where the road is just starting to be covered but has not yet hit a critical threshold of snow, water or ice. For example I-89 in Berlin on 3/7, even though Grip is relatively high (0.74) Vaisala flags an Ice Watch and conditions are deteriorating quickly. In this case Grip falls rapidly to 0.52 within the next 10 minutes. In another case, just before noon at I-89 in Hartford on 3/13, it is likely that the slushy road conditions (categorized as a "wet" surface state by Vaisala) did not reduce road friction significantly and the on-going winter maintenance activities were geared toward clearing the road surface to prevent ice from forming as temperatures dropped later in the day.

Table 10. Examples High Grip Values with Additional RSIC Required

Site	Date/ Time	Surface State	Grip	Supervisor Comments	Notes
I-89 Hartford	3/5 6:35	Ice Warning	0.6	There was a light snow. Roads are black ice.	Threshold case. Grip recovering
I-89 Hartford	3/13 7:27	Ice Watch	0.79	Roads are lightly covered and is a light steady snow.	Grip relatively stable until 2:50 PM
I-89 Hartford	3/13 11:49	Wet	0.77	Trucks are scraping off slush and salting where needed	
I-91 Wilder	3/13 7:39	Wet	0.72	Light steady snow. Road just starting to cover.	Grip volatile for much of the day during storm
Brookfield Guardian	3/2 5:54	Slushy	0.76	Started snowing around 5:30am.	Grip falls rapidly
Brookfield Guardian	3/13 7:30	Wet	0.79	Started to snow around 6 am, we are in for the long haul.	Conditions degrade slowly
Brookfield Guardian	3/13 14:45	Slushy	0.73	Snowing.	Grip falls rapidly
I-89 Berlin	3/7 19:53	Ice Watch	0.74	Started snowing at 5:00pm.	Grip falls rapidly
I-89 Berlin	3/13 7:30	Wet	0.79		Conditions degrade slowly
I-89 Brookfield	3/13 7:29	Wet	0.74		Grip falls rapidly

Taken together, these instances demonstrate that Grip does not provide the comprehensive view of road and storm conditions that VTrans personnel utilize to make RSIC decisions. RSIC decision-making considers both current and forecasted road and weather conditions while Grip provides a snap-shot of road surface conditions at a particular point in time. Given this, it is likely that for many of these instances the Grip readings correctly indicated that road friction was adequate at that point in time. More extensive data collection would help to reinforce the validity of the 0.6 Grip threshold.

5 Comparison of Grip, Speed, and Crashes

This section uses RWIS data in Vermont from the winter seasons in 2017 and 2018 to compare Grip loss, ADD, and safety outcomes. First, the correlation between Grip and ADD was calculated to determine whether or not ADD was a reasonable proxy for Grip. After determining that ADD and Grip were only weakly correlated, the “Grip” readings and the ADD measures are overlaid to look for inconsistencies in the speed of the traffic stream and the loss of friction on the road surface. Finally, these inconsistencies are compared to vehicle crashes, reported and unreported, at the same location.

During winter weather events, drivers are expected to reduce their travel speeds in response to adverse driving conditions. If drivers reliably reduced their speeds in slick conditions, there would be a very high correlation between ADD and loss of Grip, potentially indicating that Grip and ADD could be used interchangeably for performance measurement. The overall correlation between Grip and ADD is relatively modest however, indicating the ADD does not accurately capture road surface conditions. As shown in Table 11, the correlation between these two variable varies considerable by roadway but generally ranges between 0.5 and 0.75. While drivers frequently respond to adverse weather conditions by changing their speed, this reaction is not consistent enough to be used to measure RSIC performance.

