Evaluation of SSI and WSI Variables

Final Report

CLEAR ROADS
research for winter highway maintenance

The Narwhal Group

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Leigh Sturges of the Narwhal Group

Laura Fay, Karalyn Clouser, and Natalie Villwock-Witte of the Western Transportation Institute

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16. Abstract
The reliability of variables used in the calculation of storm severity indices or winter severity indices (SSIs/WSIs) was evaluated via an expansive literature review, an international survey, and two rounds of interviews with data and device managers. A Recommendations Guide was created to help agencies who want to improve upon or build anew an SSI/WSI; and included a thorough outline of reliable data, data sources, and SSI/WSI calculation methods. A spreadsheet tool was built that guides a user through the process of choosing variables and methods to address their predominant weather concerns.

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Executive Summary

This project, entitled Evaluation of Storm Severity Index (SSI) and Winter Severity Index (WSI) Variables, was sponsored by Clear Roads member states out of a desire to examine the reliability of variables used in the calculation of winter weather severity indices.

SSIs/WSIs are used by surface transportation agencies to assign a "unitless" value to the perceived severity of the weather from a maintenance perspective. In other words, the index grades the degree to which the weather impacted maintenance resources.

Almost all agencies that employ an SSI/WSI encounter challenges of some variety. Because weather and the road environment are complicated systems with many variables contributing to the ultimate road state, it is an inexact science to assign a single numerical value to the perceived severity. Moreover, the definition of severity itself will differ among maintenance departments.

This project arose because of another challenge: that of the problems with data ingested by the algorithms. Weather data frequently suffers from at least one of the following issues: poor resolution, poor quality, or it is non-existent altogether. The data may not be sampled at desirable locations, may be error-prone, or may not be the exact data required by the algorithm. Thus, this project sought to summarize the many types of data used by agencies around the world, then evaluate the reliability of each data type and data source in a severity context. Despite challenges faced by many agencies, most have found success in using their index as a normative part of maintenance management, performance measurement, or public relations.

To accomplish the outlined objectives of this project, a literature review was performed to serve as a foundation for the information-gathering tasks. As a part of this task, the research team built an exhaustive catalog, from a wide spectrum of methodologies, of the data used, the various statistical treatments of the data, and the sources from which the data come. Findings from the literature review showed that no one data source provides a perfect dataset for transportation related WSI purposes. Many indices use multiple datasets, so that one fills in where the other is lacking. This can then limit the spatial scope of the calculation, as most observational network locations are (intentionally) not duplicated with another.

The Research Team conducted a web-based survey seeking to understand the ways in which the SSI/WSI is used by local, state, and international agencies, the variables and equations used to calculate the index, and how the relevant data are collected. Information was sought from agencies who have developed and housed their WSI internally, as well as those who have implemented software or methods developed externally (by vendors or universities). Relevant survey findings include:

- The prevailing sentiment expressed among survey respondents is that the SSI or WSI has been a valuable tool for helping to contextualize performance and explain cost.
- A second major sentiment is that, because it is a tool that is so highly desired, agencies wish for it to be a reliable and accurate representation of winter severity conditions that is relatively simple to implement.

- Most, if not all, agencies are not completely satisfied with their SSI/WSI. Indeed, even for agencies reporting satisfaction, there exists some acceptance that the methodology is not perfect and that some allowance for error or caveats must be made.
- Agencies that are dissatisfied with their WSI are usually missing a critical weather data element.
- Data fidelity concerns are also often cited as an impediment to building a satisfactory SSI/WSI.
- Accounting for special weather scenarios (such as freezing rain, extreme cold, or pre-existing road snow) can confound some basic methods of SSI/WSI calculation. Freezing rain is frequently noted as a critical, but problematic, SSI/WSI parameter to include; and methods that have more successfully captured it have done so using human observation, combinations of data (specifically, precipitation type with road temperature data, or precipitation with wet-bulb and road temperature), or weather models.
- Good quality data of good resolution has been identified as a need and a challenge in SSI/WSI development. Support in terms of what this means and how to achieve this could greatly benefit states pursuing the use of an SSI/WSI.
- Many methods assess severity after a storm or after a season, and yet there is growing opinion (and demonstrated successes) that real-time severity calculation can improve maintenance decision making during an event.
- Another predominant opinion is that directly adopting a product built elsewhere is unadvisable. Building an agency's own index should, however, involve learning from other agencies and include diverse groups within the agency (upper management, maintenance decision makers, weather experts, etc.).

Using the information gathered from the survey, the Research Team was able to identify agencies and methods that have demonstrated success and to follow up with these agencies to gather more information. During two rounds of interviews—involving agency personnel, academic partners, private partners, and data managers—a great deal of detail was gathered on the reliability of the algorithms, data, and data sources described by each agency.

Recommendations Guide

The information sources described above were used to develop the following recommendations. Ten successful SSI/WSI methods were described as model examples, and their variables, data, and data sources were evaluated. From the evaluation, step-by-step recommendations were made for agencies interested in building or improving upon an SSI/WSI. Ten SSI/WSI methods were described:

1. The Accumulated Winter Season Severity Index (AWSSI; Boustead et al., 2015)
2. The Boselly Method (Boselly et al., 1993)
3. The Idaho Method
4. The Iowa Method
5. The Matthews Method (Matthews et al., 2017a,b)
6. The Minnesota Method
7. The Pennsylvania Method
8. The Road Weather Severity Based on Environmental Energy 2 (RWSBEE2) model (Baldwin et al., 2015)
9. The Utah Method
10. The Walker Method (Walker et al., 2018)

The data used for each was cataloged, resulting in over 25 different variables identified for use in the SSIs/WSIs:

Atmospheric Variables

- Air temperature
- Wet-bulb temperature
- Wind speed, gust, direction
- Visibility
- Vertical temperature profile

Pavement Variables

- Road temperature
- Surface condition
- Friction/grip
- Layer thickness

Precipitation variables

- Precipitation type
- Snow occurrence
- Snow accumulation and depth
- Snowfall rate
- Blowing snow
- Freezing rain occurrence, duration, and accumulation

Radiation variables

- Shortwave and longwave radiation
- Sensible and latent heat fluxes

Temporal variables

- Frequency of events
- Duration of events

From the highlighted SSIs/WSIs, 17 different data sources were identified and classified based on type:

- Road weather-specific data sources
    - Road Weather Information System (RWIS)
    - Operator logs
    - Maintenance Decision Support System (MDSS)
    - Mobile observations
- Federal government-managed weather station networks
    - Automated Surface Observing System/Automated Weather Observing System (ASOS/AWOS)
    - Cooperative Observer Program (COOP)
    - Remote Automatic Weather Station (RAWS)
    - Environment Canada (EC) network
    - Global Historical Climatology Network (GHCN)
- Modeled data analyses
    - Rapid Refresh (RAP) model
    - North American Land Data Assimilation (NLDAS) dataset
    - Snow Data Assimilation System (SNODAS)
    - Stage IV precipitation analysis
- Special-mention networks and databases:
    - State-owned mesoscale network (mesonet)
    - Community Collaborative Rain, Hail & Snow (CoCoRaHS)
    - Regional Climate Center (RCC) databases
    - Other external databases

A summary of each data source and the variables reported by each is provided in the body of the report. Findings from the review of data sources show that air temperature and humidity-related variables are readily available from all automated and modeled data sources. Snow accumulation is easily available from a number of sources, but one should keep in mind that there are still a number of difficulties in measuring snow, particularly using automated instrumentation. The resolution of the measurement (both in time and space) may not be to the users' desires for SSI/WSI. Freezing rain appears to be readily available from many sources, but freezing rain may be derived using multiple other observations.

Automated Observations

There are important advantages and disadvantages to automated (i.e., via a device or instrument), human-reported, and modeled data sources, as described below.

- Advantages
  - Able to be installed where measurement is needed
  - Nearly any desired environmental parameter is measurable
  - High-temporal resolution
- Disadvantages
  - Require resources to install and maintain devices
  - Require resources to quality assure data
  - Even though nearly any desired environmental parameter is measurable many automated measurements still face challenges

Human-reported Observations

- Advantages
  - High spatial resolution
  - Nuanced reporting
  - Can provide qualitative and (some aspect of) quantitative observation
- Disadvantages
  - Low temporal resolution
  - Can be biased
  - Can be inaccurate
  - No atmospheric values

Modeled Observations

- Advantages
  - Nearly any environmental parameter can be modeled
  - There is a vast amount of modeled data available online
  - Modeled values can be interpolated to any spot at the surface
- Disadvantages
  - Modeled values are an estimate based on physical equations and not a measured condition
  - Models still require vast amounts of data to run
  - Models require computational resources to run

- Because models are more often available from external organizations, the user's options are restricted to the data that is made available by the organization

Table 1 shows the data sources used by each method, marked by an "X" and those marked by a "Y" indicates that the data source is used by a modified version of the method, as described in the Method Breakdown section. Most of the methods use RWIS data, either exclusively, or as a supplement to other sources. No methods (yet) use mobile observations.

Table 1: Data Sources Used by Each Method

Method	Data Sources									
	RWIS	Operator Logs	MDSS	Mobile Observations	ASOS/AWOS, EC	COOP	RAWS	GHCN	Model Analyses	State Mesonet
AWSSI								X		Y
Boselly	X				X		Y			
Idaho	X									
Iowa	X	X								
Matthews	X				X					
Minnesota	X		X		X				X	
Pennsylvania	X									
RWSBEE2			X						X	
Utah	X									
Walker					X			X		

Because most methods use RWIS and/or a federally-managed weather station network—often using one to supplement the other—a comparison of advantages and disadvantages of each is provided here:

RWIS

- Advantages
    - Agency management allows for deployment of desired instrumentation and quick fixes when needed
    - Measurement of pavement temperature and conditions
    - Located in critical road weather areas
- Disadvantages
    - May suffer from lack of maintenance and calibration
    - Older pavement instrumentation may suffer from inaccuracies
    - Not spatially consistent; often too concentrated in urban and high winter severity areas

Federal Government Networks (ASOS/AWOS, RAWS or COOP)

- Advantages
    - Well-maintained; trusted data

- May capture precipitation type and accumulation
    - Long climate record
    - May incorporate manual measurements from well-trained observers
    - Feed into official climate databases in which external agencies (e.g., regional climate centers) quality control and process the data and make it readily available
- Disadvantages
    - No pavement data
    - Not often located on or near roads

There are certain weather events which impact maintenance resources in specific ways, but which are also challenging to measure using automated means. These special weather scenarios may happen rarely, and therefore do not play a dominant role when planning RWIS or building an index, compared to more routine winter weather.

The transportation community is finding that these special scenarios are impactful enough, even if rare, to warrant special attention in observation and index calculation. Feedback from the transportation community has identified these particularly difficult weather scenarios as *freezing rain*, *blowing snow*, and *widespread frost.*

Freezing Rain. A key challenge in incorporating freezing rain in severity indices, is that it is difficult to observe using automated, ground-based sensors. A summary of the ways in which the methods described in this report measure freezing rain include:

- Operator reports: Iowa Method collects frequency and duration of freezing rain events in maintenance crew logs.
- MDSS: Minnesota Method uses multiple environmental observations, plus a pavement model, to estimate the accumulation of ice on the road.
- RWIS:
    - Pennsylvania Method uses a present weather detector that reports the occurrence of freezing rain. (Note: many present weather detector models have the capability to identify freezing drizzle separate from freezing rain.)
    - Utah Method uses precipitation occurrence, wet-bulb temperature (> 34°F), and road temperature (≤ 32°F) from RWIS to deduce the occurrence of freezing rain.
    - Idaho Method uses friction data.
- RWIS + federal weather stations: Matthews Method uses RWIS pavement ice warnings plus rain occurrence (from EC stations) during low temperatures.

Some additional ideas of how freezing rain could also be measured include, but are not limited to:

- Using modeled or observed vertical temperature and humidity profiles;
- Using CoCoRaHS or NWS COOP data; and
- Adapting a methodology similar to that described in Sanders and Barjenbruch (2016) to automated observations.

Blowing Snow. Validating the occurrence of blowing snow also requires special observational capabilities. While it acts like precipitation, as additional snow is deposited on the road surface—the snow particles are unable to be captured by a precipitation sensor mounted at greater than 6 feet above the ground. Thus, the following alternative means have been used in methods described here to identify the occurrence of blowing snow for SSI/WSI:

- Operator reports: Iowa Method collects duration of blowing snow in maintenance crew logs.
- MDSS: Minnesota Method uses MDSS, which assimilates multiple environmental observations and feeds them into a blowing snow model.
- RWIS:
  - Idaho Method collects wind speed and surface water layer from RWIS, and the storm technically ends two hours after the road surface is bare of ice and snow (*not* after precipitation has ended).
  - Utah Method uses a relationship between wet-bulb temperature and wind gust to estimate the occurrence of blowing snow.
- RWIS + federal weather stations: Matthews Method uses RWIS wind data plus EC snowfall data to estimate the occurrence of blowing snow.
- Modeled analyses: RWSBEE2 uses wind speed, precipitation occurrence, air temperature data, and local vegetation (from Stage IV, respectively) to estimate the occurrence of blowing snow.

A critical component of blowing snow that should be kept in mind is that, by nature, it is patchy. The methods using a model grid or human observation will be able to observe blowing snow even where there are no weather stations. RWIS could be installed at known blowing snow locations in order to monitor conditions after fresh snow has fallen.

Frost is different than freezing rain in that the ice does not usually accumulate thickly but can significantly reduce roadway friction. Frost is difficult to measure using automated instrumentation. Using air temperature and humidity, paired with road temperature, road frost may be deduced using RWIS sensors. Adding a pavement condition or friction sensor will help to validate the occurrence of frost. Otherwise, operator reports or MDSS have been shown to provide a good representation of frost occurrence.

For the agency ready to develop or improve upon their SSI/WSI, there is a wealth of experience from which to draw. The methods described above represent the state of the art in SSI/WSI calculation. Moreover, the methods offer a range of methodologies, from simple to complex, from real-time to after-storm analysis. A number of common themes were identified:

- The successful methods have involved multiple groups within the agency from the get-go, with buy-in from every level.
- Often, it takes a few seasons for the index to build context and for it to mean something to the DOT.
- A severity index will never perfectly describe severity, or perfectly fit to maintenance response data. Instead, the agencies which use their index successfully understand and work within the limitations of their method.
- Many SSIs/WSIs have evolved overtime based on experience and evaluation.
- The agency that works within its computational, observational, and personnel capabilities will be successful, even when that means seeking the assistance of a trusted partner.

From the evaluation of existing methods, data, and data sources, six big-picture steps were identified to aid in the development, or improvement, and implementation of SSIs/WSIs by agencies, including:

1. Identify goals for SSI/WSI use
2. Identify who should be at the table from your agency
3. Identify variables and data source(s)
4. Develop or identify SSI/WSI method to be applied
5. Identify SSI/WSI application and how it will be utilized
6. Evaluate the results and/or improve SSI/WSI

Detailed descriptions of each step are available in the main body of the report.

The research team distilled the information available in the Recommendations Guide into a simple tool that walks a user through possible variables and methods to be used to calculate severity for specific weather patterns. The user selects (1) the weather patterns/key weather concerns for their jurisdiction and (2) variables/data of interest or that are available, and the tool highlights (3) the methods that use those variables. Using the information found in the Recommendations Guide, the user can then determine which method(s) are right for their agency, or whether building an index from scratch will be the best course of action.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
AWSSI	Accumulated Winter Season Severity Index (Boustead et al., 2015)
BSV	Blowing Snow Value (as in Utah method)
CoCoRaHS	Community Collaborative Rain, Hail & Snow
COOP	Cooperative Observer Program
CDOT	Colorado Department of Transportation
DOT	Department of Transportation
EC	Environment Canada
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRV	Freezing Rain Value (Utah method)
GHCN	Global Historical Climatology Network
GHCN-D	Global Historical Climatology Network - Daily
HRRR	High-Resolution Rapid Refresh
ITD	Idaho Transportation Department
INDOT	Indiana Department of Transportation
LOS	Level of Service
MassDOT	Massachusetts Department of Transportation
MDSS	Maintenance Decision Support System
MDOT SHA	Maryland Department of Transportation State Highway Administration
MDT	Montana Department of Transportation
Mesonet	Mesoscale network
MnDOT	Minnesota DOT
MRCC	Midwestern Regional Climate Center
MTO	Ontario Ministry of Transportation
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NeRAIN	Nebraska Rainfall Assessment and Information Network
NEWINS	Nebraska Winter Severity Index
NLDAS	North American Land Data Assimilation dataset
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NWS	National Weather Service
NYSDOT	New York State Department of Transportation
PennDOT	Pennsylvania Department of Transportation
PM	Performance measurement
QA	Quality assurance
QC	Quality control
RAP	Rapid Refresh
RAWS	Remote Automatic Weather Station

RCC	Regional Climate Center
RCV	Road Condition Value (Utah method)
RFC	River Forecasting Center
RH	Relative humidity
RTV	Road Temperature Value (Utah method)
RWIS	Road Weather Information System
RWSBEE2	Road Weather Severity Based on Environmental Energy 2 (Baldwin et al., 2015)
SII	Storm Intensity Index (Utah method)
SNODAS	Snow Data Assimilation System
SRV	Snowfall Rate Value (Utah method)
SSI	Storm Severity Index
SWI	Severe Weather Index (as in Maryland method)
UDOT	Utah Department of Transportation
US	United States
VTP	Vertical Temperature Profile
WI	Winter Index, as defined by Boselly et al. (1993)
WPI	Winter Performance Index (as in Idaho method)
WRWI	Winter Road Weather Index
WSDOT	Washington State Department of Transportation
WSI	Winter Severity Index

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This project was funded by Clear Roads and the Minnesota DOT. It would not have been possible without the time and attention of the members of the Clear Roads Project Subcommittee.

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Indiana DOT

- Dr. Mike Baldwin – academic partner

Iowa DOT

- Tina Greenfield

Massachusetts DOT

- Mark Goldstein
- Bill Arcieri – consultant

Minnesota DOT

- Jakin Koll

New York State DOT

- Joe Thompson
- Ken Relation
- Dr. Nick Bassill – academic partner

Ontario Ministry of Transportation (MTO)

- Heather McClintock – formerly of MTO
- Robert Mount

Oregon DOT

- Patti Caswell
- Ace Clark

Pennsylvania DOT

- Jason Norville
- Vince Mazzocchi
- Jonathan Fleming

Utah DOT

- Jeff Williams
- Cody Oppermann

Washington State DOT

- James Morin
- Ken Rosenow – consultant

Mike Adams from Wisconsin DOT and Brian Burne from Maine DOT also shared valuable information on experiences at their own agencies.

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- Dr. Curtis L. Walker (NCAR)
- Lindsay Matthews (University of Waterloo)
- Lisa Verzella (National Weather Service, Salt Lake City)
- Scott Jensen, Justin Connolly, and Ken Rosenow (Weathernet/The Narwhal Group)

Invaluable members of the research team who reviewed and contributed to this document are: Neil Hetherington (graphics) and Dana May and Carla Little (editors) at Western Transportation Institute, and Chris Albrecht (Director of Consulting Services) at the Narwhal Group.

Introduction and Project Overview

This project, entitled Evaluation of Storm Severity Index (SSI) and Winter Severity Index (WSI) Variables, was sponsored by Clear Roads member states out of a desire to examine the reliability of variables used in the calculation of winter weather severity indices.

SSIs/WSIs are used by surface transportation agencies to assign a unitless value to the perceived severity of the weather from a maintenance perspective. The SSI/WSI grades the degree to which the weather impacted maintenance resources. The term SSI/WSI will be used throughout the document. It should be considered an umbrella term that encompasses all possible forms of the winter-specific severity index.

There will be other terms used in this document, but only when referring to a specific method. For example, the Boselly method defines a Winter Index (WI), the Utah method defines a Winter Road Weather Index (WRWI), and so on.

Almost all agencies that employ an SSI/WSI encounter challenges of some variety. Weather and the road environment are complicated systems with many variables contributing to the ultimate road state. It is an inexact science to assign a single numerical value to the perceived severity. Additionally, the definition of severity itself will differ among maintenance departments.

Another challenge when considering the use of an SSI/WSI is with the data used by the algorithms. Weather data frequently suffers from at least one of the following issues: poor resolution, poor quality, or it is non-existent altogether. The data may not be sampled at desirable locations, may be error-prone, or may not be the exact data required by the algorithm. Thus, this project sought to summarize the myriad types of data used by agencies around the world and evaluate the reliability of each data type and data source in an SSI/WSI context.

Despite challenges faced by many agencies, most have found success in using their index as a normative part of maintenance management, performance measurement, or public relations. Ten successful SSI/WSI methods are described, and their variables, data, and data sources are evaluated. From the evaluation, recommendations are presented for the agency interested in building or improving upon an SSI/WSI. (Task 5 is the section in this report which summarizes this information and presents the research team's recommendations.)

The remainder of this report describes the project's seven tasks in full:

- Task 1: Literature Review
- Task 2: Survey of Practice
- Task 3: Follow-up Survey
- Task 4: Data Analysis and Collection Methods
- Task 5: Recommendations
- Task 6: Agency Follow-up
- Task 7: Spreadsheet Tool

The Task 5 section accounts for the bulk of the main body of the report, encapsulating one of the central goals of this project: creating an exhaustive guide that details each SSI/WSI method, variable, and data source (Chapter 1); then walking a reader through the process of creating or modifying their own SSI/WSI (Chapter 2). The Task 7 section describes a second central goal of this project: building a basic tool that walks a user through weather scenarios and potential variables and SSI/WSI methods to evaluate the severity of that weather.

Task 1: Literature Review

A literature review was performed to serve as a foundation for the information-gathering. The research team gathered information from relevant publications and presentations from the early 2000s to present, with the exception of the initial Strategic Highway Research Program (SHRP) winter index development, which was completed in 1993. A summary of the key details is provided in Appendix A. Task 1 Literature Review.

From the Literature Review, the research team built an exhaustive catalog, from a wide spectrum of methodologies, of the data used, the various statistical treatments of the data, and the sources from which the data come. As explained in the literature, no one data source provides a perfect dataset for transportation related SSI/WSI purposes. Many indices use multiple datasets, so that one fills in where the other is lacking, but this can then limit the spatial scope of the calculation, as most observational network locations are (intentionally) not duplicated with another.

There are many unique methods that have been developed to calculate SSIs/WSIs, some more involved than others. Variables tend to be chosen for inclusion in SSI/WSI calculations when they:

- Satisfy the fundamentals of environmental processes (that is, they are deemed critical for the severity calculation from a purely scientific standpoint);
- Are easily available (often this means they come from the agency's own weather stations);
- Offer good quality data;
- Show a good fit in regression analyses with maintenance data;
- Are supported by practitioner input; or
- A combination of those listed above.

In one point of view, using a very simple SSI/WSI may be advantageous for ease of calculation, manipulation, understandability, reproducibility, and end use. On the other hand, a more physically precise calculation can be more computationally intensive and require special instrumentation but may also lead to a more appropriate solutions desired by the agency.

Task 2: Survey of Practice

In Task 2, the Research Team developed and conducted a web-based survey seeking to understand the ways in which the SSI/WSI is used by local, state, and international agencies, the variables and equations used to calculate the index, and how the relevant data are collected. Information was sought from agencies who have developed and housed their WSI internally, as well as those who have implemented software or methods developed externally (by vendors or universities).

The survey was posted to Montana State University's Qualtrics website, online web -based survey tool, and can be found in Appendix B. Responses were requested from local, state and international agencies through Clear Roads, the Aurora Program, the American Association of State and Highway Transportation Officials (AASHTO) Snow and Ice Pooled Fund Cooperative Program (SICOP) Snow and Ice List Serve and the American Public Works Association (APWA) Winter Maintenance & Effects Committee; as well as individuals, agencies, and organizations identified in the Task 1 literature search summary. Efforts were made to ensure that the survey received responses from critical agencies.

The survey results are summarized in Appendix C. Task 2 Survey Results. Discussed in the survey results are: responses from agencies with and without an index, an overview of the methods used, additional reviewed literature discovered during the survey, a review of special weather scenarios which are difficult to measure, shared lessons learned, and opinions on the ideal index and how to get there.

Because international responses to the survey were lacking, the team directly contacted representatives from other countries. Thus, a section on international severity index methods is also provided in Appendix C.

The prevailing sentiment expressed among survey respondents, no matter the particular method used, is that SSI/WSI have been a valuable tool for helping to contextualize performance and explain cost. A second major sentiment is that, because it is a tool that is so highly desired, agencies wish for it to be a reliable and accurate representation of winter severity conditions that is relatively simple to implement.

Most, if not all, agencies are not completely satisfied with their SSI/WSI. For agencies reporting satisfaction, there exists some acceptance that the methodology is not perfect, and that some allowance for error or caveats must be made. On the other hand, agencies that are dissatisfied with their WSI are usually missing a critical component of their winter weather (such as freezing rain). Data reliability concerns are also often cited as an impediment to building a satisfactory SSI/WSI.

Including special weather scenarios (such as freezing rain, extreme cold, or pre-existing road snow) can confound some basic methods of SSI/WSI calculation. Freezing rain is frequently noted as a critical but problematic SSI/WSI parameter to include, and methods that have more successfully captured it have done so using human observation, combinations of data (specifically, precipitation type with road temperature data, or precipitation with wet-bulb and road temperature), or weather models.

Good quality data of good resolution has been identified as a need. Support in terms of what this means and how to achieve this could greatly benefit states pursuing the use of an SSI/WSI. Additional areas for future work include further development of how to best incorporate specific parameters such as freezing rain and ice, duration and thickness, and regional climate differences in SWI/SSI.