Table 11. Correlation between Grip and ADD

RWIS Location	Winter 2016 - 2017 30-Minute Data Aggregation		Winter 2017 - 2018 30-Minute Data Aggregation	
	Mean Volume ¹	Grip/ADD Correlation ¹	Mean Volume ¹	Grip/ADD Correlation ¹
Brookfield Guardian	176.63	0.64	101.72	0.66
I-89 Berlin	202.45	0.68	113.46	0.57
I-89 Bolton	275.21	0.53	152.97	0.32
I-89 Brookfield			77.64	0.74
I-89 Colchester			168.88	0.65
I-89 Hartford	257.27	0.74	147.41	0.65
I-89 Middlesex			37.56	0.53
I-89 Milton Bridge			118.14	0.73
I-89 Waterbury			126.50	0.74
I-89 Williston	274.35	0.72	151.79	0.71
I-91 Guilford	145.04	0.68	73.10	0.58
I-91 Thetford	117.85	0.72	63.41	0.57
I-91 Westminster	139.51	0.69	83.39	0.63
I-91 Wilder			34.05	0.52
VT103 Mount Holly			50.99	0.79
VT105 Jay	31.50	N/A		
VT11 Winhall ²			57.22	0.10 ²
VT22A Fairhaven	113.48	0.69	63.21	0.23
US 4 Mendon			31.00	0.99
US 7 Clarendon	87.24	0.69	49.57	0.59
VT78 Alburgh	119.60	0.65	70.22	0.60

Notes:

1. All calculations are for periods with at least 30 vehicles per 30 minute aggregation period on days with reduced GRIP (GRIP < 0.8).
2. VT11 Winhall Grip data is suspect, so the figures generated from it should not be used in further analyses

Figure 16 further illustrates the relationship between ADD and Grip by looking at the range of ADD values observed at different levels of Grip.