A few other key points were noted during the survey analysis. Many methods assess severity after a storm or after a season, and yet there is growing opinion (and demonstrated successes) that real-time severity calculation can improve maintenance decision making during an event. Looking ahead, the opportunities for predictive products are increasing with the demonstrated use of numerical weather models for severity forecasts (Grout et al., 2019 and Nelson, 2019). Indeed, there are many applications in which weather data from model grids can be applied to severity calculations (such as in Chien et al., 2014 and Baldwin et al., 2015).

Another predominant opinion is that directly adopting an SSI/WSI built elsewhere is unadvisable. This opinion was voiced by survey respondents and was also one of the conclusions of the Dao et al. (2019) study. If an agency chooses to build their own SSI/WSI they should first learn from other agencies and include diverse groups within their agency (upper management, maintenance decision makers, and weather experts). However, it is not always possible to build an index from the ground up; thus, when adopting a method developed elsewhere, it is advisable to make appropriate alterations to match the agency's end goals, data and software capabilities, and weather regimes.

There appear to be three (3) SSI/WSI sources of methods that are in use:

1. Developed by academia/research group (examples: AWSSI, Boselly, Matthews, and Walker)
2. Vendor-supplied software product/integrated with RWIS/data system (examples: MDSS or Vaisala's grip index [originally developed by Idaho])
3. Developed in-house (examples: Iowa or Utah)

Using the information gathered from the survey, the Research Team was able to identify agencies and methods that have demonstrated success in SSI/WSI development and use, and followed up with these agencies to gather more information on data and method reliability during Task 3.

Task 3: Follow-up Survey

The Research Team identified survey respondents which have been successful at developing and using an SSI/WSI as part of their maintenance management and planning. These respondents were contacted to collect additional information on variables and methods utilized at their agencies. A few agencies which did not respond to the initial (Task 2) survey were also contacted, because of the information gathered in literature review process and its relevance to this project.

The agencies that were contacted represent a wide range of SSI/WSI methods, development procedures (i.e., developed by in-house personnel, academia, vendor, etc.), and access to quality data and data sources. Appendix D. Task 3 Agencies and Follow-up Questions summarizes the information captured from these agencies, along with relevant details about each SSI/WSI.

Task 4: Data Analysis and Collection Methods

The Research Team conducted a second round of interviews with the agency managers of the data and/or the suppliers of the data for each agency to focus on learning about the reliability and efficacy of the instrumentation and the data collection methods used in SSIs/WSIs. Information on how well the variables and algorithms describe severity was also sought. The agencies that took part in interviews for this task effort included:

- Colorado Department of Transportation (CDOT), by way of the National Center for Atmospheric Research (NCAR)
- Idaho Transportation Department (ITD)
- Indiana DOT (INDOT)
- Iowa DOT
- Massachusetts DOT (MassDOT)
- Minnesota DOT (MnDOT)
- Montana Transportation Department (MDT)
- Nebraska DOT, by way of NCAR
- New York State DOT (NYSDOT)
- Pennsylvania DOT (PennDOT)
- Utah DOT (UDOT)
- Washington State DOT (WSDOT)
- Alberta Ministry of Transportation
- Ontario Ministry of Transportation (MTO)

The personnel contacted during Task 4 represent a detailed knowledge base on the data and data sources used for SSI/WSI calculation. They provided information to supplement that which had already been gained during the Task 1 Literature Review, the Task 2 survey, and the Task 3 follow-up.

The information gathered in Tasks 1, 2, 3, and 4 is summarized under each agency's heading in Appendix E. Task 4 Summary Report. Key information summarized for each agency includes: the SSI/WSI method used, data sources, calculation methods, and applications of the index. Information gained in Task 1-4 were used to develop the recommendations provided in Tasks 5 and 6.

Task 5: Recommendations

Introduction

The information contained in this section is presented to serve as guidance for the development or improvement of an SSI/WSI for use in maintenance departments at transportation agencies. ***This section may be used as a stand-alone Recommendations Guide.***

The term SSI/WSI will be used throughout this Guide. It should be considered an umbrella term that encompasses all possible forms of the winter-specific severity index. There will be other terms used in this report, but only when referring to a specific method. For example, the Boselly method defines a Winter Index (WI), the Utah method defines a Winter Road Weather Index (WRWI), and so on.

It is also worth noting here the difference between winter severity and performance measurement (PM). There is a delineation between the two in terms of the results sought. Though the discussions in this report have sought to stay purely in the weather severity lane, the topic often unavoidably bleeds into maintenance PM. Placing the evaluated performance of your maintenance crews into a weather severity context is a PM best practice (Xu et al., 2017; Dao et al., 2019). Thus, the two may be calculated independently, or as part and parcel of one another. There may be a drive to verify severity values with maintenance efforts (materials or labor used), and this is often done. However, many DOTs will build their SSI/WSI off of their experience, then grade their performance based on that.

A transportation agency may also be interested in assessing severity from a traffic disruption standpoint. This is also a calculation separate from those discussed herein. A potential tie-in with maintenance-focused severity indices is the effect that standstill traffic has on maintenance response; that is, when traffic density is maximized, plow trucks are unable to access roadways in a timely manner, increasing the perceived severity. For the purposes of this project, evaluating impact-based index practices and assessing traffic's impact on perceived severity will be recommended for future work.

This section of the report is organized as follows. Chapter 1 is a reference guide for contemporary SSI/WSI methodologies. Ten SSI/WSI methods were identified as prominent indices employed at North American transportation agencies. In this section each of ten SSI/WSI methods presented. The subsequent sections go into more detail regarding the variables used in each method and the sources from which the data come. A section at the end of Chapter 1 is dedicated to special weather scenarios which are difficult to measure and difficult to mitigate—freezing rain, blowing snow, and widespread frost—and how they have been or could be measured and incorporated into calculations.

Chapter 2 is a manual that takes the reader through a 6-step process of creating or improving an SSI/WSI at their own agency. Best practices and lessons learned were gathered from participating agencies and are included throughout Chapter 2.

The information in this section was assembled from published literature and personal communication with many representatives of the organizations responsible for the SSIs/WSIs reviewed here. A significant amount of time was donated by personnel affiliated with the participating agencies. These representatives have been identified in Acknowledgements. Should the reader desire more information on the methods discussed herein, contact information can be found in Appendix E.

Chapter 1: The Nuts and Bolts of Contemporary SSIs/WSIs

Overview

Chapter 1 provides an organized overview of the current state of the practice of SSI/WSI development and use. The following three sections provide summaries of the methods, variables, and data sources used in today's SSIs/WSIs. One page is dedicated to each of the 10 methods, 25+ variables, and 17 data sources reviewed in this chapter. At the beginning of each section, tables are included summarizing the information in a readily consumable format.

A final section provides information on special weather scenarios that are difficult to measure yet exact a sizable toll on maintenance resources. These weather scenarios are: freezing rain, blowing snow, and widespread frost. Experiences from agencies which have successfully captured this information are shared.

The agencies that provided the information summarized here come from a variety of climates, spanning the continental United States and Canada. Computational abilities and data availability vary at each agency. Thus, one can be reasonably assured that a wide range of techniques has been included in this summary.

(For the reader's reference, a separate, high-level review of SSIs/WSIs was recently completed by Walker et al., 2019a. This study sought to identify critical features of the SSIs/WSIs used at state agencies around the country and to group the indices by similar features.)

Method Breakdown

Ten different methods were described in this project and this section provides a one-page overview for each. Each page includes a description of the method, the variables, data source(s), and agencies using the index. They are organized on the following 10 pages in alphabetical order as:

- AWSSI
- Boselly Method
- Idaho Method
- Iowa Method
- Matthews Method
- Minnesota Method
- Pennsylvania Method
- RWSBEE2
- Utah Method
- Walker Method

The research team was involved in a parallel effort at Maryland Department of Transportation State Highway Administration (MDOT SHA) to develop a severe weather index (SWI; Fay et al., 2020). Because the Maryland project was unable to undergo the same evaluation effort put forth on the ten methods listed above, it is not included here. Instead, a 1-page summary of the Maryland Method is provided in Appendix F, and the full report is available from Fay et al. (2020).

For ease of consuming the information contained in this section, Table 2 provides a high-level summary of each method, including: variables, data sources, the spatial and temporal resolution of the index, and how the index defines a storm and a winter season.

Table 2: Summary of Key Method Features

Method	Variables	Data Source(s)	Spatial Resolution	Temporal Resolution	Defined Storm	Defined Winter Season
AWSSI	Air temperature Snow accumulation Snow depth	GHCN[1] State mesonet[2]	At GHCN sites	Daily data Daily calculation	Points only accumulate if daily temp ≤ 32°F or there is snow.	Start: Daily max temp[3] is ≤ 32°F, daily snowfall ≥ 0.1 in., or it is Dec 1st. End: Daily max temp always >32°F, snowfall no longer observed, or it is March 1st.
Boselly	Air temperature Snow accumulation	NWS[4] network (MassDOT) RWIS, ASOS/AWOS, RAWS[5]	At weather stations, and averaged over district or area	Daily data Daily calculation	Index is calculated daily or summed over a defined period	Nov 1 – Mar 31 (MassDOT) User-defined to capture storms (WSDOT)
Idaho	Wind speed Layer thickness Road temperature	RWIS	At RWIS	15-minute data Calculated per storm	Start: Precip[6] is detected and road temp <32°F. End: 2 hours after precip no longer detected on road.	November 1 – Mar 31; may be extended due to actual weather conditions or agency decision
Iowa	Number of snow and freezing rain events Snowfall amount Hours of snowfall, freezing rain, blowing snow, and sleet Road temperature	Operator logs RWIS	Per garage	Hourly & daily data Calculated per storm	Occurrence of snow, freezing rain, blowing snow or sleet	October 15 – April 15; or before or after if frozen precip occurs
Matthews	Snow accumulation Pavement condition Precipitation type Air temperature Wind speed	EC[7] network RWIS	Per maintenance area	Daily data Daily calculation	No defined storm; every winter day receives a score	October – April

[1] Global Historical Climatology Network
[2] Specific to New York State's mesonet as used for the modified AWSSI (see AWSSI subsection)
[3] Maximum air temperature (also "min" = minimum)
[4] National Weather Service
[5] Road Weather Information System, Automated Surface Observing System/Automated Weather Observing System, Remote Automatic Weather Station
[6] Precipitation
[7] Environment Canada

		Feature					
		Variables	**Data Source(s)**	**Spatial Resolution**	**Temporal Resolution**	**Defined Storm**	**Defined Winter Season**
Method	**Minnesota**	Air temperature Road temperature Dew point/RH[8] Frost/black ice occurrence Wind speed, gusts and direction Precipitation type, duration, amount Cloud cover (short- and longwave radiation) Surface pressure Blowing snow	MDSS[9] ASOS/AWOS	Per district and statewide	Sub-hourly and hourly data Calculated per season	"Any winter weather occur-rence that con-sumes resources necessary to prevent, minimize or regain the loss of bare lanes."[10]	October 1 – May 1, but extended on either side if winter weather occurs
	Pennsylvania	Snow accumulation Freezing rain accumulation Precip duration Air temperature	RWIS	Per county	Sub-hourly data Calculated per day and/or per storm	A single calendar day represents a single storm, unless there is a precip break of at least 8 hours within the day	October 1 – May 1
	RWSBEE2	Roughness length[11] Air temperature Wind speed Road temperature Shortwave & longwave radiation Sensible and latent heat fluxes Vertical temperature profile Precipitation type Visibility Wind gust Snow depth Precip accumulation	MDSS RAP[12] NLDAS[13] SNODAS[14] Stage IV precipitation[15]	$^1/_8$° latitude/ longitude (approx. 75-square-mile) grid	Hourly data Calculated in real time (hourly)	N/A (hourly calculation)	Nov-Mar

[8] Relative humidity
[9] Maintenance Decision Support System; incorporates RWIS, ASOS/AWOS, radar, satellite, numeric weather models, weather forecaster inputs, and many other weather data sources
[10] From http://www.dot.state.mn.us/maintenance/pdf/2019-winter-maintenance-report.pdf
[11] Please see Footnote 29
[12] Rapid Refresh model (more information in RWSBEE2 subsection and Modeled Data Analyses section)
[13] North American Land Data Assimilation dataset (more information in RWSBEE2 subsection and Modeled Data Analyses section)
[14] Snow Data Assimilation System (more information in RWSBEE2 subsection and Modeled Data Analyses section)
[15] Described in RWSBEE2 subsection and Modeled Data Analyses section

		Feature					
		Variables	**Data Source(s)**	**Spatial Resolution**	**Temporal Resolution**	**Defined Storm**	**Defined Winter Season**
Method	**Utah**	Road condition/grip Snowfall rate (visibility proxy) Road temperature Wet-bulb temp Wind gust Precip occurrence	RWIS	At RWIS	20-min data Calculated in real time (every 10 min)	When SII[16] remains >0 for a certain period of time	November 1 – April 30
	Walker	Snowfall total Snowfall rate (derived) Wind speed Air temperature District area Visibility Duration	ASOS GHCN	Per district	Hourly data Calculated per storm	When an ASOS is observing frozen precipitation	October – April

[16] Storm Intensity Index (see "Utah Method" subsection)

AWSSI[17]

Summary/Equation

The Accumulated Winter Season Severity Index (AWSSI) is calculated at identified Global Historical Climatology Network (GHCN) sites. This model is based on four components: (1) minimum air temperature, (2) maximum air temperature, (3) snow fall, and (4) snow depth. The resulting output is based on a daily count over the winter season (as listed in Figure 1).

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

Figure 1: Table showing points assigned to measured weather conditions: maximum and minimum air temperature, snow fall and snow depth. Source: Boustead et al. (2015)

The winter season begins when:

1) The daily maximum temperature is ≤ 32 °F,
2) Daily snowfall ≥ 0.1 in., or
3) It is December 1st.

The end of the winter season occurs when:

1) The daily maximum temperature ≤ 32 °F no longer occurs,
2) Daily snowfall ≥ 0.1 in. is no longer observed, or
3) It is March 1st.

Live AWSSI results are available at: https://mrcc.illinois.edu/research/awssi/indexAwssi.jsp#info

[17] Summary is based on information gathered from Boustead et al. (2015) and from communication with representatives of Montana DOT, New York State DOT and University at Albany.

Variables

- Air temperature
- Snow accumulation
- Snow depth

Data Source

- Global Historical Climatology Network (GHCN; used for base AWSSI calculation)
- New York State mesonet (used for modified AWSSI; see New York State DOT note below)

Agencies

- Montana DOT
- New York State DOT: Modifying AWSSI to include New York State mesonet data in hopes of including freezing rain, blowing snow and road temperature in the calculation.

Boselly Method[18]

Summary/Equation

$$WI = a\sqrt{TI} + b\ln\left(\frac{S}{10} + 1\right) + c\sqrt{\left(\frac{N}{R+10}\right)} + d$$

Where:

- TI is a temperature index. TI = 0 if the minimum air temperature is above 32°F; TI = 1 if the maximum temperature is above freezing while the minimum temperature is below 32°F; and TI = 2 if the maximum temperature is at or below 32°F. The average daily value is used.
- S is snow accumulation: mean daily values in millimeters (the number of days with snowfall was also considered but did not improve the index).
- N is number of air frosts: mean daily values of number of days with minimum air temperature at or below 32°F ($0 \le N \le 1$).
- R is temperature range: the value of mean monthly maximum air temperature minus mean monthly minimum temperature in °C.

And where *a* = -25.58, *b* = -35.68, *c* = -99.5, and *d* = 50.0. These terms account for temperature, snowfall, and frost, respectively, and *d* is a corrective term.

Variables

- Air temperature
- Snow accumulation

Data Sources

- National Weather Service (NWS) network
- RWIS, ASOS/AWOS, RAWS[2]

Agencies

- Massachusetts DOT (MassDOT)
- Washington State DOT (WSDOT): Because snow accumulation data is frequently either not trustworthy or not available across the state, modified Boselly using a binary snowfall occurrence (YES=1, NO=0) rather than accumulation[19].

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[18] Summary is based on information gathered from Boselly et al. (1993) and from communication with representatives of Massachusetts and Washington State DOTs.
[19] Please see Snow Accumulation & Depth page in Precipitation Variables section for insight into reliability of these data.

Idaho Method[20]

Summary/Equation

Storm Severity Index (SSI) = wind speed max (mph) + water equivalent layer max (mm) + 300/surface temp max (°F)

It is calculated for each identified storm event. A storm event starts when precipitation is detected and the pavement temperature is below 32°F. The storm event ends two hours after precipitation is no longer detected on the pavement.

Index values of 10-80 usually are calculated for normal winter events. Calculated indices for storms with severe cold and high winds can reach as high as 500.

Some weather events are exempt from the Winter Performance Index (WPI) scoring, namely, drifting, and powder snow events. The following weather events are modified in the WPI scoring: high winds, hydroplaning, frost events leading into storms, drifting/powder snow events that adhere to the roadway, fog that affects non-invasive sensor readings, and sensor errors.

The Storm Severity Index is used to evaluate maintenance performance using the following equation:

WPI = ice-up time (hrs) / Storm Severity Index

where *ice-up time* is the duration of the event when the grip is below 0.60 for more than ½ hour.

Variables

- Wind speed
- Water equivalent layer thickness
- Pavement temperature
- Friction[21]

Data Sources

RWIS

Agency

Idaho Transportation Department (ITD)

[20] Summary is based on information gathered from Jensen and Koeberlein (2015) and Koeberlein (2015), and from communication with representatives of Idaho Transportation Department.
[21] Technically, friction is used as part of Idaho Transportation Department's performance measure, not with the base severity index.

Iowa Method[22]

Summary/Equation

Presented here is Iowa DOT's Weather Index, originally inspired by Wisconsin DOT's index.[23] (see Appendix G for information on how Iowa DOT has evolved its index over time). Iowa's index creates an accumulated winter severity score for each garage based on the duration and frequency of events, snowfall amount, and pavement temperature over the winter. The duration and frequency of the events are normalized by the Iowa expected extreme for each event (the denominator in the equation's terms), then scaled by an "importance" factor (the numerator in the terms). The equation follows:

Weather Index = 10/57.0 * (# Snow events +
5.9/9.0 * # Freezing Rain events +
8.5/58.0 * snowfall in inches +
9.4/1125.0 * (Hours Snow +
Hours of Mixed Precipitation +
Hours of Freezing Rain +
Hours of Blowing Snow +
Hours of Sleet) –
0.25 * (*wsind* + *mpind* + *frind* + *sind*) +
0.5 * (*dsind* + *bsind*)

…in which,
wsind = average of lowest pavement temps during Wet Snow events – 29.6
mpind = average of lowest pavement temps during Mixed Precip. Events – 30.22
frind = average of lowest pavement temps during Freezing Rain events – 26.42
sind = average of lowest pavement temps during Sleet events – 29.52
dsind = 0.069 * (average of lowest pavement temps during Dry Snow events–20)^2
bsind = 0.069 * (average of lowest pavement temps during Blowing Snow events–20)^2

Variables

- Number of snow events
- Number of freezing rain events
- Snowfall amount
- Hours of snowfall
- Hours of freezing rain
- Hours of blowing snow
- Hours of sleet
- Pavement temperature

Data Sources

- Operator logs (daily logs provide each of the above variables except pavement temperature; this data source is detailed in the Road Weather-Specific Data Sources section below)
- RWIS

Agency

Iowa DOT

[22] Summary is based on information gathered from Iowa DOT-provided documents and from communication with representatives of Iowa DOT.
[23] Mike Adams of Wisconsin DOT described to the research team the index used there: it is a seasonal calculation including the number of snow events, number of freezing rain events, total snow amount, total storm duration and special incidents from operator storm reports in each county. It does not contain road surface data.

Matthews Method[24]

Summary/Equation

A point value (from 0 to 1.5) is calculated for each day. Zero points represents a day in which no maintenance efforts were "triggered;" 1 point represents a day in which routine maintenance occurs on and off throughout the day; and 1.5 points represent a day in which maintenance was required the entire day to mitigate extreme conditions. The points can then be aggregated weekly, monthly, and seasonally. Data from both RWIS and Environment Canada (EC) weather stations were used because EC data had precipitation data, and RWIS had pavement data.

The following weather conditions "trigger" the calculation (Appendix H provides greater detail):

- Three different categories of snowfall differentiated by snowfall amount (Environment Canada [EC] data)
- Two sets of conditions associated with icing (pavement ice warnings and rain with low temperatures; EC precipitation data, RWIS ice warnings)
- Series of cold days (where treatment may occur because bare pavement has not been achieved; RWIS temperature data)
- Blowing snow (RWIS wind data, EC snowfall data)

An optimization routine was built which defines appropriate threshold values for each of the weather triggers and daily scores that reflect the severity of the weather from a maintenance perspective. The program sets the severity value so as to optimize the correlation between the SSI/WSI and vehicle hours.

The index also adds in a shoulder season adjustment factor which reduces the severity scores when the average mean temperature remains above freezing for an extended period (RWIS temperature data).

The SSI/WSI is flexible, because it allows a location to tailor the number and type of weather triggers that best fit local conditions and practices. An optimization routine was built that defines appropriate threshold values for each trigger and daily scores that reflect the severity of the weather from a maintenance perspective.

Variables

- Snow accumulation
- Pavement condition
- Precipitation type
- Air temperature
- Wind speed

Data Sources

- Environment Canada (EC) stations
- RWIS

Agencies

Alberta and Ontario Ministries of Transportation

[24] Summary is based on information gathered from Matthews et al. (2017a,b) and from communication with representatives of the Alberta and Ontario Ministries of Transportation and University of Waterloo.

Minnesota Method[25]

Summary/Equation

Cost is essentially used as a proxy for severity, and cost is estimated by Minnesota DOT's (MnDOT's) Maintenance Decision Support System (MDSS). MDSS uses data from surface weather observations (RWIS and ASOS/AWOS), radar, satellite, numerical models, observations from field personnel and meteorologist inputs to simulate winter-long weather and road conditions. It then recommends treatment for those conditions and assigns costs to the recommended treatment. Eighteen routes were initially chosen across Minnesota to represent severity in those areas. (MnDOT plans to enhance their index by using each of their more than 800 plow routes to better represent each area. MnDOT initially chose eighteen routes as they did not yet have all routes entered into MDSS when this index was first developed, and they have kept it this way for consistency.) At each of those routes, the cost of materials, labor and equipment is all set to be equal; summing the total proxy cost at each district allows for comparison between districts and seasons.

Variables

- Air temperature
- Road temperature
- Dew point/relative humidity
- Frost/black ice occurrence
- Wind speed, gusts, and direction
- Precipitation type, duration, amount
- Cloud cover (shortwave and longwave radiation)
- Surface pressure
- Blowing snow

Data Sources

MDSS (RWIS, ASOS/AWOS, radar, satellite, numerical models, meteorologist input, etc.)

Agency

MnDOT

[25] Summary is based on information gathered from a Minnesota DOT white paper and from communication with representatives of Minnesota DOT.

Pennsylvania Method[26]

Summary/Equation

A WSI is calculated per winter event using the winter precipitation data recorded per calendar day. A new event occurs at the start of a new calendar day or after a precipitation break of eight hours. Winter precipitation is either snow (at any temperature) or freezing rain (which is non-snow liquid precipitation measured when air temperature is ≤32°F).[27] An event with a majority snow precipitation by duration (60% of time is snow) shall receive a Snow event designation. An event with a majority freezing rain precipitation by duration (60% of time is freezing rain) shall receive a Freezing Rain designation.

For each Snow event with a total snow accumulation of <1", calculate the SSI/WSI according to the following duration-based values:

- Event Duration < 8 hrs; Points = 5
- 8 hrs ≤ Event Duration < 16 hrs; Points = 7
- Event Duration ≥ 16 hrs; Points = 8

For each Snow event with a total snow accumulation ≥1", calculate the WSI according to the following snow accumulation based equation: Points = 8.6683(event snow accumulation$^{0.4701}$), where *event snow accumulation* is the total snow accumulation in inches, to the nearest tenth inch.

For each Freezing Rain event, calculate the WSI according to the following duration-based scale:

- Event Duration < 8 hrs; Points = 13
- 8 hrs ≤ Event Duration < 16 hrs; Points = 19
- Event Duration ≥ 16 hrs; Points = 24

Event WSI, daily total WSI, monthly total WSI, and season-to-date WSI are recorded in monthly summaries. The calculation is performed for each county.

Variables

- Snow accumulation
- Freezing rain accumulation
- Duration of precipitation
- Air temperature

Data Source

RWIS

Agency

Pennsylvania DOT (PennDOT)

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[26] Summary is based on information gathered from a Pennsylvania DOT white paper and from communication with representatives of Pennsylvania DOT.
[27] PennDOT acquires a freezing rain value from the Vaisala PWD22.

RWSBEE2[28]

Summary/Equation

The Road Weather Severity Based on Environmental Energy (RWSBEE) index starts with the hourly rate of deposition of new snow/ice and calculates the environmental energy required to melt it. The final index result is the additional energy required to melt snow and ice (e.g., by maintenance efforts), beyond the energy that is available from the environment. The RWSBEE2 is a modification of the RWSBEE that more accurately represents actual maintenance methods that use manual removal of snow and ice, not only melting. RWSBEE2 was developed by and is still run at Purdue University[10].

The index is calculated at points on an approximately 75-square-mile grid, which is equal to the resolution of modeled datasets used for the computation.

The RWSBEE2 is computed for each Indiana DOT district, sub-district, and unit over an entire season.

Variables

- Roughness length[29]
- Air temperature
- Wind speed
- Pavement temperature
- Shortwave & longwave radiation
- Sensible and latent heat fluxes
- Vertical temperature profile
- Categorical precipitation type
- Visibility
- Wind gusts
- Snow depth
- Hourly accumulated precipitation

Data Source

- MDSS
- Rapid Refresh (RAP) model
- North American Land Data Assimilation dataset (NLDAS)
- Snow Data Assimilation System (SNODAS)
- Stage IV precipitation analysis (National Centers for Environmental Prediction, NCEP)

Agency

Indiana DOT

[28] Summary is based on information gathered from Baldwin et al. (2015) and from communication with representatives of Indiana DOT and Purdue University.
[29] Roughness length is an atmospheric parameter which relates the near surface wind profile to land use/vegetation profiles. It is used by Baldwin et al. (2015) to estimate ground cover height in relation to snowpack height and, thus, to estimate the degree to which wind can access and affect the surface of the snowpack for transport (i.e., to be blown).

Utah Method[30]

Summary/Equation

Winter Road Weather Index (WRWI) = RCV + SRV + RTV + BSV + FRV

where:

- RCV is the Road Condition Value, found using road condition or grip. RCV = 1 when road condition is snow, frost, or ice; RCV = 0.75 when road condition is slush or freezing wet; RCV = 0.5 when road condition is wet; or RCV is found using a linear relationship with grip. (Figure 63 in Appendix I shows a graph of the RCV–grip relationship.)
- SRV is the Snowfall Rate Value, found using snowfall rate derived from visibility sensors. SRV = 0 when snowfall rate is 1”/hour and the road is snow covered; SRV = –0.5 when it is not snowing and the road is snow covered; SRV = 1.5 when snowfall rate is 2”/hour and road is snow covered or 3”/hour when road is wet. SRV is linearly related to snowfall rate when the road is snow covered. (Figure 64 in Appendix I shows a graph of the SRV–snowfall rate relationship.)
- RTV is the Road Temperature Value, found using road temperature data. It is determined using a linear relationship with road temperature, with an inflection point at road temperature = 22°F due to the extra effort/different materials needed at lower temperatures. (Figure 65 in Appendix I shows a graph of the RTV–road temperature relationship.)
- BSV is the Blowing Snow Value, found using wet-bulb temperature and wind gust. It is determined using the relationship shown in Figure 66 in Appendix I, with an inflection point at wet-bulb temperature = 20°F, due to an assumed change from “wet” snow to “dry” snow at that point (also assuming that “wet” snow is harder to move than “dry” snow).
- FRV is the Freezing Rain Value, found using precipitation, wet-bulb temperature, and road temperature. FRV = 0.5 when road temperature ≤ 32°F and wet-bulb temperature > 34°F.

Utah DOT’s internal program calculates WRWI in real time using RWIS data, when the road temperature is less than 35 degrees Fahrenheit and the road is not dry, or damp, or wet *and* not precipitating. The “worst” measurement over a 20-minute period is used. The Storm Intensity Index (SII) is more often calculated to better reflect maintenance performance. It removes the road condition value from the WRWI and is calculated as: SII = 2 x (WRWI – RCV) + 1.

Variables

- Road condition or grip
- Snowfall rate (visibility)
- Pavement temperature
- Wet-bulb temperature
- Wind gust
- Precipitation occurrence

Data Source

RWIS

Agency

Utah DOT (UDOT)

[30] Summary is based on information gathered from Oppermann and Williams (2018) and from communication with representatives of Utah DOT.

Walker Method[31]

Summary/Equation

The index is computed for a single storm event, defined by hourly observations of frozen precipitation. Severity categories are assigned to each variable value during the storm, as shown in Figure 2.

Variable	Category					
	Trace (1)	Marginal (2)	Slight (3)	Enhanced (4)	Moderate (5)	High (6)
Snowfall (in.) (*cm.*)	< 1.0 (*< 2.4*)	< 2.0 (*< 4.9*)	< 3.0 (*< 7.5*)	< 5.0 (*< 12.6*)	< 7.0 (*< 17.5*)	≥ 7.0 (*≥ 17.5*)
Snowfall Rate (in. hr^{-1}) (*cm hr^{-1}*)	< 0.2 (*< 0.4*)	0.2 (*< 0.6*)	0.3 (*< 0.9*)	0.4 (*< 1.1*)	< 0.6 (*< 1.5*)	≥ 0.6 (*≥ 1.5*)
Wind Speed (mph) (*ms^{-1}*)	≤ 6.0 (*≤ 2.7*)	≤ 11.0 (*≤ 4.9*)	≤ 18.0 (*≤ 8.1*)	≤ 24.0 (*≤ 10.7*)	≤ 31.0 (*≤ 13.9*)	> 31.0 (*> 13.9*)
Air Temperature (°F) (*°C*)	> 35 (*> 1.7*)	≤ 35 (*≤ 1.7*)	≤ 29 (*≤ -1.7*)	≤ 25 (*≤ -3.9*)	≤ 19 (*≤ -7.2*)	< 15 (*< -9.4*)
District Area (Fraction Area)	≤ 0.2	< 0.4	< 0.5	< 0.75	< 1.0	1.0
Duration (hr.)	≤ 2.0	≤ 3.0	≤ 4.0	≤ 5.0	≤ 8.0	> 8.0
Visibility (mi.) (*km*)	> 5.0 (*> 8.0*)	≤ 5.0 (*≤ 8.0*)	< 4.0 (*< 6.4*)	< 3.5 (*< 5.6*)	< 3 (*< 4.8*)	< 2.5 (*< 4.0*)

Figure 2: A breakdown of the variables by category. Image source: Walker et al. (2018)

Category 1 is assigned to trace snowfall or low impact storms requiring no winter maintenance operations activity, and the severity increases to Category 6: high severity, significant impact storms requiring maximum winter maintenance operations.

Weights for each variable were developed using expert opinion, and the final category was calculated as the sum of each weighted variable category. The final index (called the Nebraska Winter Severity Index, or NEWINS) calculation is:

$$NEWINS = \frac{\sum(Category \times Frequency)}{100}$$

Variables

- Snowfall total
- Snowfall rate (snowfall total/duration)
- Wind speed
- Air temperature
- District area
- Visibility

Data Sources

- ASOS
- GHCN-Daily

Agency

Nebraska DOT

[31] Summary is based on information gathered from Walker et al. (2017), Walker at al. (2018) and Walker et al. (2019b), and from communication with Dr. Curtis Walker.

Variable Breakdown

More than 25 different variables were identified as being used in the methods described in the preceding section. They were organized into five variable categories—atmospheric, pavement, precipitation, radiation, and temporal—and are listed here:

<u>Atmospheric Variables</u>

- Air temperature
- Wet-bulb temperature
- Wind speed, gust, direction
- Visibility
- Vertical temperature profile

<u>Pavement Variables</u>

- Road temperature
- Surface condition
- Friction/grip
- Layer thickness

<u>Precipitation variables</u>

- Precipitation type
- Snow occurrence
- Snow accumulation and depth
- Snowfall rate
- Blowing snow
- Freezing rain occurrence, duration, and accumulation

<u>Radiation variables</u>

- Shortwave and longwave radiation
- Sensible and latent heat fluxes

<u>Temporal variables</u>

- Frequency of events
- Duration of events

Each variable is described on a single page within this section. Each page includes the method using the variable and the source from which the data come, the ways in which the variable is used for SSI/WSI, and comments on the reliability of the data in question. Not all of the variables listed here are able to be directly measured. Instead, they are derived. For these variables, comments are included in this section as to how they are derived. For example, both the Utah and Walker Methods derive snowfall rate using proxy measurements or a combination of measurements (see Snowfall Rate subsection below). Precipitation type, blowing snow, and freezing rain are also often derived, if not directly observed by a human. It is important to understand that when deriving a variable using multiple other measurements, higher risk for error is introduced.

First, certain assumptions—which may usually, but not always, hold true—are made when estimating a weather condition using other data. Secondly, if any of the data going into the derivation are erroneous, it will render the derived variable erroneous. It is important for the builder of an SSI/WSI to understand the difference between directly measured and derived variables, and the benefits and challenges of each.

An overview of the more common variables used and methods that use them is shown in Table 3. At a quick glance, one can see that pavement variables are used in half of the methods described. Air temperature and wind speed are also frequently used. The latter is often (but not always) utilized to capture blowing snow. Precipitation type and accumulation are the other most-used variables. Air temperature and snow accumulation are each used most of all (7 out of the 10 methods). Blowing snow and freezing rain are used as distinct variables (directly measured or derived) in a few of the methods.

Table 3: Common Variables Used

Method	Variable											
	Air Temperature	Wind Speed	Visibility	Pavement Temperature	Pavement Condition	Precipitation Type	Snow Accumulation	Snow Depth	Snowfall Rate	Radiation and Heat Flux	Blowing Snow	Freezing Rain
AWSSI	X						X	X				
Boselly	X						X					
Idaho		X		X	X							
Iowa				X		X	X				X	X
Matthews	X	X			X	X	X					
Minnesota	X	X	X	X	X	X	X	X	X	X	X	X
Pennsylvania	X					X	X					X
RWSBEE2	X	X	X	X		X		X		X	X	
Utah		X	X	X	X	X			X		X	X
Walker	X	X	X				X		X			

However, because Table 3 only contains 12 variables, there are at least that many more which are also used in the methods described in this document. For example, wet-bulb temperature and vertical temperature profile are not included in Table 2; each is used by a single method (Utah and RWSBEE2, respectively). However, their usage in SSI/WSI is novel and may offer solutions to better identifying precipitation type than the standard 2-meter (6.6-ft) air temperature alone. This is most relevant for the freezing rain discussions in this section (see Wet-bulb Temperature and Vertical Temperature Profile subsections).

Also not included in Table 3 is snow occurrence. Many methods use it, although in indirect ways; that is, snow must be occurring in order to count the event. Frequency and duration of events are also not included in Table 3 but are incorporated in various ways by methods described herein. Iowa, Minnesota, Pennsylvania, and Walker use frequency or duration as an explicit part of their calculation; yet many others included it implicitly, by way of accumulating points over a month or season.

Atmospheric Variables

Atmospheric variables are those which are measured by what might be considered, the more common suite of weather station instruments, particularly air temperature, humidity (here represented by wet-bulb temperature), and wind (speed and direction). Visibility is included here, though it often is measured by a present weather detector, which can also measure precipitation (see the Precipitation Variables section). Vertical temperature profile is also included here, though it requires air temperature measurement throughout the atmosphere (usually by way of satellite or weather balloons; discussed below).

Each of the five variables in this section are examined on the following five pages entitled:

- Air Temperature
- Wet-Bulb Temperature
- Wind Speed, Gust, Direction
- Visibility
- Vertical Temperature Profile

Air Temperature

Method – Source

- AWSSI – GHCN
- Boselly – ASOS/AWOS, RWIS, RAWS
- Matthews – EC, RWIS
- Minnesota – MDSS (RWIS, ASOS/AWOS)
- Pennsylvania – RWIS
- RWSBEE2 – NLDAS
- Walker – ASOS/AWOS

Figure 3: Campbell Scientific temperature and relative humidity ("temp-RH") probe (left) and shown inserted into radiation shield (right). As the name suggests, the temp-RH probe measures both air temperature and humidity variables. Image source: https://www. campbellsci.com/

Use in SSI/WSI

Air temperature is often used as a severity indicator on its own. Usually, the severity score increases as air temperature decreases. Some calculations are only triggered when air temperature is below a certain value; or it may be used to signal the start or end of winter (as in AWSSI).

Air temperature may also be used as a precipitation type designator. Yet, when other means of precipitation type assessment are present (i.e., instrumentation that has that functionality), it may not be necessary to use for that purpose. In many climates, it is also not the most accurate estimator of precipitation type (see discussion in Wet-bulb Temperature below).

Reliability

Air temperature is a standard component of most weather station installations. The temperature probes (shown in Figure 3) are relatively inexpensive and remain fairly accurate if they are installed properly and are calibrated regularly. Correct installation is important; a radiation shield around a temperature probe shades and ventilates it. The instrument will report erroneously high values if it is exposed directly to sunlight.

Despite the ease of measuring air temperature, pavement temperature is usually a more appropriate parameter to use in severity calculations for winter maintenance, as it is more indicative of materials and methods chosen to maintain winter roads. See "Road Temperature" in the Pavement Variables section below.

Wet-Bulb Temperature

Method – Source

Utah – RWIS

Use in SSI/WSI

Wet-bulb temperature is used to determine precipitation type (e.g., rain versus snow, or "wet" snow versus "dry" snow). Freezing rain can be determined using wet-bulb temperature and pavement temperature together; in the Utah Method, freezing rain is assumed to occur when road temperature is less than or equal to 32°F and wet-bulb temperature is greater than 34°F (see FRV in "Utah Method" above).

From a thermodynamics standpoint, wet-bulb temperature is a more physically accurate way to determine precipitation type compared to air temperature (or "dry-bulb" temperature), because wet-bulb includes a moisture term, taking into account the cooling effect of evaporating snowflakes or raindrops in relatively dry air. Oppermann and Williams (2018) explain it this way: "*The wet-bulb temperature effectively combines the air temperature and relative humidity and is defined as the lowest temperature that can be reached by evaporating water into the air. In the case of winter weather, as precipitation falls it evaporates, keeping the temperature around it cooler than the surrounding air. Therefore, wet-bulb temperature is the best available distinguisher between rain and snow and dry and wet snow at the surface.*"

This is why, in more arid climates (such as that of Utah, and much of the Intermountain West), it is not unlikely to see snow falling while the air temperature is as high as 37°F (and it is possible at even greater air temperatures); in this case, the wet-bulb temperature would be less than or equal to freezing (32°F).

In the Utah method, wet-bulb temperature is also used to determine snow transportability. Greater likelihood of blowing snow occurs with lower wet-bulb temperatures (thus, drier snow) and higher wind gusts (see BSV under Utah Method above).

Reliability

Wet-bulb temperature is a relatively reliable variable from an instrumentation viewpoint. It is inexpensive and standard at most any weather station and is derived using data gathered from a temperature-humidity probe (as in Figure 3). The usual cause of inaccurate (wet-bulb or other) temperature measurement is due to improper siting or housing of the probe, as discussed in the Air Temperature section above.

Wet-bulb temperature is also a more representative variable for determining precipitation type compared to air temperature. Thus, it could be said to be more reliable when used in conjunction with other measurements in severity calculations.

Wind Speed, Gust, Direction

Method – Source

- Idaho – RWIS (speed)
- Matthews – RWIS (speed)
- Minnesota – MDSS (speed, gust, direction)
- RWSBEE2 – NLDAS (speed), RAP (gust)
- Utah – RWIS (gust)
- Walker – ASOS (speed)

Figure 4: Examples of sonic (left) and propeller (right) anemometers (from the Greek word for wind: anemos). Image source: www.youngusa.com

Use in SSI/WSI

Wind speed may be expressed as a sustained or a gust speed. The sustained wind speed is the average wind speed measured by instrumentation over the reporting period. The gust is a rapid fluctuation of wind speed with variations of at least 10 knots (11.5 mph) between peaks and lulls (NWS definition). Wind direction is usually reported as a cardinal direction or as a numerical angle corresponding to a cardinal direction (i.e., 90° is east, 180° is south, and so on). Wind direction is always expressed as the direction the wind is coming *from*.

For SSI/WSI applications, wind speed is most often used in the context of blowing snow. In general, as the wind speed increases, the severity score increases. Some calculations go a step farther, however, and the transportability of the snow is taken into account. In such calculations, blowing snow can only occur when certain thresholds are met for wind speed plus other atmospheric and surface parameters. (See discussion in Blowing Snow section below.)

New York State DOT (NYSDOT) is investigating a method to estimate freezing rain occurrence by comparing measurements from the two different anemometers on their mesonet sites (each is equipped with both a propeller and a sonic anemometer; refer to Figure 4): when the sonic anemometer is reporting wind, but the propeller anemometer is reporting calm, it is possible that the propeller has frozen in place resulting from icing. The reader is cautioned that this proxy technique is still being tested, and that there are other, non-freezing rain means by which this could occur.

Reliability

Propeller anemometers are composed of a vane that aligns to the wind direction and a rotor that determines the speed of the wind from its rate of rotation. Because their design is based on the physical principles of the force of air against an object, they are a trusted source of wind information. They can get snowed or iced over, however, which decreases their reliability during winter storms. Anemometer models that are all black are quicker to melt out, because they absorb heat from the sun more readily. Also, frequent maintenance is required on propeller anemometers, especially in windy locations. Bearings tend to wear out within 1-3 years at these types of locations.

Sonic anemometers are usually used for scientific applications in which wind data is desired in three axes (x, y, and z). They are a trusted source for wind information because their measurements are highly accurate and precise. For an additional price, a sonic anemometer can be heated, improving performance in icing or wet snow events.

Visibility

Method – Source

- RWSBEE2 – RAP
- Utah – RWIS
- Walker – ASOS

Use in SSI/WSI

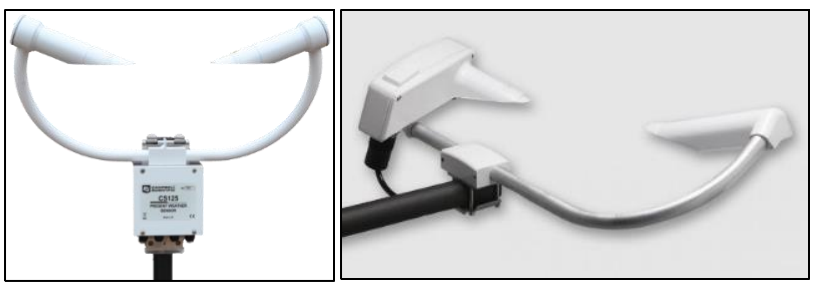

Figure 5: Examples of present weather detectors, which quantify visibility and can often identify precipitation type. Image sources: https://www.campbellsci.com (top), www.vaisala.com (bottom).

Visibility can be used to quantify storm severity from a societal impact point of view (RWSBEE2 uses it to help classify storm severity); but it is also useful to use in a winter maintenance context. In the Walker method, visibility is included, because it is the number one reason winter maintenance operations are suspended. However, it is the least numerically weighted variable in the equation.

The Utah method uses visibility data to estimate snowfall rate using the following relationship: snowfall rate = 0.5 / visibility in miles, up to 10 miles.

Reliability

While automated visibility sensors (shown in Figure 5) are considered a trusted source for this information, they can suffer from inaccuracies, as with any optical sensor placed at a roadside. Road spray and dust can contaminate the lenses, requiring routine maintenance and cleaning. However, for many visibility sensors on the market today, a correction can be made internally when the sensor detects that the lens is dirty. Thus, UDOT has observed that dirty lenses affect the data less often than may have been expected.

Depending on the end use of the data, the data may be more or less acceptable even with slight inaccuracies. Methods which place a small weight on visibility values will have more success using visibility data that is slightly erroneous. The Utah method, however, uses visibility as a foundational aspect of its calculation—by deriving snowfall rate from visibility data—and it will thus be more affected by any measurement errors. UDOT concedes there are limitations to using visibility as a proxy for snowfall rate. Non-precipitating fog can trigger snowfall rate values and confuse the calculation. (More about how the Utah method uses visibility to estimate snowfall rate is discussed in the Snowfall Rate page under Precipitation Variables.) As with any method, quality checking by a human is an important part of performing SSI/WSI calculations and interpreting results.

Vertical Temperature Profile

Method – Source

RWSBEE2 – RAP

Use in SSI/WSI

Vertical temperature profile (hereafter, VTP) is *not* used in the radiation balance component of RWSBEE2, or to diagnose precipitation type. The RWSBEE2 uses it to estimate hourly snowfall accumulation (when the RAP has already designated precipitation type as snow). Snow accumulation is estimated using a snow-to-liquid ratio, calculated using the warmest temperature in the vertical profile. Because Stage IV precipitation (described in Modeled Data Analyses section below) only gives a liquid equivalent accumulation, the snow ratio value was used to convert the mass of precipitation observed by Stage IV to hourly snowfall.

Reliability

The temperature profile of the atmosphere from the ground to the stratosphere (and beyond) is measured via weather balloons, ground-based LIDAR, or satellite, and it can be modelled.

It is a unique variable among SSI/WSI methods, but it is a critical component in atmospheric modeling, and so it is a part of routine data capture by meteorological entities. Given computational capabilities to ingest and process VTP data, it can prove useful as an SSI/WSI variable. For example, VTP is important in the calculation of radiation balance at the surface of the earth (and, thus, road weather), and is a key determiner of precipitation type when temperatures are close to freezing. Given a scenario in which the air at the surface (or the surface itself) is below freezing, but a layer of air above the surface is above freezing, snowflakes falling from clouds will melt while falling through that layer of relatively warm air, then refreeze upon contact with the surface. (Or if the surface layer of air is sufficiently thick or cold, they will refreeze before hitting the ground, forming sleet.) Figure 6 shows an illustration of this process.

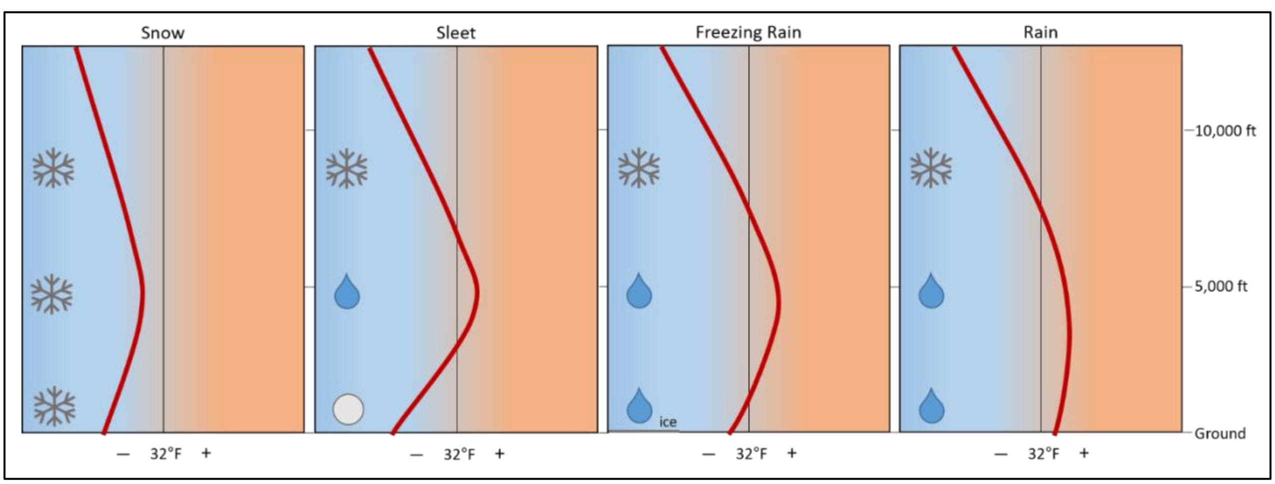

Figure 6: Vertical temperature profile schematics for four different cold-season precipitation types: snow, sleet, freezing rain, and rain. The thick, red line illustrates the vertical profile of air temperature; the vertical gray line demarcates the freezing point (32°F), with below-freezing temperatures to the left of it and above-freezing temperatures to the right. Elevation is shown on the y-axis. Adapted from Ahrens (2007), Figure 7.23

Pavement Variables

Because the SSI/WSI is ultimately about *road* weather severity, for many of the methods discussed herein it is important that the road environment be considered as part of the calculation (when possible). Road temperature and road surface state (including condition, friction, and [water] layer thickness) are used in a number of methods. Notably, subsurface or subgrade temperature has not been used. Subgrade temperature is taken in the soil at a depth of 18 inches. This data is often used for freeze-thaw modeling in the pavement subgrade and for forecasting and pavement modeling; it becomes an important parameter on longer time scales. For SSI/WSI purposes, it need not be included, as surface/pavement temperatures will suffice for information needed on the storm-scale.

The Road Temperature and Surface Condition, Friction, Layer Thickness topic subsections are available on the following two pages.

Road Temperature

Method – Source

- Idaho – RWIS
- Iowa – RWIS
- Minnesota – MDSS (RWIS)
- NYSDOT – mesonet, mobile[32]
- RWSBEE2 – NLDAS[33]
- Utah – RWIS

Figure 7: Examples of road temperature sensors: at left, an in-pavement sensor, or "puck;" at right, a non-invasive, roadside sensor. Image sources: https://www.campbellsci.com/irs21 (left), www.vaisala.com www.vaisala.com (right).

Use in SSI/WSI

Road temperature may be considered one of the more critical components of maintenance decision making, and, thus, weather severity. In fact, UDOT's Oppermann and Williams (2018) observed that snowfall rate and road temperatures have the greatest impacts on roads. The Utah method scores severity higher with lower road temperatures, with greater weight ascribed to the road temperature value at 22°F and below, due to the extra effort and change in materials needed at lower temperatures. Road temperature is also used by Utah to diagnose freezing rain.

In the Idaho and Iowa methods, road temperature is used with other weather variables to increase the severity score of whatever else is occurring. In the RWSBEE2, pavement temperature is a critical part of the radiation balance equation. In the Minnesota method, MDSS incorporates RWIS data into a pavement model from which weather severity is determined.

It should be noted here that road temperature can be used in conjunction with atmospheric dew point temperature to diagnose frost occurrence. MnDOT, for example, uses these variables to determine frost occurrence.

[32] NYSDOT is investigating the use of *ground* (not road) temperature to assist with freezing rain determination (NYS mesonet sites measure the temperature of the ground surface around the site, not the road). They are considering using road temperature data from agency trucks, as well.

[33] RWSBEE2 uses a surface temperature from a land-surface model and is not a direct measurement of the road surface. In the model, the "surface" is assumed to be the road surface.