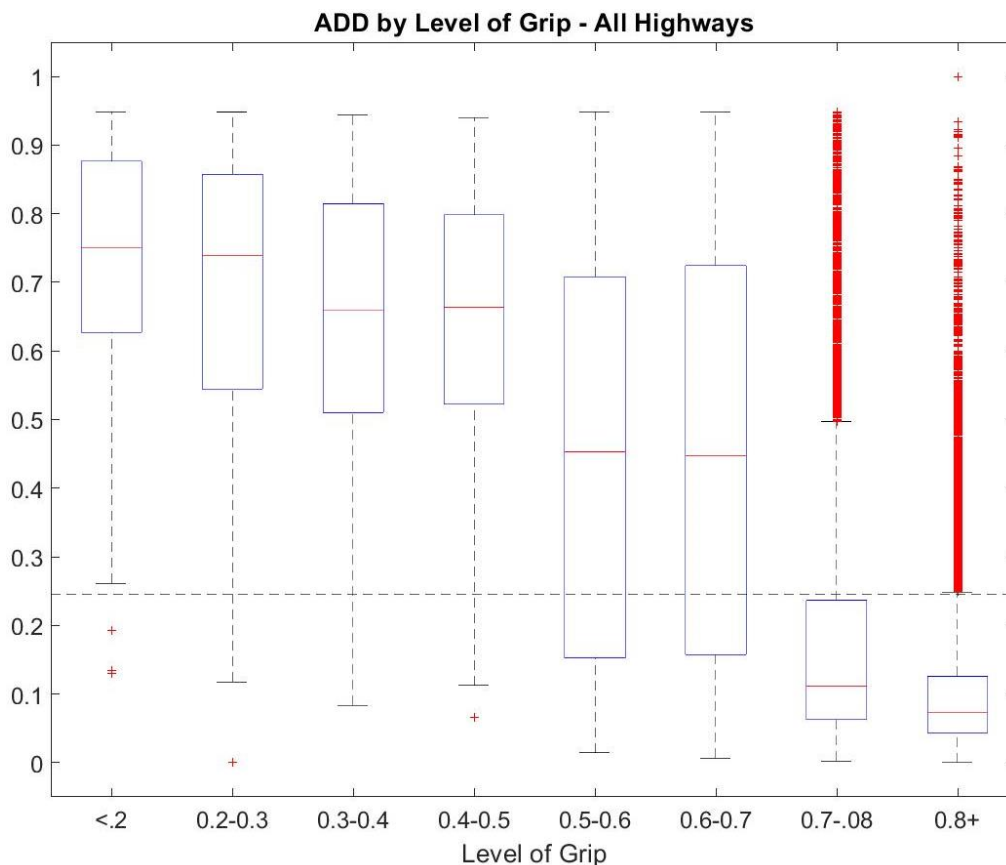


Figure 16. ADD versus Grip - winter 2016-17

Higher ADD values indicate a more substantial change in the speed distribution. When Grip is very compromised, the ADD is generally large (upper left of the Figure) but there are a number of observed cases where the ADD is within the normal range (below the dashed horizontal line), showing that driving speed have not changed substantially even though the roads are very slick. Normally ADDs occur more commonly when Grip is in the 0.5 – 0.6 range. In all instances when Grip is compromised and the ADD is relatively normal, driver safety may be at increased risk.

Since the response of the traveling public is not always consistent with Vermont's "safe roads and safe speeds" policy, circumstance where speeds are not reduced (or not sufficiently reduced) in response to road conditions, can create increased accident risk. Since the ADD considers the speed distribution of the entire traffic stream, the effect of individual inconsistencies (overly dangerous or overly risk-averse drivers) are muted. Therefore, situations in which the traffic stream is not reacting to the road

surface conditions (as indicated by Grip loss) as expected may be indications of increased risk to drivers. An increased occurrence of crashes would confirm that this increased risk is present.

To identify high risk periods, the research team extracted records where the ADD was within the normal range and Grip was less than or equal to 0.6. These cases indicate that speed distribution of the traffic stream did not differ from the typical speed distribution for non-weather days but that road conditions were degraded. This analysis was performed using the ADD calculated at 10-minute intervals. This subset of data represents some of the highest risk periods since traffic speeds have not adjusted appreciably from normal patterns. Risk might still be elevated in other periods with ADD above the ADD threshold as a change in travel speed distributions does not guarantee that travel speeds are sufficiently reduced for the road conditions. Records for VT11 Winhall were ignored because the Grip readings are suspect, indicating a near-total loss of Grip continuously, even in clear weather with a dry road surface.

An example of one such high-risk period occurred on March 15, 2017 at 8:15am on I-89 in Bolton. At this time, the Grip loss on the road surface was 0.6 (Grip = 0.22), indicating extremely icy, slippery conditions, but the ADD was 0.00, indicating that the traffic stream was perceiving the road surface conditions as normal.

Consecutive inconsistencies were grouped and identified by RWIS site and by day of occurrence, creating disparity-days (Ddays). Ddays correspond to a day and a location when the ADD and the Grip were inconsistent for at least 15 minutes. In order to measure the relative frequency of these events, the total number of site-days was also calculated. Site-days correspond to the product of the total number of winter days and the total number of sites with Grip readings. For example, in 2017 there were 20 RWIS sites reporting Grip (out of a total of 35) and 120 days of winter in January, February, March, and April, creating 2,400 possible site-days. 68 of these site-days (or approximately 3%) were identified as Ddays because ADD and Grip were inconsistent for at least 15 minutes during that day. In 2017-2018, there were 3,900 site-days because the number of RWIS sites reporting Grip increased to 26 and the research team was able to include December in the analysis. 105 of these site-days (or approximately 3%) were identified as Ddays.

Safety outcomes were measured using the crashes and other state police dispatches associated with snow and ice. To determine if these safety outcomes were over-represented on Ddays, the two data sets were overlaid geographically to identify crashes and incidents that were near an RWIS site with a Dday. "Nearness" was considered to be within a mile of the RWIS site

on the same roadway where the RWIS station was measuring road conditions. Then, this proximate set of crashes and incidents were combed to determine which, if any, occurred on the same date as the Dday. If both of these conditions were satisfied, then the Dday was determined to have had an adverse safety outcome. The difference between the % of Ddays with an adverse safety outcome and the % of non-Ddays with an adverse safety outcome might be an indicator that Ddays have some predictive power for adverse safety outcomes.