Reliability

At many agencies, road temperature has historically lacked reliability. In early RWIS installations, road pucks (see Figure 7) were the standard device used for measuring conditions on the road surface. Though their measurement accuracy is considered to be high, the pucks or their cables risk being damaged during construction or maintenance. Additionally, they can be difficult—and dangerous, for the technician—to calibrate and maintain, as it usually requires a lane closure to access them. In recent years, many agencies have made the investment in optical, non-invasive road sensors. Yet, non-invasive sensors come with their own maintenance needs, requiring calibration at regular intervals, or when the pavement surface is altered, in order to report correctly.

Surface Condition, Friction, Layer Thickness

Method – Source

- Idaho – RWIS (layer thickness)
- Matthews – RWIS (condition)
- Minnesota – MDSS (RWIS)
- Utah – RWIS (condition or friction)

Figure 8: Three examples of non-invasive road condition sensors. Note: A road puck, shown in Figure 7, may also be used to measure road conditions, but it is not shown here. Image sources: www.vaisala.com (left), hsierra.com (center), www.lufft.com (right).

Use in SSI/WSI

The variables used to describe the contents and nature of the road surface—surface condition, friction or grip, and layer thickness—are a relatively direct measure of severity. Roughly speaking, the thicker and slicker the road surface contents, the higher the severity score. When road condition values are included in SSI/WSI, a clearer picture of severity from a maintenance perspective emerges.

Surface condition is a descriptive variable; however, it can still be used in numerical equations. At UDOT, for the RWIS sites that report surface condition, but not friction, qualitative road condition values are translated into numerical equivalents in order to work with their SSI/WSI equation. The "road condition value" is set to 1 when road condition is reported as snow, frost, or ice; 0.75 when road condition is slush or freezing wet; and 0.5 when road condition is wet. In the Matthews method, road condition information is used as a trigger to add points onto the severity total for each day.

Because friction (or grip) is a numerical value, it is more straightforward to include it in a calculation. It is used at UDOT, and at the RWIS sites that have the ability to measure friction; their road condition value has a linear and inversely proportional relationship to friction. At ITD, the storm severity index feeds directly into a performance index that includes the duration of time friction is below a critical threshold.

Layer thickness is a measure of the depth of the water, ice, or snow layer atop the road surface. It can be a more straightforward picture of the deposition of rain, snow, and ice on the road surface than accumulation from a roadside instrument, because what ultimately matters is what is on the road surface, itself. Because of traffic, road temperatures, and maintenance activities, what is on the road surface is often different than what is beside the roadway.

Reliability

Non-invasive road surface state sensing (see examples in Figure 8) has gained trust in recent years, and a number of agencies have based their maintenance performance measurement program solidly on reported friction (for example, ITD; Xu et al., 2017). However, because they require having a clear optical view of the road surface and can suffer from optical drift, it is critical that they are maintained and calibrated on a regular basis.

Precipitation Variables

Precipitation is incorporated (whether directly or indirectly) into every one of the methods discussed herein. The key variables used are precipitation type; snow occurrence; snow accumulation and depth; snowfall rate; blowing snow; and freezing rain occurrence, duration and accumulation. Note that blowing snow—though not precipitation—is included among these precipitation variables. Blowing snow works well within this category, as it manifests as precipitation on the road surface, even when nothing is falling from the sky. However, it also must be measured differently than actual precipitation, as traditional means of precipitation measurement capture particles falling vertically, not blowing horizontally. This will be further examined in the subsections below.

The measurement techniques used to evaluate variable reliability in this section largely include direct means of observation, whether reported by an instrument or a human. Remote sensing of precipitation (i.e., via radar) is included only in the RWSBEE2 (via Stage IV precipitation analysis) but is otherwise not used in SSI/WSI. (Note that Stage IV precipitation analysis is a highly processed, quality controlled, radar-based product used to estimate liquid equivalent precipitation accumulation. More information can be found under the Stage IV Precipitation Analysis heading in the Data Source Breakdown, Modeled Data Analyses section.)

Radar can be a useful tool for precipitation accumulation estimation where the signal is strong, but radar has the potential for error and lack of coverage, particularly during the winter, and particularly in areas with complex terrain.[34] Within the past decade, a major dual-polarization (National Weather Service, 2018) upgrade was made to the NWS radar network, allowing for vastly improved estimates of precipitation type and the removal of scatter (non-precipitation signals); however, the same elevation- and distance-related errors inherent in radar data in the United States will remain.

Future research could evaluate the degree to which dual-polarization radars provide accurate enough estimates of precipitation type and accumulation to be useful in SSI/WSI applications at ideal locations. Still, for the purposes of this project, the discussion of variable reliability will mostly be from an in-situ instrumentation perspective.

Some of the variables discussed here are derived, rather than directly measured. A number of examples of deriving precipitation variables are examined in this section. One example: snow accumulation in RWSBEE2 is derived using daily snowpack depth values from SNODAS with hourly accumulated liquid equivalent data from Stage IV precipitation analysis. Another example is snowfall rate: the Utah method estimates snowfall rate using a visibility proxy, and the Walker method derives an average snowfall rate over the course of a storm using total accumulation divided by duration. Freezing rain is another oft-derived weather condition. Among other techniques, it is frequently derived by means of non-snow precipitation observed when the road temperature is below freezing.

The variable descriptions are available on the following pages entitled:

- Precipitation Type

[34] Because a radar beam is emitted at a minimum 5° angle, it gains in height with distance from the radar. Winter precipitation occurs at lower elevations in the atmosphere relative to summertime precipitation. This lower elevation precipitation, along with the curvature of the earth, increase the chances that the radar beam will overshoot winter precipitation at greater distances from the radar. Other potential errors in radar data include: blockage from complex terrain, bright-banding (when radar reflectivity is artificially high due to melting snowflakes), and the presence of non-precipitation atmospheric particulates.

- Snow Occurrence
- Snow Accumulation & Depth
- Snowfall Rate
- Blowing Snow
- Freezing Rain Occurrence, Duration & Accumulation

Precipitation Type

Method – Source

- Iowa – operator logs
- Matthews – EC
- Minnesota – MDSS (multiple data source inputs)
- Pennsylvania – RWIS
- RWSBEE2 – RAP
- Utah – RWIS

Use in SSI/WSI

The precipitation types most critical for maintenance severity assessment are solid precipitation (snow, graupel or sleet) or liquid precipitation that freezes on contact with the road (i.e., freezing rain). Even variations in the snow type—"wet" or "dry"—impact severity (e.g., as reflected in the Utah method). Usually, freezing rain is given a higher weight in the calculations compared to snow, as glaze ice is very slick and very difficult to mitigate. The Iowa and Pennsylvania methods, for example, use precipitation type data to weigh freezing rain events greater than snow or other precipitation events.

The Utah method uses wet-bulb temperature to evaluate the nature of the precipitation to evaluate its transportability in potential blowing snow scenarios. The RWSBEE2 uses precipitation type to estimate winter weather hours (i.e., wintry precipitation occurrences count toward winter hours). MDSS (Minnesota method) measures and categorizes precipitation type for its weather and road surface models.

Reliability

Precipitation type may be gathered by automated present weather detectors (shown in Figure 5, under Visibility), or by human observers. Automated measurement of precipitation type can be prone to error. Traditionally, instrumentation that reported precipitation type has required additional verification or close quality assessment. As optical physics improve, however, the reliability of automated precipitation type measurement will also improve. Those sites for which precipitation type identification is critical (e.g., for airport weather stations—ASOS or AWOS), human observers are often used to report or verify measurements. Precipitation type thus may not be a trusted variable to gather from remote weather stations.

Snow Occurrence

Method – Source

- Boselly (WSDOT modification) – ASOS/AWOS
- Utah – RWIS (to define start and end of storm, and to differentiate snow from fog)
- Many, to diagnose storm start/stop

Use in SSI/WSI

In the absence of quantitative means of measuring precipitation amount, a binary (yes/no) snowfall measurement system may be used. The use of snow occurrence, rather than accumulation, at WSDOT allowed them to use the Boselly method in a modified manner (i.e., the *S* term in the Boselly equation will equal 0 or 1).

The Utah method first verifies that the precipitation occurring is snow in order to use its visibility sensors to calculate snowfall rate.

In many of the methods discussed herein, a calculation will be triggered simply by the verified occurrence of falling snow.

Reliability

A present weather sensor (Figure 5) is most often used for precipitation type designation. Human observation is often used, where available. *Please see above, the discussion under Precipitation Type.*

Snow Accumulation & Depth

Method – Source

- AWSSI – GHCN (accumulation and depth)
- Boselly – NWS network, ASOS/AWOS (accumulation)
- Iowa – operator logs (accumulation)
- Matthews – EC (accumulation)
- Minnesota – MDSS (accumulation; multiple data source inputs)
- Pennsylvania – RWIS (accumulation)
- RWSBEE2 – Stage IV (accumulation), SNODAS (depth)
- Walker – GHCN (accumulation)

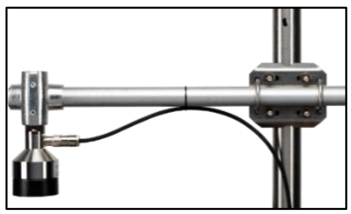

Figure 9: Sonic depth sensor. Can be used for snow depth or water height. Image source: www.campbellsci.com

Use in SSI/WSI

The AWSSI, Matthews, Pennsylvania and Walker methods use total daily or event snow accumulation to add points to the severity value. Simply put, they have a method for which, at various predetermined thresholds, the number of points ascribed to the day or the storm increases as the accumulation increases. The Boselly and Iowa methods insert daily snow accumulation directly into the calculation (Pennsylvania does this, too); in the Boselly, the score increases logarithmically with accumulation (in millimeters). The RWSBEE2 compares snow depth to land use characteristics to determine mobility of the snowpack (see roughness length definition [footnote 29] in RWSBEE2 section above). Snow and ice cover data are a critical component to the energy balance model used for this method.

Reliability

As with all automated precipitation measurement, great care and quality assurance must be taken for snow accumulation measurement. Human observation is often preferred, when available. According to National Weather Service (2013), snow accumulation and depth "*are some of the most difficult, but important, weather elements to measure in an accurate, consistent manner.*" NWS thus trains both employees and volunteers across the country to measure snowfall using a very specific process.

In remote installations, a sonic snow depth sensor (such as in Figure 9) is often used. Yet, sonic sensors require frequent maintenance, and their data prove to be noisy and inaccurate at high resolutions. It is also difficult to interpret accumulation when snow falls onto an existing snowpack using sonic sensors.

In-house experience with snowfall data at UDOT steered the team away from using accumulation or depth in their WSI. (Note: the Utah method is calculated in *real time*, and their assessment of snowfall measurement is specific to that use—not for post-storm or daily calculation. Thus, they decided on snowfall *rate*, as discussed below.) UDOT reported that "*Factors such as wind, melting, compaction, sublimation, and proper placement will impact any automated measure of snowfall.*" (Oppermann and Williams, 2018).

Interestingly, the Boselly method relies on daily snowfall measurement on the millimeter scale. Snow measurement at that fine of a scale may be a risky proposition, since snowfall is already difficult to measure by the inch (note: a single inch is 25.4 mm). However, by using a logarithmic scale, the impact of snowfall amount increases more slowly with increasing accumulation, helping to mitigate some of the errors that may be caused by shifting and settling of the snowpack over time during a storm.

Snowfall Rate

Method – Source

- Utah – RWIS
- Walker – GHCN

Use in SSI/WSI

The Utah method uses visibility data as a proxy for snowfall rate. A linear, proportional relationship assigns the snowfall rate value (see Utah Method) from snowfall rate (provided the road is snow-covered). It roughly equals the following: -0.5 when it is not snowing and the road is snow covered; 0 when snowfall rate is 1”/hour and the road is snow covered; 1.5 when snowfall rate is 2”/hour and road is snow covered or 3”/hour when road is wet.

The Walker method finds the average snowfall rate over the duration of the storm by dividing the total snow accumulation by the hours of precipitation. Its categorical score is found (e.g., a category of 1 is assigned for rate <0.2 in/hour, and 6 is assigned for rate ≥0.6 in/hour; see Figure 2 for more detail), and summed with the categorical scores of the other variables (i.e., snowfall total, wind speed, air temperature, district area, duration, and visibility).

Reliability

There are some limitations with using visibility as a proxy for snowfall rate. According to UDOT’s Jeff Williams and Cody Oppermann: “*Most variables that feed into the [index] are just the raw data from the sensors. The exception being the snowfall rate, which is estimated via visibility and the presence of precipitation. This estimation is performed by the RWIS’s Campbell Scientific datalogger program and not via the [index] algorithm’s own calculations. This presence of [a] precipitation check detects most fog events, but on the relatively rare occasion when there is light snowfall concurrent with foggy conditions, the snowfall rate will be over-estimated. The visibility sensor is what also provides this precipitation identification, but also provides the variable ‘particle count,’ which detects the number of particles that have passed through the sensor during the course of a minute. This value was initially used to ‘cap’ snowfall rates to 2” per hour during foggy events when particle count values were low. The accuracy of this value has been determined to be largely suspect, however, so most sites’ snowfall rates are only capped at 5” per hour regardless of particle count. Other data from the visibility sensor could be used, but as of this writing has not been investigated. If snowfall rates are so erroneous as to impact the [index], this data is flagged and not counted towards storm total and winter total values.*” In regard to manually assuring the quality of the data, one should be aware that not only is the process time consuming, but a trained expert should be the one performing the quality assessment.

One limitation of the Walker snowfall rate estimation method is that it can tend to underrepresent the severity of peak snowfall periods, and also has the potential to over-represent quick squalls. As Dr. Walker suggests, “*The ability to assess instantaneous snowfall rate (and subsequent impacts) would be a valuable future avenue*” (personal communication, 6 December 2019).

Blowing Snow

Method – Source

- Iowa DOT – operator logs
- Minnesota – MDSS (multiple data source inputs and blowing snow model)
- RWSBEE2 – NLDAS + SNODAS
- Utah – RWIS

Use in SSI/WSI

Operators at Iowa DOT report hours of blowing snow. The hours add points to the accumulated severity index.

At MnDOT, MDSS uses a multitude of environmental observations—including road conditions, precipitation, and wind—in order to build a picture of the weather. Blowing snow can be either observed, reported, or modeled in MDSS.

The RWSBEE2 accounts for the physical processes that must occur in order for a snowpack to become mobile. The method assumes that, given a wind speed that meets a certain threshold, blowing snow can occur if (1) it has recently snowed, (2) the air temperature has stayed below freezing since it stopped snowing, and (3) the local vegetation is not obstructing wind flow (estimated using the roughness length parameter in a land-use model; see roughness length definition [footnote 29] in RWSBEE2 section above).

The Utah method computes a Blowing Snow Value, using a relationship between wet-bulb temperature and wind gust, as is shown in Figure 65 in Appendix I. Assuming that "wet" snow is harder to move than "dry" snow, there is an inflection point at wet-bulb temperature = 20°F, due to an assumed change from "wet" snow to "dry" snow at that point.

Reliability

The experience in Iowa is that, though human reported data can be "erratic," Iowa DOT still uses it because it is so useful. "*There is no sensor in the world (that is easily deployable) that can detect blowing snow along the entire stretch of the highway*," but the humans can. Blowing snow is a significant part of their operational response (and many snow and ice agencies will agree with this sentiment).

At MnDOT, many districts complained that wind and blowing snow were not accounted for, causing some areas of the state to look as though their winter was less severe than reality. As with Iowa DOT, MnDOT reports that blowing snow is a huge factor in winter maintenance in many areas of the state. The use of MDSS has helped to account for blowing snow occurrence across the state.

Because Utah DOT uses RWIS to estimate blowing snow, the condition will only be counted if it occurs at the location of the RWIS. UDOT suggests that as mobile observations become a trusted source of information along a roadway, fewer gaps in this critical information will be seen.

Freezing Rain Occurrence, Duration & Accumulation

Method – Source

- *AWSSI (NYSDOT modification) – mesonet (in development)*
- Iowa – operator logs (occurrence and duration)
- Pennsylvania – RWIS (occurrence and duration)
- Utah – RWIS (occurrence)

Use in SSI/WSI

NYSDOT is using a proxy measurement to determine freezing rain occurrence.

Human observation in Iowa.

Pennsylvania logs freezing rain accumulation but does not include it in the SSI/WSI. The Vaisala PWD22 reports seven different precipitation types (rain, freezing rain, drizzle, freezing drizzle, mixed rain/snow, snow, ice pellets) and accumulation.

Utah: Freezing rain value – found using precipitation, wet-bulb temperature, and road temperature; equals 0.5 when road temperature ≤ 32°F and wet-bulb temperature > 34°F.

Alberta does not explicitly use a freezing rain designation but does include rain with cold temperatures as a trigger for their calculation, whether as a precursor to rain changing to snow or to represent freezing rain conditions. Either way, the ice warning pavement conditions reported by their RWIS represent conditions that may have occurred from freezing rain.

Reliability

Freezing rain is difficult to measure from an automated sensor for a number of reasons. Rain must be freezing on the road surface and not simply elevated structures (such as weather instrumentation). Thus, at least two observations must be made: (1) it must be raining (precipitation type must be reported as rain; but, as discussed above, there are errors inherent in estimating precipitation type using instrumentation); (2) the pavement temperature must be at or below freezing; *and/or* (3) road conditions and friction values must be indicating glaze ice. More complicated still, the impacts of freezing rain will likely persist long after it stops precipitating, and so an effort to track road conditions until the roads are clear should be made.

PennDOT determines freezing rain using the Vaisala PWD22. They have a performance-based contract with Vaisala for RWIS maintenance. They feel very confident that the precipitation data is fairly accurate and provides a good representation.

Radiation Variables

The absorption and emission of radiation and heat from the environment drive road temperature. Solar (or shortwave) radiation absorption warms the road surface. At night, the road surface rapidly emits the radiation it gained during the day (via longwave radiation) and the surface cools. When the pavement subgrade is warmer than the pavement, heat fluxes toward the road surface, keeping it relatively warm. (This is called sensible heat flux.) Pavement on bridges cools more rapidly than that over solid ground, because the air cools more quickly than the soil, increasing the heat flux below the roadbed and cooling the road. Precipitation falling onto a road surface also affects this radiation balance; for example, snow falling onto a warm road will melt and lower the temperature of the road surface. (This is called latent heat flux.) An illustration of some of the radiation inputs to the pavement is shown in Figure 10.

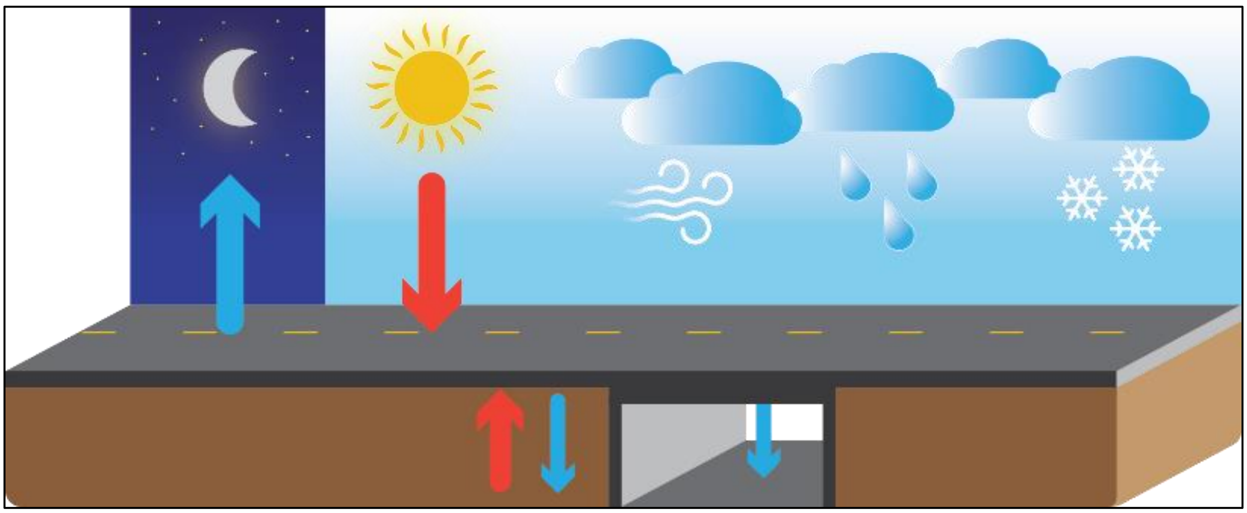

Figure 10: Graphical illustration of radiation inputs to and outputs from the pavement surface. The image includes a sampling of weather impacts to road temperature, including the presence of sun, clouds, precipitation, and wind, and the impacts of air or soil temperatures that are markedly different than the road temperature.

Thus, when building a pavement model, it is critical to include all potential radiation and heat fluxes. As described in the Method Breakdown, RWSBEE2 uses radiation balance as a central component of its equation; that is, the severity is estimated to be the manual energy required to remove snow, after the input of environmental energy (i.e., radiation) is considered. For the purposes of most other SSI/WSI methods, road temperature—being the end product of radiative effects—is a sufficient variable to use.

In this section, shortwave and longwave radiative inputs are described alongside of sensible and latent heat fluxes, as they all add or remove energy from the road surface and drive pavement temperature.

Shortwave and Longwave Radiation, Sensible and Latent Heat Fluxes

Method – Source

- Minnesota – MDSS (from data within MDSS)
- RWSBEE2 – NLDAS

Figure 11: At left, a net radiometer, which includes two pyranometers (to detect incoming and outgoing shortwave radiation) and two pyrgeometers (to detect incoming and outgoing longwave radiation). At center, a pyranometer. At right, a temperature probe with cable.

Description

The following radiation inputs are the primary components of temperature changes at the pavement surface:

1. Shortwave radiation (i.e., incoming from the sun)
   Incoming shortwave (solar) radiation changes with day of the year, latitude and cloud cover. The greatest shortwave gain occurs on a cloudless day when the sun is directly overhead.
2. Longwave radiation (i.e., emitted from the pavement surface)
   Everything with a temperature radiates in the longwave spectrum. Roadways cool when longwave radiation emission is greater than incoming shortwave radiation (the most effective cooling occurs on a clear, windless night).
3. Sensible heat (i.e., felt or measurable)
   The most effective sensible heat flux into or out of the road surface is from the road substrate. Heat flux into the pavement comes from a warm substrate; bridges cool more quickly than the rest of the road because they lose heat through having no input from below. Smaller sensible heat fluxes can also come from the air.
4. Latent heat (i.e., released or absorbed molecular energy from a change of state—evaporating, melting, freezing, etc.)
   Latent heat flux into or out of the road surface comes from melting (cooling of surface), evaporation (cooling of surface), or freezing (heating of surface) of precipitation on the surface. It is counterintuitive to think, for example, that the transition of liquid raindrops to frozen ice on the surface acts to warm it, but it arises as a result of the energy released

when water molecules transition from a higher energy state (e.g., liquid) to a lower energy state (e.g., solid). It is a small, but important (when road temperatures are near the freezing point), input to the overall energy balance at the road surface.

These radiative inputs and heat fluxes at the road surface can be measured (using pyranometers, pyrgeometers, and subsurface temperature probes; refer to Figure 11) or modeled (using thermodynamics) and summed to find the radiative gain or loss, and thus temperature increase or decrease at the road surface.

Use in SSI/WSI

Pavement models calculate radiation balance at the road surface to estimate or predict road temperature changes. MDSS contains a pavement condition model, built using multiple sources of data (including radiation-based data). MDSS can thus simulate the road conditions across a winter, and then MnDOT can back out the severity of the weather as it affects cost.

From Baldwin et al. (2015): RWSBEE2 "*is based upon the idea that winter severity can be derived by finding the additional energy required to melt snow and ice that has been deposited on the surface, beyond the energy that is freely available from the environment. This additional energy can be considered an amount of work that [a DOT] must perform in order to maintain the road surfaces.*" Thus, in building a radiation balance model at the surface, the RWSBEE2 uses shortwave and longwave radiation, and sensible and latent heat fluxes

Reliability

Radiation may be measured from space using radiometers mounted on satellites, or it can be measured from the ground using pyranometers, pyrgeometers and temperature sensors. Measurements of the ground from space can suffer from attenuation or contamination from clouds, water vapor, and other atmospheric particles. Even so, these variables are considered reliable enough to be assimilated by weather prediction and climate models. Ground measurement of radiative input (i.e., solar gain) is most common for DOT operations. Pyranometers are a trusted source for this information.

Temporal Variables

A category of variables was created to incorporate so-called temporal variables that depend on some element of timing, i.e., frequency (or number of occurrence) and duration. This class of variables was set aside because there are very specific ways in which frequency and duration are used in the methods described here, and it warranted a separate discussion. Thus, the next page details the ways in which frequency and duration are used in SSI/WSI methods.

Frequency and Duration of Events

Method – Source

- Iowa – operator logs
- Minnesota – MDSS (duration)
- Pennsylvania – RWIS (duration)
- Walker – GHCN (duration)

Frequency (or number) and duration are implicitly included in any calculation that calculates a cumulative index (over the course of a storm, month, season, etc.)

Use in SSI/WSI

The Iowa method relies heavily on frequency (number) and duration of events. Per Tina Greenfield, Iowa DOT: "*Snowfall amount is a poor predictor of how much we'll spend. It has more to do with duration and frequency.*" It also breaks down the frequency by type: number of snow events and freezing rain events; and it breaks down duration by type: hours of snowfall, freezing rain, blowing snow, and sleet.

Along with accumulation and precipitation type, the Pennsylvania method assigns greater points to a storm the longer it is (less than 8 hours, between 8 and 16 hours, and longer than 16 hours).

In a sense, many of the agencies who calculate a seasonal SSI/WSI—particularly if the seasonal value is an accumulation of all storm indices—are including the number of events by default.

Interestingly, Boselly et al. (1993) found that including frequency (or number of days with snowfall) did not improve that particular index.

Reliability

Tina Greenfield, Iowa DOT reports that there are some issues when dealing with human-reported data. For example, start and stop times for precipitation will be different across a garage's area, and may be reported differently per garage. Embellishment is also possible, and there have been certain quality assurance measures taken to mitigate this.

Must clearly define an event.

Penn: All the precipitation accumulation during the midnight-to-midnight period are considered part of one event unless a precipitation gap of at least eight hours is recorded within the same calendar day. "*All accumulation and durations recorded after the gap will be assigned to a new event. A change in Calendar Day will begin a new event. The total event duration is measured in hours from the start of winter precipitation to the end of winter precipitation within that event to the nearest quarter-hour.*"

Data Source Breakdown

The purpose of this section is to provide a comprehensive itemization of all the data sources from which the variables are pulled. The following list divides 17 sources by category. The "special mention" category is used to include sources that fall outside of the other categories, but which are discussed in a few index calculations, and are thus important to explain.

- Road weather-specific data sources
  - Road Weather Information System (RWIS)
  - Operator logs
  - Maintenance Decision Support System (MDSS)
  - Mobile observations
- Federal government-managed weather station networks
  - Automated Surface Observing System/Automated Weather Observing System (ASOS/AWOS)
  - Cooperative Observer Program (COOP)
  - Remote Automatic Weather Station (RAWS)
  - Environment Canada (EC) network
  - Global Historical Climatology Network (GHCN)
- Modeled data analyses
  - Rapid Refresh (RAP) model
  - North American Land Data Assimilation (NLDAS) dataset
  - Snow Data Assimilation System (SNODAS)
  - Stage IV precipitation analysis
- Special-mention networks and databases:
  - State-owned mesoscale network (mesonet)
  - Community Collaborative Rain, Hail & Snow (CoCoRaHS)
  - Regional Climate Center (RCC) databases
  - Other external databases

Table 4 links the more commonly used variables from Table 3 to the sources described here. An "X" indicates it is usually available via the source's standard instrumentation configuration. A lowercase "x" indicates it is not usually standard but may be added or may be available on some systems. This table largely serves an illustrative purpose and is not meant to be taken as absolute.

There is often flexibility in these networks and systems that may allow additional, non-standard measurements. The reader is encouraged to perform their own research into the possibilities of data sources of interest.

Table 4: Availability of Common Variables from Key Data Sources

Data Source	Variable											
	Air Temperature	Wind Speed	Visibility	Pavement Temperature	Pavement Condition/Grip	Precipitation Type‡	Snow Accumulation	Snow Depth	Snowfall Rate‡	Radiation and/or Heat Flux	Blowing Snow‡	Freezing Rain‡
RWIS	X	X	X	X	X	x	x	x	x	x		x
Operator Logs					X	X	X				X	X
MDSS*	X	X	X	X	X	X	X	X	X	X	X	X
Mobile Observations**	X		x	X	X					x		
ASOS/AWOS, EC	X	X	X			x	x		x	x		x
COOP	X					X	X					X
RAWS	X	X								X		
GHCN	X						X	X				
Model Analyses†	X	X	X	X	X	X	X	X	X	X	X	X
State Mesonet	X	X	x			x	x	X		X		

*MDSS collects data from multiple other sources and packages it into a single data stream.

**Variables included here are those with real potential to be collected in most mobile observing system configurations.

†In reality, one could model almost any environmental condition. However, one should understand that the modeled environment represents a *likely* condition—not an actual condition—and still requires nearby observations to perform its calculations.

‡These variables are often derived—not directly measured by sensors—meaning they require multiple data elements to be determined.

From Table 4 one can see that air temperature (and, not included, but likewise humidity-related variables) are readily available from all automated and modeled data sources. It looks, at a glance, that snow accumulation is easily available from a number of sources, but one should keep in mind that there are still a number of difficulties in measuring snow, particularly using automated instrumentation. Moreover, the resolution of the measurement (both in time and space) may not be to the users' desires for SSI/WSI. Freezing rain also looks to be readily available from many sources, but, again, one should remember that either humans or models are involved in most of the sources listed here; or, freezing rain may be derived using multiple other observations.

Within this section, automated (i.e., via a device or instrument), human-reported and modeled data sources will be described. There are important advantages and disadvantages to all, as are summarized here:

Automated Observations

- Advantages
    - Able to be installed where measurement is needed
    - Nearly any desired environmental parameter is measurable
    - High-temporal resolution
- Disadvantages

  - Require resources to install and maintain devices
  - Require resources to quality assure data
  - Even though nearly any desired environmental parameter is measurable many automated measurements still face challenges

Human-reported Observations

- Advantages
  - High spatial resolution
  - Nuanced reporting
  - Can provide qualitative and (some aspect of) quantitative observation
- Disadvantages
  - Low temporal resolution
  - Can be biased
  - Can be inaccurate
  - No atmospheric values

Modeled Observations

- Advantages
  - Nearly any environmental parameter can be modeled
  - There is a vast amount of modeled data available online
  - Modeled values can be interpolated to any spot at the surface
- Disadvantages
  - Modeled values are an estimate based on physical equations and not a measured condition
  - Models still require vast amounts of data to run
  - Models require computational resources to run
  - Because models are more often available from external organizations, the user's options are restricted to the data that is made available by the organization

Table 5 shows the data sources used by each method, marked by an "X." Here, a lower-case "x" indicates that the data source is used by a modified version of the method, as described in the Method Breakdown section. Again, Table 4 is meant to be illustrative. At a quick glance, one can see that most of the methods use RWIS data, either exclusively, or as a supplement to other sources. No methods (yet) use mobile observations.

Table 5: Data Sources Used by Each Method

Method	Data Sources									
	RWIS	Operator Logs	MDSS	Mobile Observations	ASOS/AWOS, EC	COOP	RAWS	GHCN	Model Analyses	State Mesonet
AWSSI								X		x
Boselly	X				X		x			
Idaho	X									
Iowa	X	X								
Matthews	X				X					
Minnesota	X		X		X				X	
Pennsylvania	X									
RWSBEE2			X						X	
Utah	X									
Walker					X			X		

Because most methods use RWIS and/or a federally-managed weather station network—often using one to supplement the other—a comparison of advantages and disadvantages of each is provided here:

RWIS

- Advantages
    - Agency management allows for deployment of desired instrumentation and quick fixes when needed
    - Measurement of pavement temperature and conditions
    - Located in critical road weather areas
- Disadvantages
    - May suffer from lack of maintenance and calibration
    - Older pavement instrumentation may suffer from inaccuracies
    - Not spatially consistent; often too concentrated in urban and high winter severity areas

Federal Government Networks (ASOS/AWOS, RAWS or COOP)

- Advantages
    - Well-maintained; trusted data
    - May capture precipitation type and accumulation
    - Long climate record
    - May incorporate manual measurements from well-trained observers
    - Feed into official climate databases in which external agencies (e.g., regional climate centers) quality control and process the data and make it readily available

- Disadvantages
    - No pavement data
    - Not often located on or near roads

What follows are 17 one-page summaries of each data source including: a description of what it is and what entity manages it, typical data output or user base, and comments on data reliability and procedures for maintaining data quality. The pages are organized into their categories and are presented under these categories:

- Road Weather-Specific Data Sources
- Federal Government-Managed Weather Station Networks
- Modeled Data Analyses
- Special-Mention Networks and Databases

Road Weather-Specific Data Sources

The sources described in this section—RWIS, operator logs, MDSS and mobile observations—provide road weather data for SSI/WSI. Mobile observations are included here, though they are not currently used in practice. Many agencies are interested in the future use of mobile observations to increase data resolution along roadways.

Each data source is discussed on the following pages entitled:

- RWIS
- Operator Logs
- MDSS
- Mobile Observations

RWIS

Description

Road Weather Information Stations (RWIS) are comprised of sensors that report real-time conditions on roadways. RWIS usually measure air temperature, relative humidity, pavement temperature, wind speed and direction, and may have cameras, friction sensors, and other relevant road weather sensors.

RWIS location and density varies greatly across the US, with some state agencies managing over 100 sites across their jurisdiction. An RWIS site may be located in a problem area to measure hyper-localized conditions, or in an open area to take measurements that would be considered representative of conditions across the entire area.

Management Entity

The RWIS stations and components themselves are usually owned and managed by the agency. Maintenance may be performed by in-house personnel, or by the product vendor or another contractor.

Management of RWIS data includes polling/collecting, quality controlling, storing, visualizing, and transferring the data to other applications. Data management can be performed by the agency itself, a product vendor, or a separate contractor.

Output/User Base

The data output from each RWIS station is used to make decisions about winter maintenance operations. The data can feed into models for road weather forecasting. RWIS data is often made available to the public, as well.

Real-time viewing of data may be the primary use of the RWIS data, with annual data stored for storm summary analysis each year. When possible, longer-term data storage (5 to 10+ years) is imperative for performing longer-term analyses, such as for building an SSI/WSI model.

Data Quality

Many agencies have found that to ensure quality data from their RWIS network, they have created a specific position at their agency that either oversees RWIS management; or serves as a point person with the product vendor or contractor. A common target used is 90% RWIS functionality.

Some of the information provided from RWIS are *derived* values that the vendor has developed. It is important to know which values are direct measurements, and which values are derived. Inaccurate assumptions of the data can be made from derived values.

Some parameters—namely those which measure road conditions and precipitation—have historically been less trusted by agency personnel, usually as a result of the measurement or derivation techniques or the location of the sensors. The science of non-invasive measurement has improved greatly over the past decade, improving the trustworthiness of these parameters. Nevertheless, agencies both at the state and federal level may still use humans to observe some of the more difficult, yet very important parameters (such as snowfall or freezing rain), as will be discussed in the subsections below.

Operator Logs

Description

Most agencies have a resource-tracking system that records maintenance operations. Weather and road condition information is often collected in these logs, whether recorded manually via operators or automatically via sensors. Human-reported storm values allows an agency to capture conditions that are missed by automated sensors.

Management Entity

The operators themselves provide the data, and the data are collected and managed by the agency itself or a contractor the agency has hired.

Output/User Base

As an example (Figure 12), operators at Iowa DOT provide: number of snow events and freezing rain events; snowfall (in inches); and duration (in hours) of snow, mixed precipitation, freezing rain, blowing snow, and sleet. The data is used both for real-time decision making and for long-term assessments.

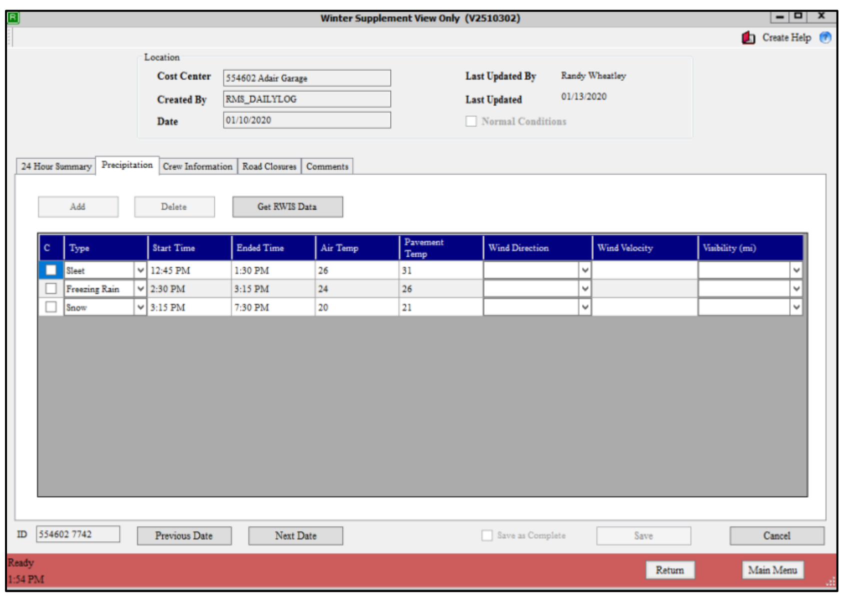

Figure 12: A screenshot of Iowa DOT's reporting page for operators. Image provided by T. Greenfield, Iowa DOT

Data Quality

Human-reported data can provide a nuanced assessment of weather conditions that automated sensors cannot provide. According to Tina Greenfield, Iowa DOT, "*There is no sensor in the world (that is easily deployable) that can detect blowing snow along the entire stretch of the highway*," but humans can. A similar statement could be said of freezing drizzle or widespread frost.

However, some issues arise when dealing with human-reported data. For example, start and stop times for precipitation will be different across a maintenance area, and may be reported differently per garage. Embellishment is also possible. Personnel may be tempted to inflate certain values (i.e., the number of events or amount of snow), because it gives them leniency on salt usage. Moreover, the more detailed the logs, the more useful the information, but also the more room for error.

Thus, when using human-reported data, certain quality assurance measures should be taken to mitigate errors. Human-reported data has to be monitored and quality checked just like automated data. Quality assurance of human-reported data will likely involve a more manual (versus automated) method. Training is also important. Also, Iowa DOT employs a social pressure trick: "*You can keep outliers at bay by showing contour maps of reported data. No one wants to be the bullseye*" (T. Greenfield).

MDSS

Description

Maintenance Decision Support System (MDSS) uses data from surface weather observations at airports and RWIS stations, radar, satellite, numerical models, field personnel observations, meteorologist inputs and other resources to piece together the picture of what has happened weather-wise. This information feeds into pavement models that predict the state of the road surface and recommend treatment. The MDSS version produced by Iteris also contains a blowing snow model.

Management Entity

MDSS is usually provided and managed by vendors.

Output/User Base

MDSS assimilates atmospheric and road conditions and outputs current and future (modeled) atmospheric and road conditions along an agency's road network, as well as treatment recommendations. It can be used as a data source for SSI/WSI calculation because it serves as a consolidation of measured and modeled atmospheric and road data across an agency's road network.

Data Quality

The data that come from MDSS are as good as the data it pulls in and the algorithm that assimilates it all. When support is available from a meteorologist, the quality of the output data may improve, because a human can make educated adjustments to modeled values or provide nuanced assessment of the model, as needed. As observational density and capabilities improve and as model physics advances, MDSS output data will only improve.

Mobile Observations

Description

The term, mobile observations, here refers to any environmental observation that is collected from a moving vehicle. It may encompass observations from externally mounted sensors or vehicle status data from the vehicle's Controller Area Network (CAN). Each will be briefly described here.

Air temperature, relative humidity, and road temperature are already commonly collected variables from fleet vehicles. They are used to support maintenance activities. Vehicle-mounted road condition/ grip sensors have also become available. Outward-facing cameras have been used to assist in maintenance activities; they can serve as a qualitative weather information gathering tool.

Weather-relevant CAN data may include wiper status (a proxy for precipitation), headlight status (a proxy for visibility), vehicle speed, brake status, traction control status, stability control status, and yaw rate (proxies for road condition). However, CAN data are not readily available. They must be read, transmitted, and converted into meaningful weather data. Moreover, many of the codes from the on-board diagnostics or CANs are proprietary (Gopalakrishna et al., 2018; Siems-Anderson et al. 2019). In recent years, work has been done to access, convert and utilize CAN data within road weather applications (e.g., within the FHWA's Integrating Mobile Observations project: FHWA, 2019).

These data may be transmitted in real time using cellular or dedicated short range communications (DSRC) or may be logged for later uploading to a computer. Downstream applications have been developed in order to better utilize these data for maintenance purposes. In particular, in partnership with the National Center for Atmospheric Research (NCAR), FHWA has developed the Pikalert Vehicle Data Translator (VDT; Anderson et al., 2016), which assimilates many environmental measurements, including vehicle-based data, and converts it to usable data. The Enhanced-MDSS (Pisano et al., 2017) is another application that uses mobile data.

As part of a broader Connected Vehicle (CV) effort, Wyoming DOT has tested the collection of weather information from fleet vehicles' CANs using DSRC signals to roadside units (vehicle-to-infrastructure, V2I) and between vehicles (vehicle-to-vehicle, V2V). Various applications that leverage V2I and V2V connectivity are being tested, such as distress warnings from other vehicles and weather alerts. More information can be found here: https://wydotcvp.wyoroad.info/.

Though progress is being made toward pulling environmental data from private vehicles, accessing weather data en masse from the public is still far from being made a reality. The widespread availability of vehicle-based weather data may not be an immediate reality, but fleet vehicles currently have the ability to collect and transmit weather data as they travel along a roadway. The potential this data has to contribute to SSIs/WSIs has yet to be thoroughly investigated.

Data Quality

Standards for mounting and maintenance of externally mounted instrumentation are still being developed. Recommendations often vary per vendor. Vehicle sensors must also be ruggedized to handle being jarred by the vehicle's motions. Moreover, the sensors must be cleaned and maintained properly and routinely, since they exist in a dirty environment.

One should also remember that most data from CANs must be used as proxy information, not actual measurement. Very detailed quality assurance and conversion measures can help to improve the use of these proxy measurements for weather applications (Anderson et al., 2016; Siems-Anderson et al., 2019).

Also, while mobile observation provides the opportunity to fill in data gaps, this data may be high resolution in space, but not necessarily in time, since a vehicle would only make one pass along a road at a time. Thus, the timing of data gathering would be somewhat scattered; that is, until weather proxy information is more available from private vehicles.

Moreover, not every variable relevant to road weather would be able to be gathered. Wind, for example, is one whose measurement presents a particular challenge on a moving platform. However, a human at the wheel of the vehicle would be able to make both qualitative and quantitative observations on the weather that could be used in a downstream application (such as SSI/WSI).

Federal Government-Managed Weather Station Networks

The networks discussed in this section are distinct because they are managed by federal government agencies; are high-quality, well-maintained, and with largely atmospheric observational capabilities; and their data provide an important foundation to climatological analyses and model forecasts. Each is described on the following pages entitled:

- ASOS/AWOS
- COOP
- RAWS
- Environment Canada Network
- GHCN

ASOS/AWOS

Description

The terms ASOS and AWOS are often referred to together or used interchangeably. They are a similar deployment of high-quality atmospheric sensors, usually located at airports, but are managed by different federal agencies. They may report as frequently as every five minutes at the most critical locations (e.g., at major airports). Examples are shown in Figure 13.

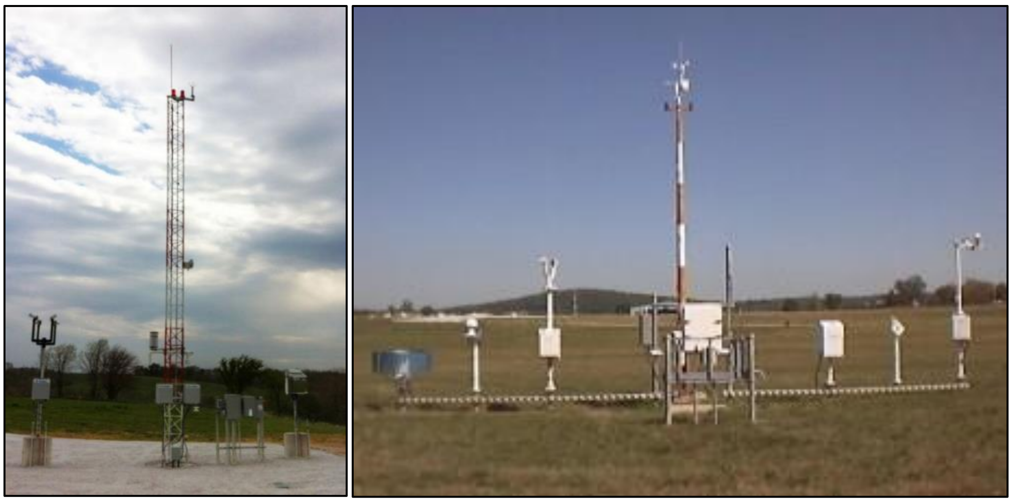

Figure 13: Example images of ASOS (left) and AWOS (right). Image source: https://www.allweatherinc.com/programs/.

Management Entity

- ASOS: Automated Surface Observing System
  - owned and operated by NWS (in partnership with FAA)
  - located at airports or other strategic locations
- AWOS: Automated Weather Observing System
  - owned and operated by FAA
  - located at airports

Output/User Base

Both systems measure:

- Wind Speed & Direction
- Altimeter/Pressure
- Relative Humidity/Dew Point
- Air Temperature
- Precipitation Type & Amount
- Visibility
- Cloud Height & Density
- Lightning Detection

The data is used for real-time airport operations and forecasting and is also assimilated into weather models.

Data Quality

ASOS and AWOS data are of the highest quality. Preventative maintenance on these sites conforms to the highest recommended standards by the device manufacturers and by standards set by NOAA. Each NWS forecasting office has a staff of technicians that provides maintenance and calibration on each device at regular monthly, quarterly, semi-annual, and annual intervals. Preventative maintenance reduces the likelihood of emergent fixes, but response maintenance is also prioritized. The data is then put through a rigorous quality control system before being distributed.

COOP

Description

The NWS Cooperative Observer Program (COOP) relies on citizens around the country who are willing to deploy instrumentation at their homes or businesses and/or take manual measurement of conditions such as snowfall. Examples of the instrumentation deployed by observers is are shown in Figure 14.

Figure 14 NWS COOP header image, showing (left to right): temperature instrumentation housing, snow board and ruler, another version of temperature instrumentation housing, and an 8-inch standard rain gauge. Image source: https://www.weather.gov/box/coop.

COOP observers measure snowfall with a ruler (in tenths) from a 2'x2' white-coated plywood snow board, located in a semi-sheltered area near their home/institution. Snow depth measurements are an average of several measurements taken in a representative area in the yard/station vicinity, rounded to the nearest inch. These measurements are submitted daily by computer or monthly via a paper form (Lisa Verzella, Observations Program Leader, NWS, Salt Lake City office; personal communication; 12 November 2019).

Outside of the COOP program, NWS works with a network of private/public individuals who submit manual observations, including ski areas, members of the public who set up a snow board/camera system, and social media users who send reports to the NWS during events (L. Verzella, 12 November 2019).

Management Entity

NWS

Output/User Base

Daily temperature statistics (maximum and minimum) and precipitation are the predominant data collected by COOP observers. The program has existed and grown since 1890, and over the decades has built an important climatological record across the US. The data are used in daily, monthly, seasonal, and annual assessments and applications of climate and weather.

Data Quality

These observers undergo rigorous training in order to provide scientific-grade observations of environmental parameters. Because the measurement of snowfall is difficult yet very important, the observers must go through a training and followed a detailed guide. These volunteer observers take manual measurements of snow water equivalent, 24-hr snowfall and accumulated snow depth every day. While manual measurements in these mostly rural areas can be a bit of an art, given sometimes extreme wind and location variations, many of the records are decades long with consistent observers and equipment placement.

RAWS

Description

Remote Automatic Weather Stations (RAWS) are located in areas away from population centers, often in woodlands or grasslands. Their expressed purpose is to monitor fire conditions, but they provide weather observation for any user base. They are also not usually near a road. An example RAWS is shown in Figure 15

Figure 15: Example of a RAWS. Image source: https://raws.nifc.gov

Management Entity

RAWS are owned and operated by US Forest Service and Bureau of Land Management.

Output/User Base

RAWS output atmospheric values, with an emphasis on fire-specific parameters: temperature, humidity, solar radiation, and wind. RAWS usually measure fuel temperature and moisture, as well.

Data Quality

As with other government-managed observation networks, RAWS undergo a high level of maintenance, requiring routine calibration and replacement of components. However, their remote nature means they may more often be offline—especially during wintertime—compared to stations near city centers.

Environment Canada Network

Description

The Environment Canada (EC) network functions similarly to the NWS network in the US. It is a large network of federally owned weather stations that capture atmospheric data at critical locations nationwide.

Management Entity

Environment Canada (weather.gc.ca) is the weather research, forecasting and observing body in Canada that functions in a similar manner to the NWS in the US. They also own and operate weather stations that are deployed around the country at strategic locations.

Output/User Base

The data collected is atmospheric data, including precipitation data. The stations would be used in a similar manner to the NWS stations in the US. The data are available for the public to use, and there is an emphasis on placing stations at critical locations, such as airports. The data are easy to work with. According to Lindsay Matthews: “You can use python/R (rclimatica) to scrape the data and process it or an amateur can download the Excel files on a station by station basis” (personal communication, 25 October 2019). However, as with other networks, the differences in their data format compared to RWIS stations can make for a challenging task to use the two together in calculations.

Data Quality

The EC network has good quality data, but there are fewer stations in northern Canada, and rural stations have been trending toward decommission. Their weather stations undergo similar strict maintenance procedures as those owned by the NWS. The maintenance on the remote stations is still of a high quality, but because of their remoteness, the data can suffer from gaps if a station goes down for a time.

GHCN

Description

The Global Historical Climatology Network (GHCN) is an "*integrated database of climate summaries from land surface stations across the globe that have been subjected to a common suite of quality assurance reviews*" (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn).

The daily version of the GHCN—GHCN-Daily—is an "*integrated database of daily climate summaries from land surface stations across the globe. Like its monthly counterpart (GHCN-Monthly), GHCN-Daily is comprised of daily climate records from numerous sources that have been integrated and subjected to a common suite of quality assurance reviews. Both the record length and period of record vary by station and cover intervals ranging from less than a year to more than 175 years*" (https://www.ncdc.noaa.gov/ghcn-daily-description).