A second way of identifying the predictive power of these Ddays is to measure the difference between Ddays with an adverse safety outcome and those without in the set of adverse safety outcomes (crashes + incidents). In the winters of 2016-2017 and 2017-2018, there were a total of 70 and 55 adverse outcomes near RWIS sites with Grip, respectively. Of these, 21% (or 15) and 49% (or 27) occurred on Ddays.

Taken together, these two measures support the tendency of adverse safety outcomes to occur on Ddays, although not supported by statistical testing. Table 12 summarizes the co-occurrence of Ddays and adverse safety outcomes.

Table 12 Summary of Ddays and Adverse Safety Outcomes in 2017 and 2018

	2016-2017	2017-2018
Total Site-Days	2,400	3,900
Total Ddays	68	105
Ddays with Adverse Safety Outcome	22% (15)	17% (18)
Non-Ddays with Adverse Safety Outcome	2.4%	1.2%
Statewide All Adverse Safety Outcomes...	4,192	5,690
...Near RWIS with Grip	70	55
...Near RWIS with Grip on a Dday	21% (15)	49% (27)

Table 13 summarizes the adverse safety outcomes on Ddays by winter month for 2016-2017 and 2017-2018.

Table 13 Summary of Ddays and Adverse Safety Outcomes in Vermont

Winter Month	2016-2017			2017-2018		
	Ddays		Vermont AWSSI (Burlington / Rutland)	Ddays		Vermont AWSSI (Burlington / Rutland)
	Total identified	..with adverse safety outcome		Total identified	..with adverse safety outcome	
December	-	-	mild / average	35	6	severe / extreme
January	11	3	mild/mild	27	6	severe / extreme
February	25	8	mild/mild	23	4	moderate/severe
March	19	4	mild/moderate	8	2	moderate/extreme
April	13	0	mild/moderate	12	0	moderate/extreme

Although there were no adverse safety outcomes on Ddays in April for either year, none of the other winter months seemed consistently associated with the co-occurrence of Ddays and adverse safety outcomes. In addition, the severity of the winter did not seem to be a good predictor of how adverse safety outcomes and Ddays would be related. For example, the month of February 2017 saw 8 Ddays with adverse safety outcomes out of a total of 25 Ddays, yet the winter was rated as “mild” at both the Burlington and Rutland weather stations.

The locations in Vermont with the most frequent occurrences of Ddays were the Fair Haven, Bolton, and Brookfield RWIS sites. Locations with occurrences of Ddays which also exhibit relatively frequent adverse safety outcomes are Berlin, Bolton, Brookfield, and Hartford – all along the I-89 corridor between Burlington and the New Hampshire border.

6 Conclusions and Recommendations

One of the primary outcomes of this research is a comprehensive validation of RSIC performance measures for Vermont, especially those that are reported in the Vaisala RWIS data reports. In particular, the imputed Grip measure showed great promise for use in RSIC performance measurement, but its imputation algorithm was unknown and its relevance to on-the-road decision-making had not been validated.

The level of Grip reported at RWIS sites was found to be a proxy for skidding friction, with the following reported correspondence to road surface conditions (Jensen et al., 2014):

- 0.6 to 0.8: usually dry (or wet) surface
- 0.5 to 0.6 slush or ice forming
- 0.4 to 0.5 snow pack or icy
- 0.3 to 0.4 icy - vehicles may start sliding off
- 0.0 to 0.3 icy - multiple vehicle slide offs possible; mobility greatly affected