Management Entity

GHCN is managed by the National Centers for Environmental Information (NCEI, formerly National Climate Data Center), a division of the National Oceanic and Atmospheric Administration (NOAA).

Output/User Base

GHCN-Daily provides a number of daily variables, including maximum and minimum temperature, total daily precipitation, snowfall, and snow depth; however, about half of the stations report precipitation only.

Data Quality

All of the data streams that feed into the database undergo a suite of quality checks. In addition, the dataset is reconstructed each weekend from its 25-plus data source components to ensure that GHCN-Daily is generally in sync with its growing list of constituent sources. During this process, the system applies quality assurance checks to the full dataset. The GHCN datasets are complete and trusted sources for climatological information within the meteorological community.

Modeled Data Analyses

The sources discussed in this section provide data that has been modeled. The models use data from multiple networks, plus model physics, to estimate the past, current and future state of the environment. The data is provided on grids, not at specific spots with a weather station. If data is desired at a specific spot, interpolation between grid points must be performed.

Summaries of each modeled data source are provided on the following pages entitled:

- RAP
- NLDAS
- SNODAS
- Stage IV Precipitation Analysis

RAP

Description

The Rapid Refresh (RAP) is an hourly, short-range weather prediction and data assimilation system. More information and visuals are available here: https://rapidrefresh.noaa.gov/. The model assimilates land-surface and atmospheric observations across North America, produces an analysis (its best-guess at the current state of the atmosphere), and produces forecasts of each weather variable at regular time steps (1 hour). All weather models work this way. The RAP is a particularly powerful model to use for local scale applications, as its grid spacing (points at which data is validated and calculations occur) is 13.9 km (8.6 mi), making it a relatively high-resolution continental-scale model. Its higher-resolution counterpart is the High-Resolution Rapid Refresh (HRRR), with grid spacing of 3-km. Because of its very high spatial resolution, HRRR must be computed over the regional scale.

Management Entity

NOAA's Earth System Research Laboratory, Global Systems Division

Output/User Base

The model outputs high-resolution atmospheric analyses and forecasts. The meteorological community (and other Earth science fields) use RAP for forecasting and to provide data for other Earth system and related models.

These data are pulled from RAP for SSI/WSI:

- Vertical temperature profile
- Categorical precipitation type (yes/no)
- Visibility
- 10m wind gusts

Its higher-resolution cousin, HRRR, may also be well-suited for local-scale applications such as SSI/WSI.

Data Quality

The RAP is a model, and so it provides a best guess of the atmospheric environment; it is not observation, but it consists of a vast suite of observations. As a high-resolution model with state-of-the-art physics and frequent versions/updates, it is one of the most trusted high-resolution models and data assimilation systems used by the meteorological community and government bodies.

NLDAS

Description

North American Land Data Assimilation dataset (NLDAS) a land-surface model dataset available over North America. It models the surface of the earth, including land cover (e.g., vegetation and water bodies) and processes (radiative, thermodynamic, physical, and others) that take place at the lowest levels of the atmosphere.

It operates at an approximately 13.9-km (8.6-mi) spatial resolution and hourly temporal resolution.

Management Entity

NASA's Hydrological Sciences Laboratory, and several other federal and university partners

Output/User Base

NLDAS output includes atmospheric variables near the surface (e.g., air temperature at 2 meters [6.6 ft] and wind speed at 10 meters [32.8 ft]) and land surface conditions (e.g., surface temperature, soil moisture, radiation fluxes, snowpack, etc.).

Data Quality

NLDAS is a data assimilation system made of "*quality-controlled, and spatially and temporally consistent, land-surface model datasets from the best available observations and re-analyses to support modeling activities*" (NLDAS website). NLDAS's particular goal is to reduce the errors in surface radiation balance which are often present in weather models. It operates on a 4-day lag.

SNODAS

Description

Snow Data Assimilation System (SNODAS) is another modeling and data assimilation system providing a framework to integrate snow and ice cover data from satellites and aircraft with surface observations and numerical weather model estimates of snow and ice cover and depth (National Operational Hydrologic Remote Sensing Center [NOHRSC]).

It operates at a 1-km (0.6-mi) spatial resolution and 24-hour temporal resolution.

Management Entity

Built by NOAA's NOHRSC. Housed at National Snow and Ice Data Center; Cooperative Institute for Research in Environmental Science; University of Colorado, Boulder

Output/User Base

Output: Snow depth, solid and liquid precipitation, and other snowpack physical and thermodynamic properties.

Data Quality

SNODAS provides the "*best possible estimates of snow cover and associated parameters to support hydrologic modeling and analysis*" (NSIDC website). It is built using the state-of-the-art data assimilation techniques.

A disclaimer in the SNODAS User Guide (https://nsidc.org/data/g02158) states: "*The SNODAS product is model output and should not be confused with actual observations. These data are not suitable for snow fall events or totals for specific regions. For information on snowfall events or snowfall totals, please contact one of [these] climate centers: American Association of State Climatologists, NOAA Regional Climate Centers, NOAA National Climatic Data Center.*"

Stage IV Precipitation Analysis

Description

Stage IV precipitation analysis (National Centers for Environmental Prediction, NCEP) uses NWS data from the 12 River Forecast Centers to create an hourly mosaic of precipitation accumulation from water gauges and radar data. An example of the product is shown in Figure 16.

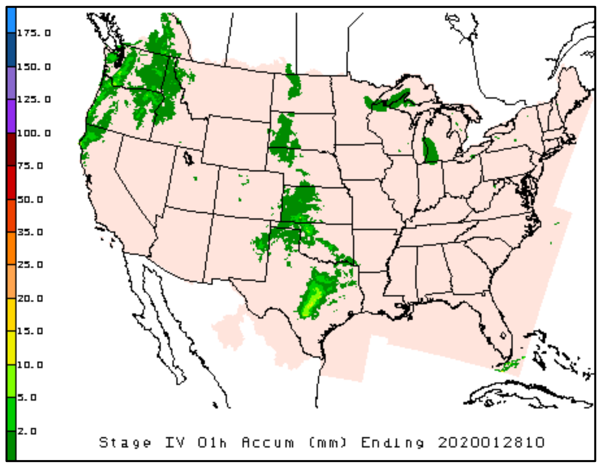

Figure 16: An example of Stage IV Precipitation data displayed across the continental US. Data shown is accumulated liquid precipitation over the hour ending 28 January 2020, 10:00 GMT. Image source: https://www.emc.ncep.noaa.gov/

Management Entity

NCEP's Environmental Modeling Center, Mesoscale Modeling Branch; cooperation with NWS River Forecast Centers (RFCs)

Output/User Base

Stage IV precipitation is used in any model of the earth's environment (over the US), including weather, climate, snowpack, hydrology, etc. It is also used by any application (such as SSI/WSI) that requires verified precipitation data.

Data Quality

Stage IV Precipitation uses a multi-sensor (i.e., radar plus gauges) data set. Manual quality control is done at the RFCs.

Special-Mention Networks and Databases

The data sources in this section represent networks and databases that do not necessarily fall into the categories outlined above. CoCoRaHS is a nonprofit weather observation network. State-owned mesonets are not available in every state, may be owned by different state agencies, and differ in what they collect. The New York State mesonet is described as the prototypical mesonet in this section. RCC Databases are included here because they are usually a clearinghouse of climate data rather than a singular network. An "other" category provides brief mention of databases that have also been used in the past for SSI/WSI applications.

These special-mention databases are described on the following pages entitled:

- CoCoRaHS
- State-Owned Mesonets
- RCC Databases
- Other External Databases

CoCoRaHS

Description

Community Collaborative Rain, Hail and Snow (CoCoRaHS, https://www.cocorahs.org/) is a nonprofit program composed of volunteer precipitation observers around the country. Example CoCoRaHS precipitation reports are shown in Figure 17. CoCoRaHS data provides an important contribution to the GHCN.

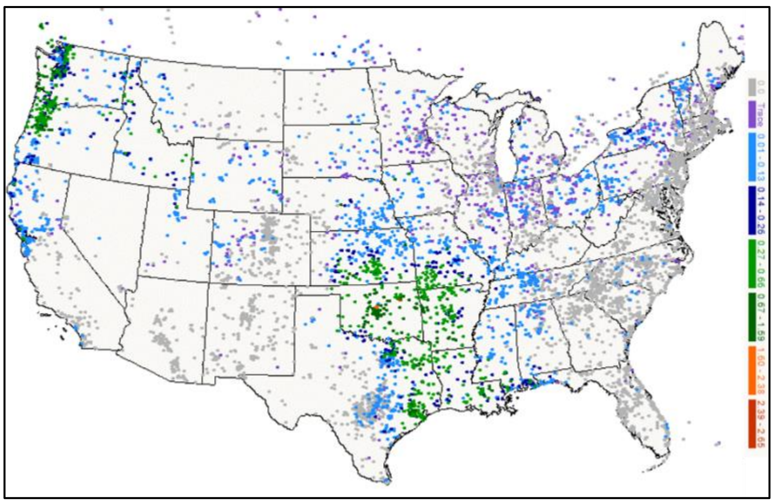

Figure 17: An example of CoCoRaHS daily precipitation reports over the 24-hour period ending 29 January 2020, 7:00 AM EST for the continental US (plus southern Canada). Image source: https://www.cocorahs.org/

There are state-scale precipitation monitoring networks that function similarly to, and in partnership with, CoCoRaHS. The Nebraska Rainfall Assessment and Information Network (NeRAIN) is one such state-specific precipitation database.

Management Entity

The program is a nonprofit, but it is sponsored by NOAA, the National Science Foundation, and others.

Output/User Base

Precipitation type and totals are recorded by volunteers daily. Volunteers also provide general observations on the weather and climate. The text data streams thus are often non-standard and would be challenging to incorporate into an equation. The precipitation type and totals, however, would be more easily included in numerical analyses. The GHCN system assimilates CoCoRaHS data, quality assures the data, and makes it readily available to external users.

Data Quality

The program requires training and education, and the volunteer observations are trusted. In most cases, if accessing CoCoRaHS via GHCN, the data have been quality assured, as well.

State-Owned Mesonets

Description

"*A mesonet is typically a network of collectively owned and operated automated weather stations that are installed close enough to each other—and report data frequently enough—to observe, measure, and track mesoscale meteorological phenomena*" (American Association of State Climatologists, 2020). In meteorology, mesoscale is the term used to encompass phenomena affecting areas from a few to a few hundred miles in area. Mesonets can capture weather such as isolated windstorms (e.g., canyon winds), localized frost pockets, fast-moving snow squalls, and other phenomena that occur on a micro-climatological scale. Mesonet sites typically have a standard suite of atmospheric sensors and, often, soil sensors, too.

Many states have some version of a mesonet; some have a higher density of sites than others. In a number of agricultural states, the agricultural industry has funded the establishment of a robust network. After Hurricanes Irene (2011) and Sandy (2012), New York State made a significant investment in their mesonet (see NYS mesonet data example in Figure 18. Of the $30 million allocated to the mesonet, half went to the purchasing of instruments.

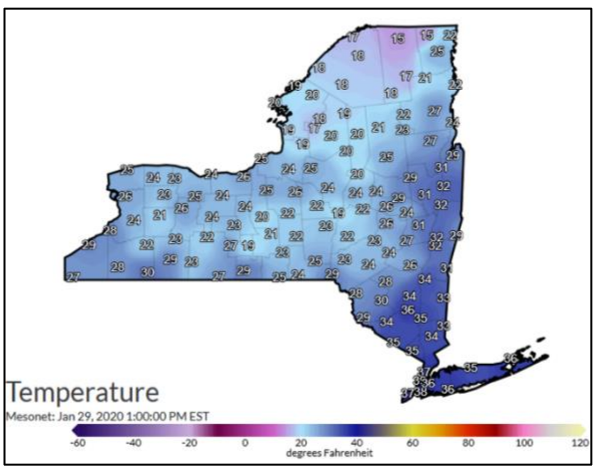

Figure 18: Temperature data from the NYS Mesonet on 29 January 2020, 1:00 PM EST. Image source: http://www.nysmesonet.org/

Management Entity

Official mesonet sites are typically managed separately from the DOT, and usually by universities or other public partnerships.

Output/User Base

Data from mesonets is supplied to forecasters, models, industries, climate databases, etc. The data are important on short time scales (such as for fast-moving weather events) and longtime scales (such as for climate databases and models).

Data Quality

Mesonets require a high level of maintenance and calibration because of the vast range of data users and applications. In order to assist in this mission, high quality or ruggedized sensors are used.

RCC Databases

Description

Many agencies use data provided by Regional Climate Centers. "*The RCC Program provides climate services to six regions encompassing the United States, [such as]: . . . (1) Provision and development of sector-specific and value-added data products and services; (2) Establishment of robust and efficient computer-based infrastructure for providing climate information; and (3) Seamless integration and storage of non-NOAA climate data with traditional NOAA data sources*" (https://www.ncdc.noaa.gov/customer-support/partnerships/regional-climate-centers)

RCCs collect data from multiple networks, quality control it, and make it available in an easy-to-access retrieval locale. Minimal processing may be done to fill in data gaps or interpret raw data.

Management Entity

NOAA's NCEI manages the RCC Program

Output/User Base

Information made available from RCCs range from raw weather data to highly processed products (such as those that track certain climate markers).

Data Quality

The RCCs are a highly trusted source for quality weather and climate information.

Other External Databases

Description

Often, a university, government and/or private partnership will develop to provide a specific type of quality-controlled data to a specific user base. Some of the databases mentioned in this project include: MesoWest/SynopticLabs (https://synopticlabs.org/), the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/) and the Weather Data Environment (https://wxde.fhwa.dot.gov/).

Management Entity

It varies. For example, SynopticLabs is a university/private partnership and the Weather Data Environment is funded by the Federal Highway Administration (FHWA).

Output/User Base

There are many different data types from road to atmospheric.

Data Quality

These services usually pull in raw data, and often provide their own quality assurance/quality control (QA/QC) processes. The users of these sources should be educated on whether QA/QC is performed.

Special Weather Scenarios

There are certain weather events which tax maintenance resources in special ways, but which are also challenging to measure using automated means. Moreover, these special weather scenarios may only happen rarely, and so tend not to play a dominant role when planning RWIS or building an index, compared to more routine winter weather. Indeed, what the transportation community is finding is that these special scenarios are impactful enough, even if rare, to warrant special attention in observation and index calculation.

Feedback from the transportation community has identified these particularly difficult weather scenarios as freezing rain, blowing snow, and widespread frost. Each scenario is discussed here, and the ways in which agencies have measured it and incorporated it into their indices are also mentioned. Examining and evaluating means of capturing and integrating these weather events into SSIs/WSIs is recommended for future work.

Freezing Rain

Freezing rain requires four key environmental conditions: (1) cold-season precipitation (meaning, the precipitation leaves the cloud as snow), (2) a layer of above-freezing air in the mid-to-lower atmosphere, sufficiently thick to melt snowflakes into rain as they fall through it, (3) a layer of below-freezing air in the lower atmosphere, sufficiently thin not to re-freeze the rain drops into sleet as they fall through it, and (4) a surface-contact temperature (on the pavement, specifically) at or below freezing, such that the rain drops refreeze on contact with the surface. Figure 6 illustrates this process.[35]

Freezing rain is notoriously difficult to treat from a maintenance perspective. Glaze ice can accrete very rapidly, becomes instantaneously bonded to the road surface, is usually very hard, and is extremely slick. Traffic may be completely halted during a freezing rain event, further impeding maintenance efforts. Because of the difficulty it presents to maintenance operations, freezing rain often receives a higher weight in SSI/WSI equations compared to other precipitation.

A key challenge in incorporating freezing rain in severity indices, is that it is difficult to observe using automated, ground-based sensors. The following lists some of the ways in which the methods described in this report measure freezing rain:

- Operator reports: Iowa Method collects frequency and duration of freezing rain events in maintenance crew logs.
- MDSS: Minnesota Method uses multiple environmental observations, plus a pavement model, to estimate the accumulation of ice on the road.
- RWIS:
    - Pennsylvania Method uses a present weather detector that reports the occurrence of freezing rain. (Note: many present weather detector models have the capability to identify freezing drizzle separate from freezing rain.)

[35] There is a significant anomaly to consider in the discussion of freezing rain: freezing drizzle. Light icing due to freezing rain can occur even when the entire temperature profile is below freezing. Thermodynamical processes in the lower atmosphere account for the occurrence of liquid rain below the freezing point. This section does not attempt to identify methods for the incorporation of freezing drizzle, specifically, into severity indices. Instead, this may be considered for future work.

    - Utah Method uses precipitation occurrence, wet-bulb temperature (> 34°F), and road temperature (≤ 32°F) from RWIS to deduce the occurrence of freezing rain.
- RWIS + federal weather stations: Matthews Method uses RWIS pavement ice warnings plus rain occurrence (from EC stations) during low temperatures.

Utah Method's use of wet-bulb temperature presents perhaps the most thermodynamically correct way to estimate the occurrence of freezing rain using automated sensors.

Some methods (e.g., Idaho) avoid having to directly measure freezing rain by using road conditions or friction. Road conditions equal to ice or friction equal to some critically low value imply ice accretion, and, thus, could be weighted more highly in an SSI/WSI equation.

The following idea using automated instrumentation was proposed by University at Albany researchers working with NYSDOT as a modification to AWSSI, and is still being tested: a proxy estimation of the occurrence of icing due to freezing rain may be possible using wind sensors from the state mesonet; each mesonet site contains a propeller anemometer and a sonic anemometer. If the propeller anemometer is no longer reporting wind speed, but the sonic anemometer is still reporting, one may infer that the propeller anemometer has iced up and its propellers can no longer rotate (note: the sonic anemometer can still report with a light ice coating, and some models are heated). Some wind must be present for this method to work. Again, this method is only proposed at this point, and is still being tested.

Some additional ideas of how freezing rain could also be measured include, but are not limited to:

- Using modeled or observed vertical temperature and humidity profiles;[36]
- Using CoCoRaHS or NWS COOP data; and
- Adapting methodology similar to that described in Sanders and Barjenbruch (2016) to automated observations.

Investigating and evaluating potential freezing rain measurement is recommended for future work.

Blowing Snow

Blowing snow adds to the overall impact of a snow event, requiring treatment long after precipitation has ended. For some locations, the climatology is such that it is a frequent issue.

The likelihood of blowing snow is highest when the snowpack is fresh, and especially when the snowpack is cold (i.e., low density or so-called "dry"). With time and warmth, the ability to move snow decreases. Also, the higher the wind speed, the easier it is to move snow; yet even a light wind can easily move fresh, cold snow very efficiently.

Validating the occurrence of blowing snow also requires special observational capabilities. While it acts like precipitation—insofar as additional snow is deposited on the road surface—the snow particles are unable to be captured by a precipitation sensor mounted at greater than 6 feet above the ground. Thus, the following alternative means have been used in methods described here to identify the occurrence of blowing snow for SSI/WSI:

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[36] Note: this sort of technique will not be appropriate for all locations—especially those with complex terrain—or for all weather scenarios—especially when freezing drizzle occurs via processes described in Footnote 35.

- Operator reports: Iowa Method collects duration of blowing snow in maintenance crew logs.
- MDSS: Minnesota Method uses MDSS, which assimilates multiple environmental observations and feeds them into a blowing snow model.
- RWIS:
    - Idaho Method collects wind speed and surface water layer from RWIS, and the storm technically ends two hours after the road surface is bare of ice and snow (*not* after precipitation has ended).
    - Utah Method uses a relationship between wet-bulb temperature and wind gust to estimate the occurrence of blowing snow.
- RWIS + federal weather stations: Matthews Method uses RWIS wind data plus EC snowfall data to estimate the occurrence of blowing snow.
- Modeled analyses: RWSBEE2 uses wind speed, precipitation occurrence, air temperature data, and local vegetation (from Stage IV, respectively) to estimate the occurrence of blowing snow.

A critical component of blowing snow that should be kept in mind is that, by nature, it is patchy. Thus, the methods using a model grid or human observation will be able to observe blowing snow even where there are no weather stations. Still, RWIS may be installed at known blowing snow locations in order to monitor conditions after fresh snow has fallen.

Widespread Frost

Frost is the deposition of atmospheric water droplets or water vapor onto a road surface that is below freezing, creating a layer of ice. This may be a result of the presence of fog or the reduction of the road temperature to the dew point temperature, when below freezing. For the purposes of this discussion, any non-precipitation ice accretion on the road surface is considered.

Frost is different than freezing rain in that the ice does not usually accumulate thickly; yet it can still be incredibly slick. Often it takes drivers by surprise relative to a more obvious freezing rain icing event.

It is also difficult to measure using automated instrumentation. When RWIS are located in known freezing fog or regular frost locations (e.g., a road or bridge adjacent to water), an agency will be able to better capture this event, but because it essentially requires proxy measurements that suggest its occurrence, automated means still may miss some events. Using temperature and humidity, paired with road temperature, road frost may be deduced using RWIS sensors. Adding a pavement condition or friction sensor will help to validate the occurrence.

Otherwise, operator reports or MDSS have been shown to provide a good representation of frost occurrence. The model datasets used in RWSBEE2, for example, may be of a large enough scale to miss the more localized frost events. Even when fog occurs over a large area, the models may still miss the impact it has on the roads, because there may not be a road temperature or friction component to the models—a critical component to frost development in fog cases.

Chapter 2: Recommendations for Developing or Improving Your SSI/WSI

Introduction

For the agency ready to develop or improve upon their SSI/WSI, there is a wealth of experience from which to draw. In Chapter 1, ten North American SSI/WSI methods from leading agencies, universities and private sector partners were described. A few of those described have been or are being modified or built upon from their original foundation in order to make the method more suitable for the agency or climate, or to utilize additional resources that that agency has available to them. The methods described above represent the state of the art in SSI/WSI calculation. Moreover, the methods offer a range of methodologies, from simple to complex, from real-time to post-processed. A number of common themes were found including:

- The successful methods have involved multiple groups within the agency from the get-go, with buy-in from every level.
- Often, it takes a few seasons for the index to build context and for it to mean something to the DOT.
- A severity index will never perfectly describe severity, or perfectly fit to maintenance response data. Instead, the agencies which use their index successfully understand and work within the limitations of their method.
- Many SSIs/WSIs have evolved overtime based on experience and evaluation.
- The agency that works within its computational, observational and personnel capabilities will be successful, even when that means seeking the assistance of a trusted partner.

This chapter uses the information reviewed in Chapter 1, plus information gathered from discussions with and feedback from representatives of the agencies highlighted herein and applies it to the development of an SSI/WSI at any interested agency. The sections in this chapter describe the following six big-picture steps to follow in developing and implementing an SSI/WSI:

1. Identify goals for SSI/WSI use
2. Identify who should be at the table from your agency
3. Identify variables and data source(s)
4. Develop or identify SSI/WSI method to be applied
5. Identify SSI/WSI application and how it will be utilized
6. Evaluate the results and/or improve SSI/WSI

Figure 19 illustrates these steps.

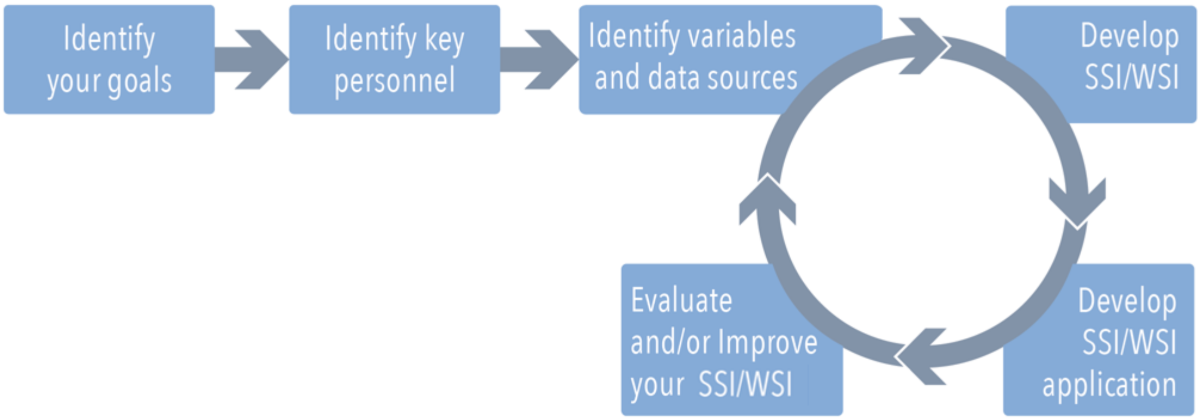

Figure 19: Flowchart illustrating the process of SSI/WSI development.

Sharing lessons learned is an important aspect of guiding any agency through development and implementation. Each section contains lessons learned from the agencies whose SSIs/WSIs are described in this project. Where possible, references to the methods described in Chapter 1 will be provided, so the reader can refer to these methods for more information.

1. Identify Goals for SSI/WSI Use

Prior to initiation of a project to create an SSI/WSI, it is paramount that you and your organization identify your overarching goals for the project. For example:

- Goal 1 – Have a better metric to gauge winter maintenance operations based on climatic and weather conditions
- Goal 2 – Use it to aid in reallocation of equipment, personnel, and materials
- Goal 3 – Scale the use of winter maintenance product use statewide, in each district, in each garage, for each truck/person, etc. based on climate and weather conditions
- Goal 4 – Provide an internal user interface for staff to use as a tool
- Goal 5 – Provide a tool for communicating with upper management or legislature
- Goal 6 – Provide an external interface for the public

These are just examples of commonly noted goals that have driven state DOTs to pursue development and application of an SSI/WSI. Your agency's goals may include some or all of these, or you may have other goals not mentioned above. Knowing your goals for the index upfront provides guidance for achieving them. This is critical because SSI/WSI development is a marathon, not a sprint; but the benefits of a well-developed and tested SSI/WSI can be enormous for an agency.

Within goal development it may behoove your agency to assign a timeline or phase for each goal. For example:

GOAL	TIME FRAME / PHASE
• Goal 1 – Develop an SSI/WSI	1 – 2 years / Phase 1
• Goal 2 – Apply SSI/WSI for resource allocation	2^{nd} yr / Phase 2
• Goal 3 – Develop an internal user interface	2^{nd} – 3^{rd} yrs / Phase 3
• Goal 4 – Develop an external/public user interface	3^{rd} – 4^{th} yrs / Phase 4

Again, these are just examples of goals and timelines which will likely vary for each project and goal.

Using SSI/WSI as Part of Performance Measurement

Xu et al. (2017) and Dao et al. (2019) suggest that using a severity index is an important component of performance measurement, because it places the performance of the crews in the context of the weather, and how difficult it actually was to treat. At many agencies, a severity index is developed first, and is then incorporated into a performance index (see, for example, Koeberlein, 2015, and Oppermann and Williams, 2018).

The discussions here will focus specifically on the index as a measure of winter severity from a maintenance perspective, but not as a performance measure. Providing details and recommendations for incorporating winter severity into performance measurement is recommended for future work.

Assessing Traffic or Societal Impact Using SSI/WSI

One could also create a winter severity index from a traffic or societal impact perspective. This means that the index assesses weather severity using traffic or societal metrics, such as traffic speeds and damage costs. This research has not attempted to evaluate indices that do that, but the reader is directed to publications by Strong et al. (2005), Qiu (2008), Cerutti and Decker (2011), and Fu et al. (2017) for more information on traffic and societal impact indices.

2. Identify Who Should Be at the Table

In the SSI/WSI development process it is key to have every potential player involved from the beginning. Err on the side of too many rather than not enough. One of the biggest mistakes noted by other agencies who have developed SSIs/WSIs is not having the right people involved up front. To accurately identify individuals from your agency, you want to think big picture which groups inside (or external to) your agency will be involved.

- **Identify a champion, lead person.** This person will serve as the main point of contact and will shoulder the program, serving as the dedicated project champion. This person may be a maintenance manager, engineer, or meteorologist at the agency. This person will lead a team of individuals, listed below, to ensure the success of the creation, implementation, and maintenance of the program.
- **Invite your director or a high-level manager to participate.** This will help to foster top-to-bottom and statewide support for the implementation of the SSI/WSI. This person will also help to provide winter maintenance contacts, historical knowledge, etc. This person will likely aid, support, and help acquire longer term funding and program structuring.
- **Invite key meteorologists that are affiliated with your agency.** Meteorologists have a deep knowledge of the instrumentation, variables, and data sources (models, external databases, etc.) that would be available to support your project. They understand proper QA/QC procedures to manage the data. They also have a physical and thermodynamical knowledge of the atmosphere to provide meaningful use of the data.
- **Invite key maintenance managers and operators (i.e., plow drivers) to participate.** This will help ground your project in reality, aid in identifying key variables to consider in your SSI/WSI, provide information on good data sources, and evaluate whether results are reasonable. These will be the personnel who may ultimately be "graded" by the index, so they need to see benefits of the application so they can aid in providing buy-in once it rolls out. It is important that the individuals selected are genuinely interested in the project and willing to assist.
- **Invite key software and technology staff to participate.** They will help streamline data acquisition, data processing, and database development and management, and help to build the SSI/WSI application.
- **Invite trusted instrumentation vendors to the table.** Most agencies have a close working relationship with one or more instrumentation vendors in which open conversations can be had about the project, project goals, and how the vendors can assist. They can provide advice on the proper instrumentation, installation, settings, data recording and transfer, etc. to make the SSI/WSI work best. At some agencies, the vendor is highly involved: processing the data, calculating the SSI/WSI, and reporting the values to the transportation agency. At others, the vendor is not involved.
- **Invite the personnel who regularly perform maintenance on the RWIS instrumentation** (if not otherwise included in the above categories). If the demands on your RWIS network will be increasing, they will need to be on board with any changes and may be able to provide an honest account of what will be possible for them and their colleagues to accomplish.
- **Others?** There may be other key individuals at your organization that could provide valuable insights in the development and application of the SSI/WSI, or aid in garnering support. Invite these individuals to participate as well.

Thinking forward to SSI/WSI data management, development, and implementation, identify personnel—internally or externally—who will build the SSI/WSI, pull the data (will it be manual or automated?), run the calculation (manually or automated), compile the results, and QA/QC the data and results. Thinking long term, identify personnel that will evolve with your SSI/WSI. If you do not have anyone who fits this description or who can take this on, your agency may consider creating a position that deals specifically with data accuracy and management such as a Winter Maintenance Data Specialist or a Meteorologist position.

Lessons Learned
Creating an SSI/WSI program with top-down and bottom-up support will create the most successful program.
Meteorologists have a particular knowledge set that make them valuable members of an SSI/WSI team.
Frequent communication (e.g., monthly) is highly encouraged to maintain momentum, ask questions, and gather feedback from users.
The SSI/WSI needs a singular champion: a position whose assigned responsibility is to oversee the management and operation of the SSI/WSI.

3. Identify Variables and Data Source(s)

With your overarching SSI/WSI goals identified and your team assembled, you can now focus in on identifying the specific question you wish to answer, and the data and data sources that will lead you to the answer. Figure 20 illustrates the process. First, develop the key question you want your index to answer. You may wish to start with something simple—for example: "What is the general winter weather severity across our state for season-to-season comparison?" Or you may have identified in Steps 1 and 2 that your goals are very specific, and your team is well-prepared to take on the challenge. In this case, your question may be: "What is the winter severity on each maintenance section of roadway, so that we can evaluate maintenance performance in real time?" With this central question identified, the data (variables) and data sources can be identified.

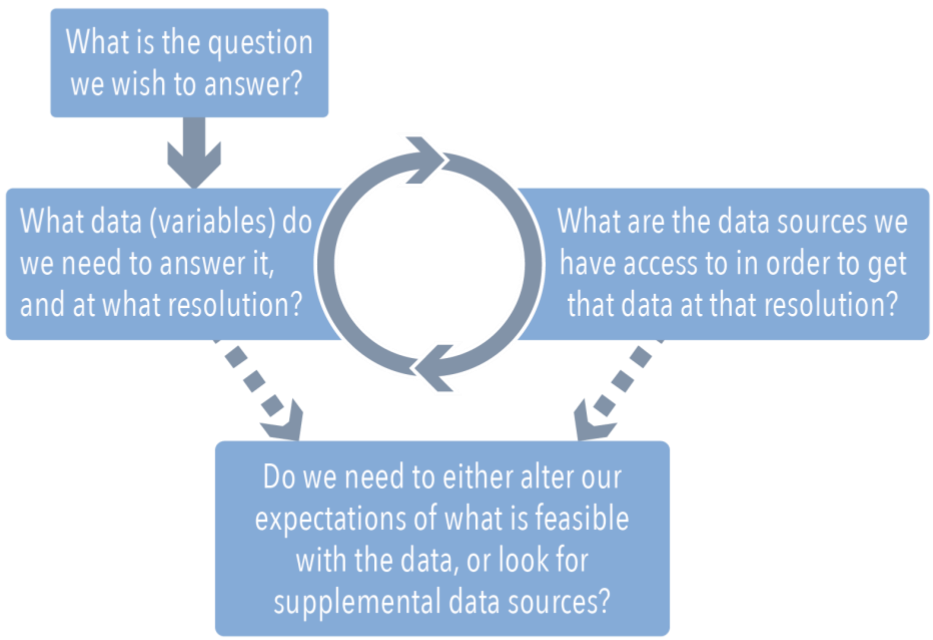

Figure 20: Flowchart illustrating the process of identifying appropriate variables and data sources for SSI/WSI development.

Consider what key variables will be needed to answer your question, or what variables matter most to your agency's specific maintenance challenges or maintenance methods. Chapter 1 provided an exhaustive list of variables that have been used in contemporary SSI/WSI methods. The process of choosing which variables to include will likely be an iterative process. You may start wide (everything you can think of) and then narrow your list. You might start very basic, working off an existing method, and adding variables as you seek to make the method more applicable to your climate. It may be of interest to know that the most often used variables in the methods discussed herein are air temperature, wind speed (and/or gust), road temperature, and snow accumulation (and/or depth).

Agencies have also found success using more unique variables. (One example: UDOT found that, in the absence of other precipitation type measurement, wet-bulb temperature was found to be a better estimator of precipitation type than [dry-bulb] temperature. As an added bonus, it was readily available from every RWIS station.) Blowing snow and freezing rain are often used as standalone variables in many of the methods reviewed herein. Temporal terms such as duration and frequency (of the variables) are often deemed necessary parts of the equations, as well.

Working with the data experts (the operators and meteorologists who use it every day), you can start to rank the importance of each variable. This ranking will be used for assigning variable weights (see section on Variable Weights under Step 4).

Identifying the variables to use is also the point in which you should be considering the resolution of the data you will need to answer your question. At what resolution (in time and space) do you need to have data in order to answer your question? Common spatial resolutions used are per county, per maintenance shed, per RWIS (or other weather station), or pre-set by a model grid. Common temporal resolutions are daily, hourly, and real time. Consider the benefits and limitations of methods calculated at each spatial and temporal resolution. For your agency's needs, does the resolution need to be very high, or will a moderate resolution, that fits within your agency's available resources serve to address the goals you identified in Step 1. More information on resolution considerations can be found in The Resolution of your SSI/WSI, under Step 4.

Next, identify the data sources that provide the variables of interest, and at the desired resolution. The list of data sources in Chapter 1 can help guide your search. However, it is recommended that you seek first the data sources that are closest to home. Using your own data (whether RWIS or operator logs) allows you to tailor your data collection to meet your specific needs. When you use your own data, you have more control.

The process of narrowing in on the data and data sources you will use is a cyclic process, in which the desire to use certain variables is married with the ability of the data sources to provide the data at the desired resolution. At some point in the process, the agency may need to ask whether there is need either to alter expectations on what data can be gathered, or to look outside the box for supplemental data sources. For example, there are a few instances of agencies supplementing their RWIS data with a secondary trusted source (usually a federal government-managed network) for high quality precipitation data.

Once the variables and data sources are identified, the data must be gathered and processed—evaluated for quality and readiness for use in the equation—and fixed, where possible. Figure 21 illustrates this process. As the flowchart shows, there are a number of determinations that must be made along the way, including: the accessibility of the desired data from available sources, the means of acquiring and processing the data, whether historical data will be available to use when calibrating the index/model, and so on.

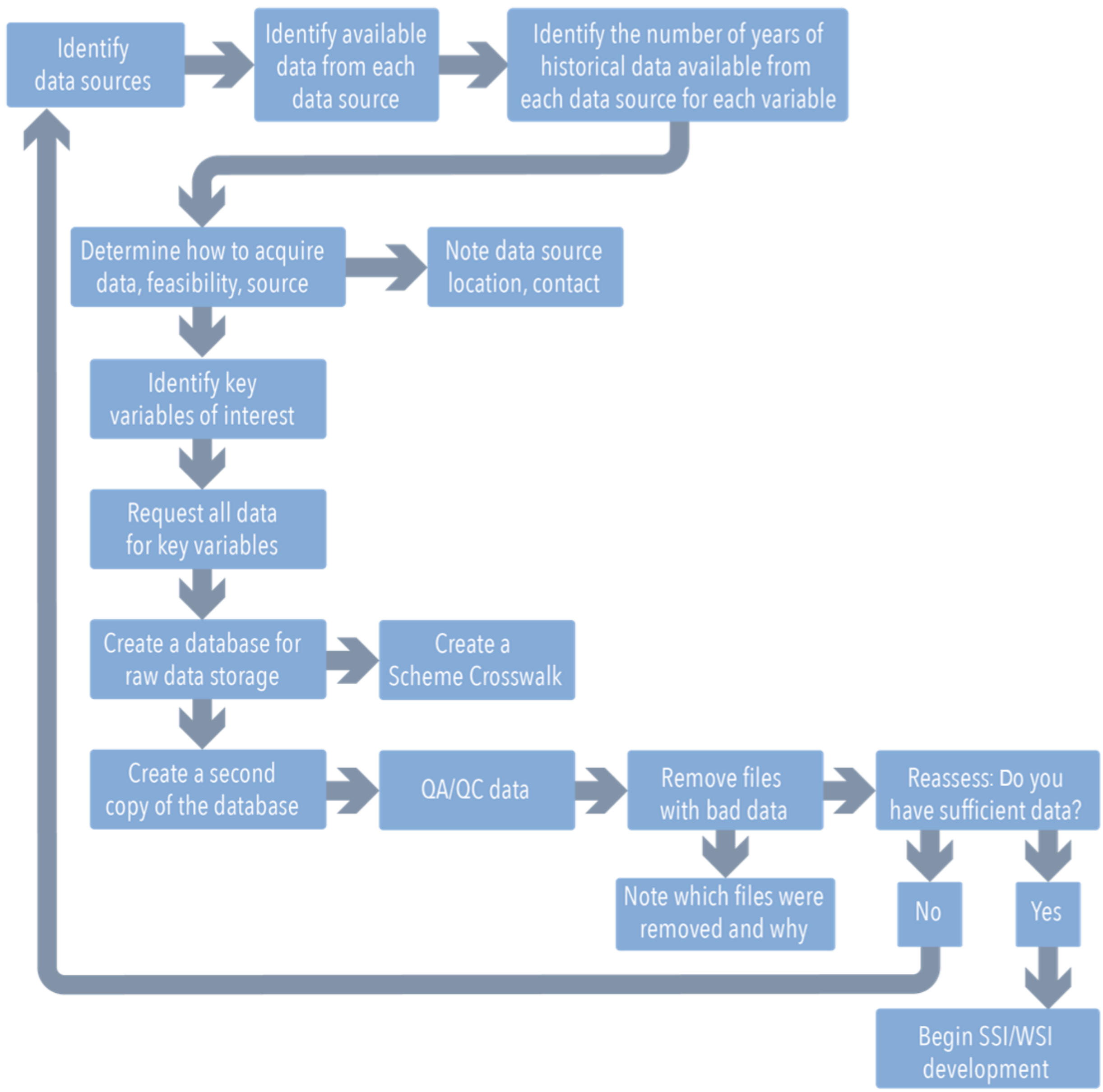

Figure 21: Flowchart illustrating a process by which data sources, variables and database set-up and management occurs in SSI/WSI development.

Lessons Learned
When identifying critical variables for the index, make sure to include the specific personnel who have an intimate knowledge of the road weather across your state—namely, meteorologists and operators.
If your software/technology personnel will be the ones importing and processing the data, ensure they are at the table for this step.
Identify the person within your agency that will serve as the point of contact for the data, data management, and storage.

Similarly, identify the point of contact at the organization (if external) from which you are acquiring the data to aid in streamlining data requests and processing. You may decide to include this external point of contact in all relevant communications surrounding the project, provided they are willing.
Data sources provide their data at varying latencies (i.e., time from measurement to retrieval) and rates (i.e., data uploads every 5 minutes, 1 hour, 24 hours, and so on). Ensure that you know the latency and rate of data retrieval.
Mobile observations are an enticing future option for improving resolution of SSIs/WSIs. Work is still needed to understand how the information will best be collected and incorporated in the methodologies.
Develop a written description of the data sources, where the data is located and accessed, the database architecture and nomenclature, how the data was processed, what data was lost (or not used) and why, additional data sources used, and the final database storage location.

Including Traffic Data in SSI/WSI Calculations

One potential consideration for SSI/WSI development is whether to include traffic data in the calculation, particularly for metro areas that experience frequent high-density traffic. For example, when traffic is at a standstill, maintenance equipment cannot access the roads. This has the potential to decrease the efficiency of maintenance efforts and can artificially increase the perceived severity of the weather. Another example, is the effect of increased trafficking of the pavement by vehicles during peak travel times which can both increase winter operation efficiencies (e.g., added heat to the system, mixing of deicing with snow and ice) and reduce them (e.g., a smaller storm may have a larger impact during peak travel time). This research effort has not made an effort to include traffic, but it may be worth examining in future research projects.

Data Quality Assurance and Quality Control (QA/QC)

The databases discussed in Chapter 1 may QC the data before providing it, but they also might simply provide raw data. The user should understand whether or not and how the data are quality controlled before using the data.

Moreover, when using any source of data, you need to have confidence not only in its quality, but also in what it is telling you about the road weather environment. Make sure you fully understand what the data means, how it is reported, and the units. What can occur over time as sensors change, are that the reporting or methods change, and the data management organization may not be aware of this.

The agency interested in using their own RWIS data for their SSI/WSI must ask: *How reliable is our RWIS data?* In some cases, state DOTs are realistic about the problems inherent in maintaining accurate RWIS data; however, it has also been found through the process of developing an SSI/WSI, that while the RWIS data may be sufficient for maintenance operations, when it comes to developing a data-intensive, highly detailed model, deficiencies begin to show regarding the reliability of the RWIS stations and data.

Because a high level of confidence is needed in the data source for calculating an SSI/WSI, an agency may wish to set goals for percent of RWIS devices online. Procedures should be developed outlining, for example, the maximum allowed downtime of any device (e.g., 48 hours during winter). In order to consistently reach the goals set by the agency, a few state DOTs have chosen to hire someone with the specific job of keeping the RWIS network in working order and calibrated (e.g., ITD). There are other options. Some data service providers will do this for you (for a fee), or you can hire a contractor to manage RWIS station maintenance and calibration, as well as quality assure the data to ensure it is high quality (e.g., UDOT). Your agency may already be doing some of or all of this to ensure good quality data. Fortunately, ensuring data reliability under the auspices of SSI/WSI will also improve other downstream data uses, such as maintenance decision-making and forecasting.

UDOT's experience, from Jeff Williams and Cody Oppermann: "*Since many variables feed into the calculation of these indices, all sensors that calculate it need to be working appropriately. This can impact storm total and winter total values via automated methods if only one sensor is not working correctly. However, readily available data shows for the current year-to-date, UDOT/Weathernet has continuously kept at least 94% of all tracked RWIS devices online. The majority of the RWIS that are compatible with the [Snow and Ice Performance Measure] have maintained appropriate up-time for the automated storm and winter value totals to be useful.*"

PennDOT uses RWIS for their SSI/WSI. Pennsylvania monitors RWIS functionality through the vendor as uptime functionality. Vaisala has a performance-based contract. RWIS repair is also done by Vaisala, but Vaisala has a group they have subcontracted with to do maintenance. Pennsylvania likes the concept of the vendor monitoring and responding to sensor failures, they are still working out the kinks in terms of practical application.

ITD developed a Weather Performance Index (WPI), which rates the treatment effectiveness to the storm (recovery time to safe grip). This effort required a full RWIS overhaul statewide, which now includes 132 RWIS sites that are actively monitored by an ITD staff position created for this job [Winter Operations Program Specialist] and are maintained by a contractor. To get the RWIS data to the highest quality level they have a policy of looking at "every site, every day" by the Winter Operations Program Specialist. RWIS uptime, or functionality, and analytics relate directly to this person's job performance. If a sensor goes down or is providing odd data, an email is sent by the Winter Operations Program Specialist to the RWIS maintenance contractor. The contractor is required to respond within 72 hours of receiving notification. ITD has a performance measure called RWIS uptime that reports on the percent of time valid data is provided. While the RWIS uptime was started to support the WPI and lead by an individual, this is now a statewide effort and now each foreman has at least one RWIS site to use.

From these examples, it is clear that there has been a high bar set at the agencies which rely on their RWIS for SSI/WSI. They have set aside funding or created specific programs simply to support their initial investment. Thus, it is critical that the extended cost of the RWIS installation and its components is understood and planned for at the outset, so that the ongoing maintenance of the devices has programmatic and monetary support for years to come.

Fortunately, building a successful index which has downstream uses, particularly for performance measurement, can increase programmatic and monetary support for your RWIS program. The experience at UDOT showed that: "*as the index grew the usability of the data grew as well making it that much more important*" (S. Jensen, Weathernet meteorologist, personal communication, 30 April 2020). He goes on to list some downstream impacts of UDOT's successful index:

- "*As the index expands it becomes helpful for folks not only in the field but also planning and supervising. This means you have quickly increased the number of stakeholders and visibility of the program so when it is down, people notice.*

- *We found that as the index grew and people were invested, the funding followed. At UDOT, RWIS devices were moved up to tier 1 devices, meaning when they are down they need to be repaired quickly. They were no longer an afterthought but something that was viewed as critical to UDOT operations.*
- *As this data became reliable and accurate more of it was desired. Jeff [Williams]'s budget included numerous funding sources (this continues today) to expand the network to additional areas.*"

Another important consideration to make when using RWIS data is the location of the RWIS station. Was the RWIS location chosen to serve as observation representative of conditions of the area around it; or, was the RWIS location chosen to measure conditions at a microclimatic "problem" spot (such as a localized frost pocket, a mountain summit, or an accident-prone location)? An equal sampling of RWIS that fall into both categories will help even out the severity scores calculated at each. Otherwise, a statewide severity calculation may be pulled in one direction or the other.

Providing supplemental assistance to weather stations, operator logs can be a useful source for data that can be managed at the agency. The reports can provide descriptive or nuanced information about the weather that automated devices cannot necessarily provide. They can also come at any point along a road or can be valid for the entire road segment. They can serve as ground truth for the automated sources, especially for precipitation and special weather scenarios like blowing snow. There are some issues to account for when using human-reported data, however: (1) timing, (2) bias, and (3) doctoring. Iowa DOT, for example, has had to be creative in order to reduce instances of bias and doctoring. Moreover, they should be added as a supplement to numerical weather data, as environmental conditions such as air or road temperature tend to be critical components to SSI/WSI calculation.

No matter the source of the data, it is easy to have some unrealistic expectations of it. These may include:

- The Resolution of your SSI/WSI section below)
- Having the desired data all the time—by their nature, weather stations or individual devices may go offline from time to time; the trick is to stay on top of it.
- Having the data tell you exactly what is going on in the environment—weather stations simply sample the environment, and sometimes what they report is contrary to what you may expect; getting to know your data intimately will help to shed light on these confusing occurrences.

The take-home message from this discussion is that all data sources and many of the variables have issues; every data source takes management and resources. Using operator logs may be appealing because it may seem "free," particularly if the operators are already in the habit of noting conditions in their daily logs, but it does take work at the operator level and work by someone to quality check the data. Management and maintenance of the data takes place through software fixes, quality controlling, and training.

Most importantly, when using any source of data in your SSI/WSI, understand that manual checking of the data and the index results will be a critical aspect of maintaining consistency and accuracy in your calculation. Though necessary, this step is time intensive and requires an experienced or trained eye.

Lessons Learned
Talk to the personnel that look at the data the most (usually the operators and the meteorologists). They will have an intimate knowledge of how reliable the different variables are.
Have a real person check the data; automated programs can fall short and not catch subtle problems in sensor data. Quality control algorithms do a good job of catching big errors, but there are times they fall short. One example is that a spatial consistency test may flag a hyper-localized phenomenon erroneously. Another example is that a quick moving storm that changes weather conditions rapidly may cause data to be flagged by a temporal consistency test. Note, however, that this step is time intensive and requires an experienced or trained eye.
If you choose to use RWIS data from stations your agency manages, then you can directly control this. It is recommended that your agency develops a program for maintenance and calibration of RWIS. If your weather data provider does this, make sure you understand the frequency and QA/QC protocols they use. If a contractor maintains and calibrates your agency's weather stations, make sure they are aware of and held accountable for proper maintenance and calibration in a timely manner. Or, your agency may wish to create a position for weather data management and QA/QC.
Ensure the extended costs of accessing your data (whether via RWIS or an alternate source) are considered, planned for, and included in annual budgets.
If your agency will be using RWIS in their SSI/WSI but would like to use precipitation as a key variable, consider including supplemental data sources. Past work has identified difficulties in using RWIS precipitation data in SSI/WSI calculations (Matthews et al., 2017a,b; MRCC, 2019; Fay et al., 2020; and others).
It is highly recommended to use a schema crosswalk: a table that shows equivalent elements or defines the origin and units of data pieces within your database. The importance of this cannot be overstated in your database management. It is likely, in your database development, you will have data sources that have different names at different agencies. For example, a DOT may name RWIS stations by location, e.g., I-70 at National Bridge, whereas the data provider may name the RWIS station by the order in which it was installed, e.g., #57. This is just an example, but a very real scenario that can complicate your data management. By cross-walking in the data base that RWIS station "I-70 at National Bridge" and "57" are the same, will save you time in long run. By teaming with key staff at your agency, from IT and GIS departments, who routinely build databases, this should be standard practice for them.
Reports from the field (operator logs) can be a valuable data source. They provide ground truthing of automated data and nuanced descriptions of weather that automated sources cannot provide, yet they are also not without error, and still require QA/QC.

Should We Upgrade Our RWIS System to Gather the Desired Data?

Of course, it is not required that your RWIS system be upgraded, additional sensors installed, or additional RWIS stations deployed. Yet, for many agencies, the addition of needed sensors or sites has improved their ability to calculate a severity index. For example, UDOT upgraded the sites that were lacking so that all had non-invasive road sensors and visibility sensors, and some required additional solar power. Also, in recent years, MnDOT made a large push to install more sites in strategic locations in order to optimize the network and fill in gaps. They also upgraded their precipitation sensors to get precipitation rate and accumulation, and installed upgraded road temperature, road condition, and friction sensors. ITD also performed a major overhaul of their network in order to comply with the needs of their Winter Performance Index.