Two significant findings of this research support the usefulness and effectiveness of the Grip measure for RSIC performance measurement. First, the algorithm for the calculation of Grip was reverse-engineered from the RWIS data over the winters of 2016-2017 and 2017-2018 and the resulting algorithm is consistent with research connecting these layer thicknesses to skidding friction. The algorithm includes consideration of thicknesses of ice, snow, and water on the road surface, as well as the surface temperature. . Therefore, the Grip measure seems to be the best proxy for road surface friction, exhibiting a strong tendency to signal dangerous conditions on the roadway. Second, the Grip measure was validated with supervisor reported conditions of the road surface by obtaining simultaneous reports of both. An app was developed to solicit supervisor feedback on the need for RSIC, and that feedback was found to correlate well with the Grip values reported at the nearby RWIS site. Where the two diverged, a plausible explanation was always found. For example, the reports of a supervisor who is dispatching RSIC vehicles to pre-treat a roadway in advance of a storm or in advance of a temperature drop will not correlate well with the Grip readings at that time, but that does not mean that either indicator is erroneous.

Once its effectiveness had been established, the relationship between Grip and the speed of the traffic stream was explored to better understand their correlation. The team used the ADD to explore this correlation. The ADD and Grip were found to be relatively poorly correlated (0.60), indicating that each measure is independently useful and one cannot be used as a proxy for the other. In fact, the exploration revealed that instances when ADD and Grip

diverge maybe especially useful for signaling high-risk situations, or situations when the traveling public is not correctly perceiving the road surface conditions. In other words, these divergences can indicate one of two troublesome situations:

3. Grip has been compromised but the traffic stream has not responded by generally decreasing speeds
4. Grip is sufficient but the traffic stream has slowed as if it has been compromised

The team found that unmeasured outcomes like visibility and traffic congestion could be to blame for some of these divergences. The first situation is particularly troubling, since it indicates potentially increased risk from adverse safety outcomes. These discrepancies between ADD and Grip, identified as “Ddays” in this research, show a strong co-occurrence with crashes and other snow and ice-related incidents, increasing the risk of one of these adverse outcomes by 3-4 times. However, this conclusion is based on a very limited set of data for the winters of 2016-2017 and 2017-2018, so more research is needed to support this conclusion.

If the ADD-Grip discrepancies can be used to predict crashes, then this finding could be extremely useful for winter traffic safety in Vermont. For example, a programmable message board, linked to the real-time calculation of the ADD-Grip discrepancy, can be used to communicate poor Grip situations, with special urgency added when the ADD is indicating that current speeds are not safe. This research also supports the use of variable speed limits that are responsive to real-time reports of Grip and ADD.

RSIC performance measurement includes benchmarking measures of effectiveness with measures of winter storm and season severity. To that end, a series of winter storm and season severity indices were reviewed for their effectiveness and applicability to Vermont:

- The Severity Index (SI) from Vaisala and the Idaho Transportation Department
- Winter Severity (WS) by Meridian Environmental Technology
- The Storm Severity Index (SSI) by the University of Iowa
- The Accumulated Winter Season Severity Index (AWSSI) by the Midwestern Regional Climate Center
- The Winter Storm Severity Index (WSSI) by the National Weather Service

Of these, the AWSSI was found to be effective, based on sound research, applicable to Vermont, and relying on easily obtainable data. In addition, although the AWSSI was developed as a seasonal measure of winter severity,

its daily updating algorithm makes it an effective indicator of storm-specific conditions. The MRCC currently calculates the AWSSI for two locations in Vermont. However, these locations are not sufficient to capture the significant local variation in winter storm trends across Vermont. Therefore, the research team recommends the use and expansion of the AWSSI (or the pAWSSI) in Vermont.

To demonstrate its usefulness, the pAWSSI was calculated for 27 weather stations across Vermont, using data obtained from the NOAA's GHCND program for the winters of 2016-2017 and 2017-2018. Future research should include the development of a web-based tool, similar to the one developed by MRCC, to calculate the pAWSSI at all 27 locations in Vermont on a daily basis, with real-time updates. This step would allow supervisors and decision-makers to benchmark RSIC performance in real-time, evaluating storm-specific performance as well as seasonal performance.

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