As was likely the case in the examples of these three agencies, when the promise of better performance measurement is a key result of the upgrades, the added cost of the upgrades may quickly become worthwhile to the agency.

4. Develop or Identify SSI/WSI Method to Be Applied

There are three options for SSI/WSI development:

- Option 1 – Use an existing index
- Option 2 – Modify an existing index
- Option 3 – Develop a unique index

Using the information presented in Chapter 1, you should consider which option is right for your agency.

Start by considering whether one of the existing SSIs/WSIs can be applied at your agency. Does an agency whose jurisdiction has similar geography, weather phenomena, climate, or data availability as yours already use a successful SSI/WSI? This may help narrow down your search. Note, also, that some will be more easily transferrable than others (e.g., the Matthews method was intended to be flexible enough to be applied in other provinces and states).

There may be an index that is general enough to be applied but is then modified to meet your specific needs or enhanced by adding variables from data sources your agency may have access to. The AWSSI and Boselly methods have been found to be universal indices that can serve as foundations on which to build, as could the Walker method.

If you cannot find an SSI/WSI that adequately satisfies your agency's goals, you will need to work to develop your own. While this option requires significantly more effort than using an SSI/WSI already developed, they have been shown by many agencies to be worth the effort. In fact, one common theme identified is that SSIs/WSIs should be tailored to your states specific conditions, needs, and level of service (LOS) to most accurately portray the effort associated with your winter maintenance operations.

Please note that you should not feel alone in this process. Do not build your SSI/WSI in box, instead talk to your colleagues at other agencies, your partners at academic institutions, and trusted vendors. Expect that as more of these indices are developed, updated, and applied, one can anticipate advances in knowledge and a more streamlined understanding of what is needed.

In your agency's pursuit of options for SSI/WSI development that is best for you, know that there are many ways this can be achieved, for example:

- A person within your agency, serving as champion, can take on development of the SSI/WSI. (Examples of agencies that have done this are ITD, Iowa DOT, MnDOT, UDOT, and others.)
- Utilize a university, research partner, or consulting firm to develop the SSI/WSI. (Examples of agencies that have done this are INDOT, Nebraska DOT, NYSDOT, and others.)
- Work with your weather data provider to develop an SSI/WSI or use their proprietary version[37]. (At ITD, for example, Vaisala worked with agency champions to support data needs and streamline the calculation.)

Geographical and Climatological Considerations

A common theme among agency representatives is that while their climate may vary greatly from one end of their jurisdiction to another, with many unique micro-climates, the index they have developed is

[37] If you choose to use a vendor's proprietary SSI/WSI make sure you understand what variables it uses, any assumptions that are made, whether you can modify the SSI/WSI for your needs, if the data is available to your agency, etc.

able to capture the variability pretty well. Simply including a term (in the statewide calculation) which accounts for the occurrence of a localized phenomenon will help to level climatological transitions. For example, in a mountainous state, freezing rain may solely be a valley concern, yet including a term for freezing rain will capture it, even when it does not occur in the mountains.

There is the option to build a spatially flexible WSI that varies the calculation with topography, storm type, etc. Strong et al. (2015) built a model that varied the calculation with topography. Additionally, because climate also considers the time of year that certain weather occurs, some methods add a correction term for shoulder-season storms (usually ranking them as less severe); the Matthews and AWSSI methods alter the calculation for shoulder season/warm events.

When incorporating SSI/WSI into maintenance performance measurement, one should also consider their agency's LOS guidelines, what their maintenance crews are expected to be able to keep up with, and how the public perceives "severity." For example, a 1"/hour snowfall rate will be perceived as less severe to a northern Midwestern state versus a southern state.

Lessons Learned
Every state is unique based on climate, weather, topography/complexity of terrain, LOS guidelines, driver expectations, maintenance capabilities, location of urban versus rural populations, and unique weather phenomena. For these reasons it is highly recommended each state, or region, develop an SSI/WSI to address their specific needs.
How your state defines its severity scale in the SSIs/WSIs will be unique. This is true even within a state's borders, due to terrain and weather phenomena. Options are to include all terms that will be important in all climates of the state, or the scale of severity may need to be calibrated to address climatological differences.
Consider adding a shoulder-season adjustment if your index is over-representing fall and spring storms.

Variable Weights

Because different weather conditions have larger or smaller effects on the severity of the weather, each variable or equation term is often assigned a weight so that it has a larger or smaller impact on the index value. Expert opinion is often used to start the process of assigning weights; for example, experience suggests that freezing rain terms will have a higher weight versus dry snow terms. Maintenance data may also be used to adjust variable and term weights.

Using regression analysis, weights may be adjusted to maximize fit between index values and maintenance expenditures, as an example. The Matthews Method uses an optimization routine that maximizes the fit with maintenance data, such that "thresholds and weighting of the triggers are directly related to maintenance demand" (Matthews et al., 2017b). When going through this process, some variables may be deemed insignificant enough as to be removed from the calculation, simplifying your method without *over*simplifying it.

Do not get too narrowly focused on having a perfect fit between SSI/WSI severity values and maintenance data. There are many variables influencing this correlation. Instead, focus on what severity means in the context of your maintenance crews, and identify proper weighting and calculating based on that.

How Sophisticated Does My SSI/WSI Need to Be?

SSIs/WSIs vary greatly in the level of sophistication or complexity. This variability may come from the number of variables that are used, the quality and availability of desired data, the calculation method, the use of model physics, the optional inclusion of maintenance activities, and so on.

An example of an SSI/WSI starting out fairly simply and growing in sophistication is the method developed by ITD. The “Basic” index was developed by a district engineer and used three variables initially. The index was tested for a year in that district, and then shared with upper management for consideration for statewide implementation. Once implemented statewide, ITD sought support from their data provider to provide data processing and calculation and utilized the data output/user interface already provided to each maintenance district by the vendor. By handing off the storm-by-storm data processing and index calculation, they were able to test more variables in the index to assess their needs more accurately. Now ITD uses the more “Advanced” index which was also handed off to the vendor to be calculated.

Start with something simple and test it; build from there. Do not get frustrated if your SSI/WSI does not give you the answer you want everywhere you want it. Every method comes with limitations and caveats. That being said, the more experience and time you put into the calculation, the better you can make it.

Lessons Learned
A key takeaway from ITD’s and other states’ experience with SSI/WSI developed is that once developed, whether basic or advanced, they take time to test, and will evolve. SSI/WSI development is an iterative process and you should accept that it will change over time (see Step 6 section below).
Having the most comprehensive and detailed SSI/WSI calculation method that uses complex models or atmospheric physics, may be the right choice for your agency, but do not overlook a more basic method simply because it is just that—basic. A basic SSI/WSI can still give you useful information for comparing storms, seasons, maintenance garages’ performance, resource expenditures, etc.

The Resolution of your SSI/WSI

The term “resolution” accounts for both the spatial and temporal granularity of the data or calculation. Chapter 1 reviewed methods that calculated their SSI/WSI at various scales: at each RWIS, garage, county, or airport, or on a 75-square-mile grid (as in RWSBEE2). The index can be calculated at different time scales too, from near real time (i.e., automatically as the data come in) to daily or monthly (i.e., after the weather has happened).

The resolution of your SSI/WSI will likely be determined not by what you want, but by the quality and resolution of your data and/or your agency’s capabilities to process the data automatically or manually. Your goal may be to develop an SSI/WSI down to each maintenance shed or RWIS location. Only rarely can the data support this.

Often, data from weather stations needs to be grouped by maintenance district, climate regions, etc., so that sufficient data is available to have a statistically significant SSI/WSI. As a key takeaway from this project, agencies should identify locations for additional weather stations that aid in all maintenance operations and improve resolution for the index.

Examples of how states have improved their data resolution via upgrades and installations, or by using external resources:

- Utah DOT's strategic RWIS deployment and maintenance practices included, as a goal to work toward, installing a single RWIS for every garage. Existing RWIS stations were upgraded to a visibility sensor and the RWIS that did not have a non-invasive road sensor got one. UDOT has recently started adding satellite or slave locations that contain only a non-invasive road sensor and visibility sensor. A nearby (within 5 miles) full RWIS is used to supplement the other variables. This strategy has been found to be useful in urban environments, and it keeps installation costs down.
- PennDOT—which calculates its index per county—assigned a single representative RWIS to each county even if it one was not located in the county or there was more than one.
- MnDOT is in the process of installing around 60 new sites, which will bring the total number of RWIS sites close to 160. This is to optimize the network and fill in gaps. The newer sites will help to represent areas with more diverse land use/terrain. A number of instrumentation upgrades have also been made: Precipitation sensors which give them rate and amount, road temp and road condition, and non-invasive friction.
- Modeled data is used to fill in gaps at MnDOT (MDSS) and Indiana DOT (RWSBEE2).
- Using data from other data sources (i.e., as a supplement to RWIS) has been done at NYSDOT and WSDOT, and in the Minnesota and Matthews methods, among others.
- While mobile mounted sensors provide real time data with high resolution, incorporation of this and CV data into SSIs/WSIs has proven to be challenging and has not yet been done successfully.

How to Incorporate Weather Changes during a Storm

Fay et al. (2020) reported encountering issues with accounting for changes over time (e.g. snow to slush or freezing rain to snow). Some of the methods discussed herein are able to capture changes in storm characteristics over time. Human reporting, such as in the Iowa method, allows the operator to enter hours of a specific type of weather condition. High-resolution observation and simultaneous calculation can also help to capture changes; since the Utah method is calculated in real time, it produces an instantaneous severity value at 20-minute intervals throughout a storm, capturing the changes that occur during that time.

Yet, when calculating a single, overall storm index (as many methods do), it may be sufficient to capture the predominant character of the storm, even if changes occur during it. The Pennsylvania Method uses a 60% rule—the score is based on the type of precipitation that was falling at least 60% of the time. The Walker Method averages snowfall rate over the entire course of the storm. As often as this technique may underrepresent the high impacts during peak snowfall within a long-duration storm, it may just as often over-represent the impact of a quick-moving snow squall. Thus, the effects may average out over the course of a season.

5. Identify SSI/WSI Application and How It Will Be Utilized

The application (i.e., user-facing manifestation) of your SSI/WSI can take many forms, such as: a spreadsheet that shows calculated SSI/WSI values or an automated dashboard that provides a visualization tool to understand the data.

A few examples of visualization tools used to show SSI/WSI data are presented below—those from AWSSI, Iowa and Utah Methods.

The Midwestern Regional Climate Center provides the AWSSI Winter Index calculated at each US site in a season-to-date view (Figure 22) and a season-long view from past years (Figure 23). Colors are used to represent severity relative to climatological severity.

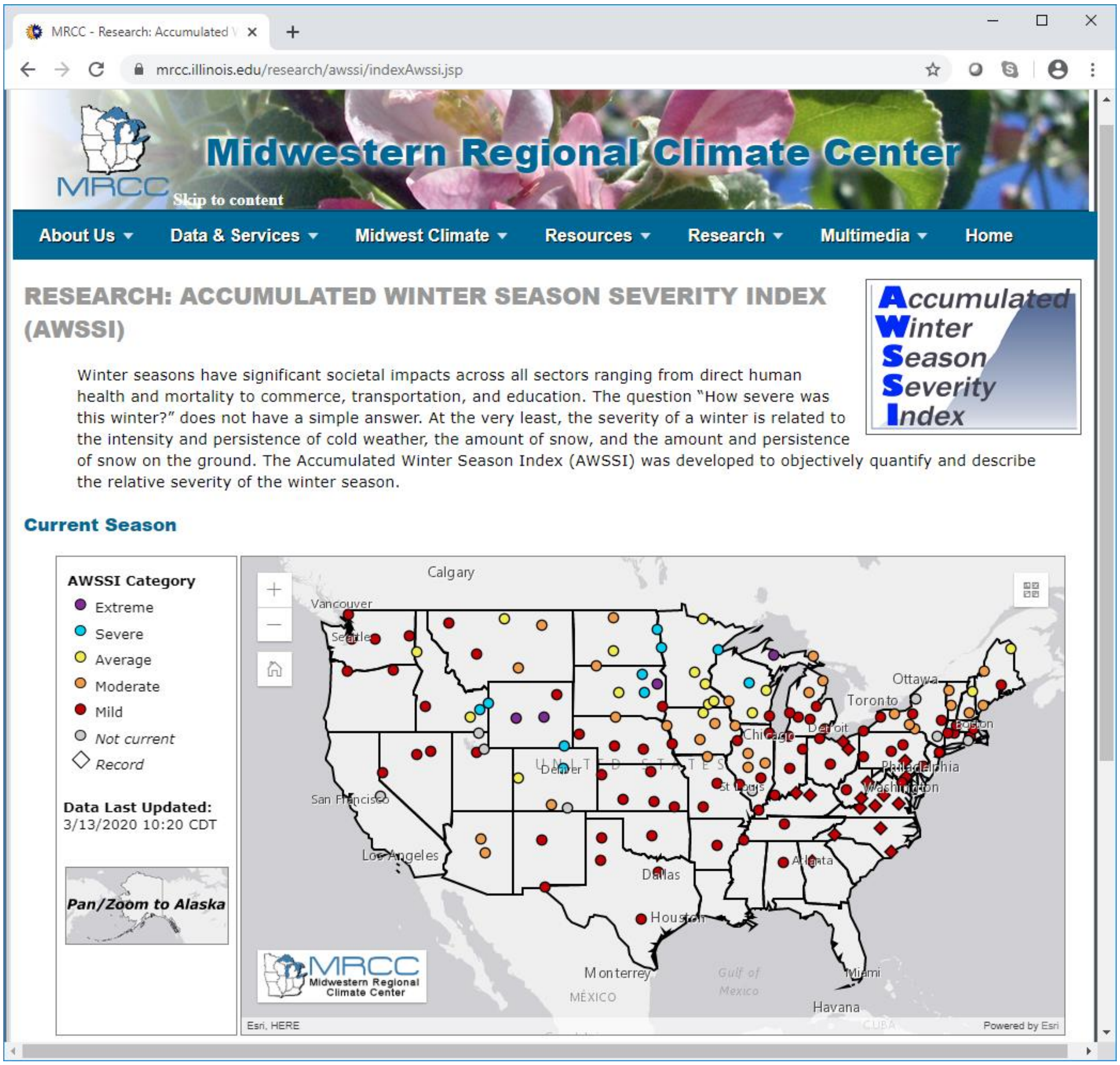

Figure 22: Online tool to access the current AWSSI Winter Index located at https://mrcc.illinois.edu/research/awssi/indexAwssi.jsp

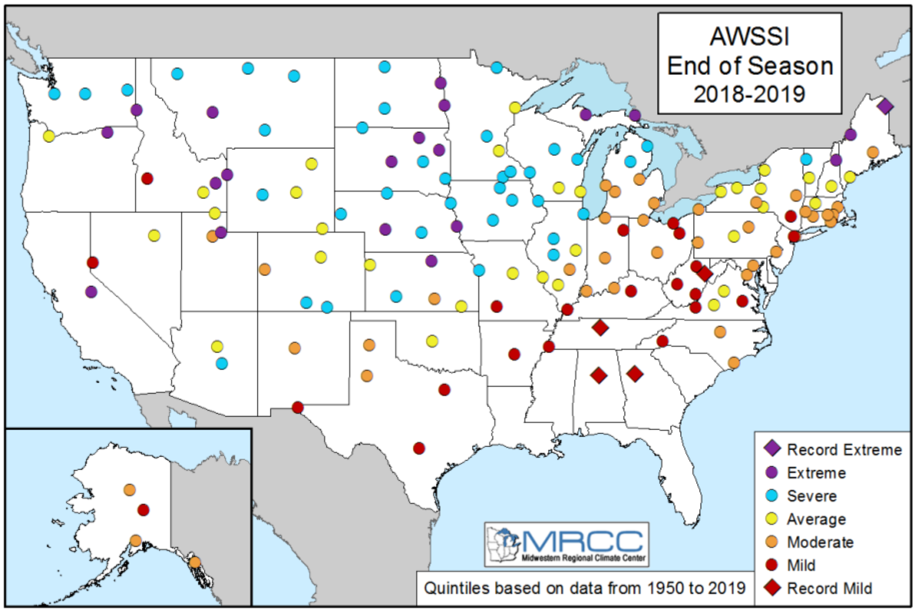

Figure 23: AWSSI winter index calculated for the 2018-2019 winter season.

You can also view the AWSSI winter index in real time for each site by clicking on a dot (which represents an AWSSI weather station) and then clicking on the link to Open Chart (see Figure 24). The current season's values are shown with a black line. There is an option to show AWSSI values from the last five winter seasons for comparison (red lines). The color shading on the graph shows the climatological values for a mild, moderate, average, severe, and extreme season at that location.

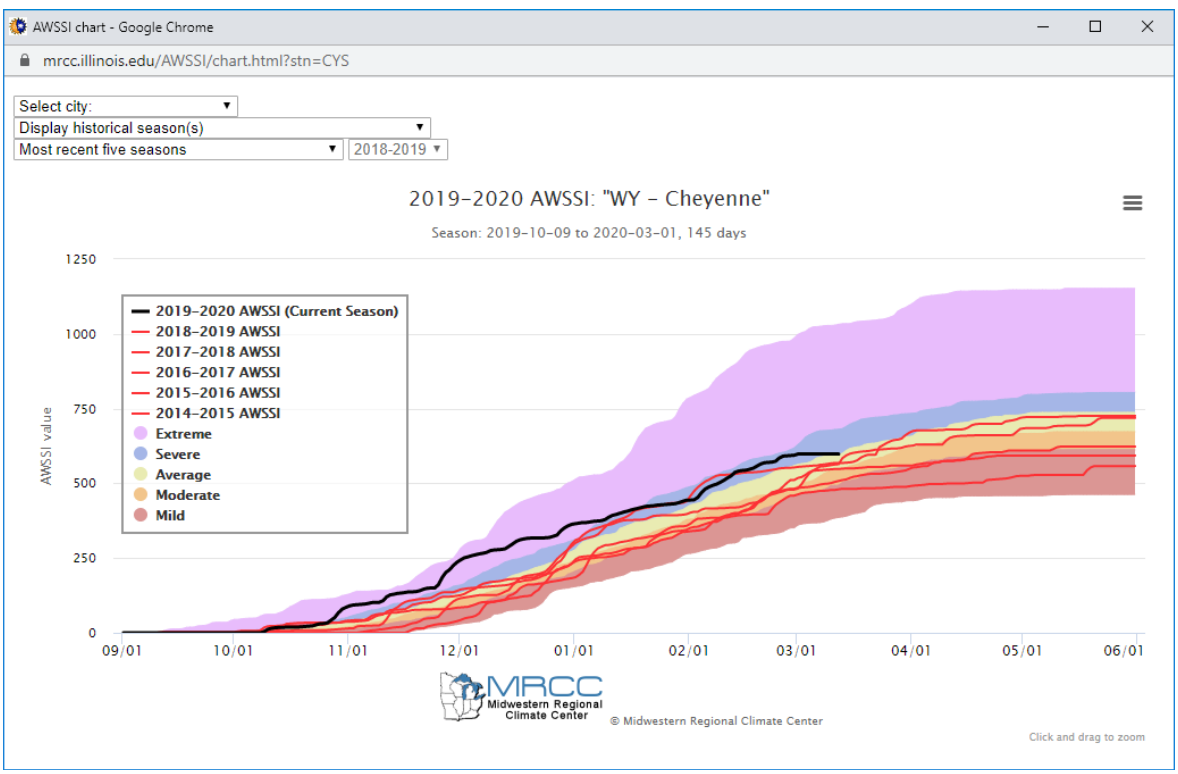

Figure 24: AWSSI winter index showing real-time calculations for the 2019-2020 winter season (black line) compared to the last five winter seasons (red lines) and to climatology (shading) in Cheyenne, WY.

The public-facing winter operations performance page for Iowa DOT shows the current cumulative index compared to the average in a time-series graph (Figure 25), as well as a bar graph of past seasons' index values to provide comparison and context (Figure 26).

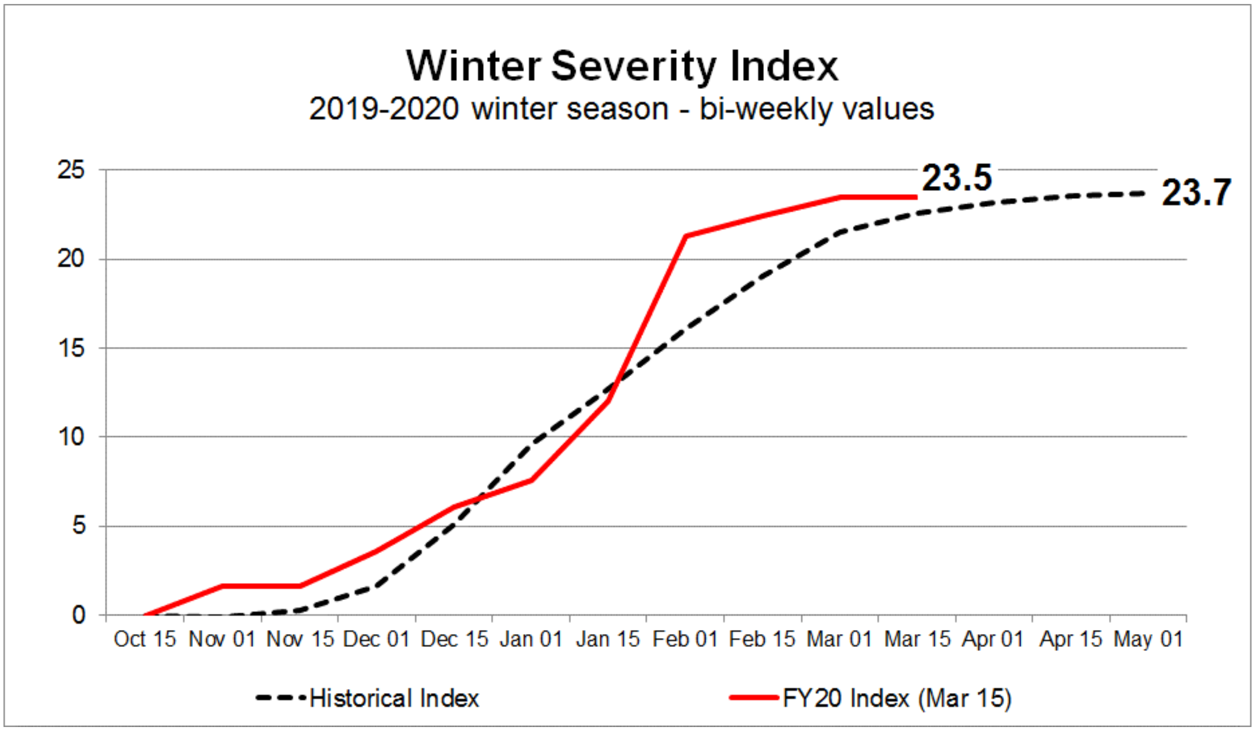

Figure 25: Public-facing Iowa DOT visualization of the current season's winter severity versus the average (https://iowadot.gov/performance/winter-operations).

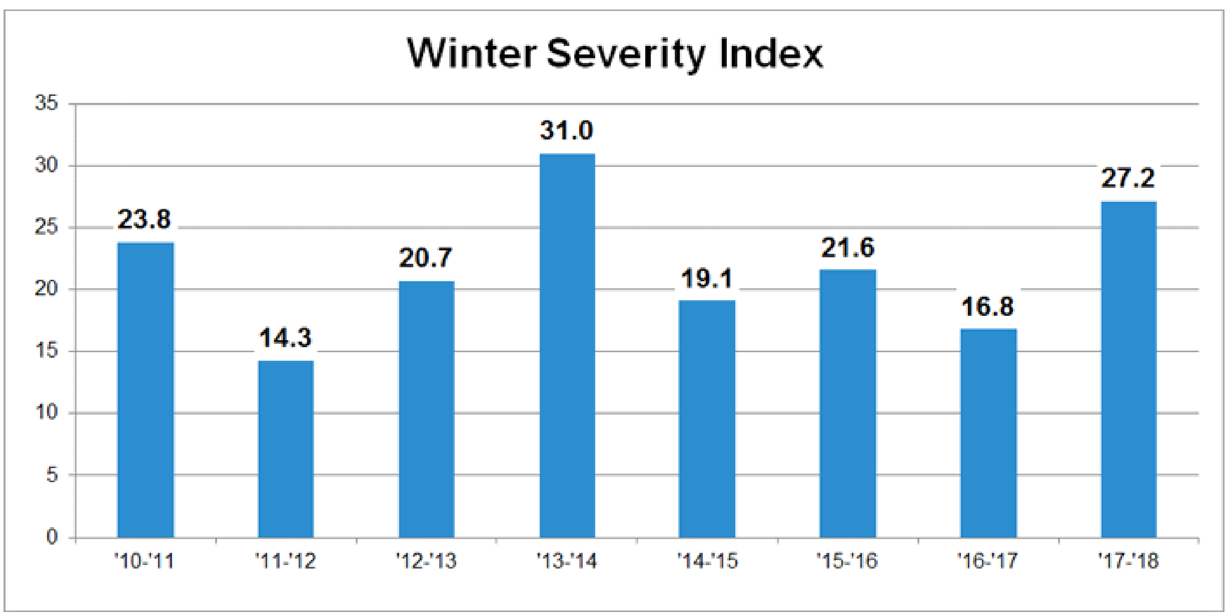

Figure 26: Public-facing Iowa DOT visualization of the past season's winter severity (https://iowadot.gov/performance/winter-operations)

The visuals developed by UDOT are used internally for operations and performance measurement. An example of a severity index calculation charted over time at a single RWIS location is shown in Figure 27.

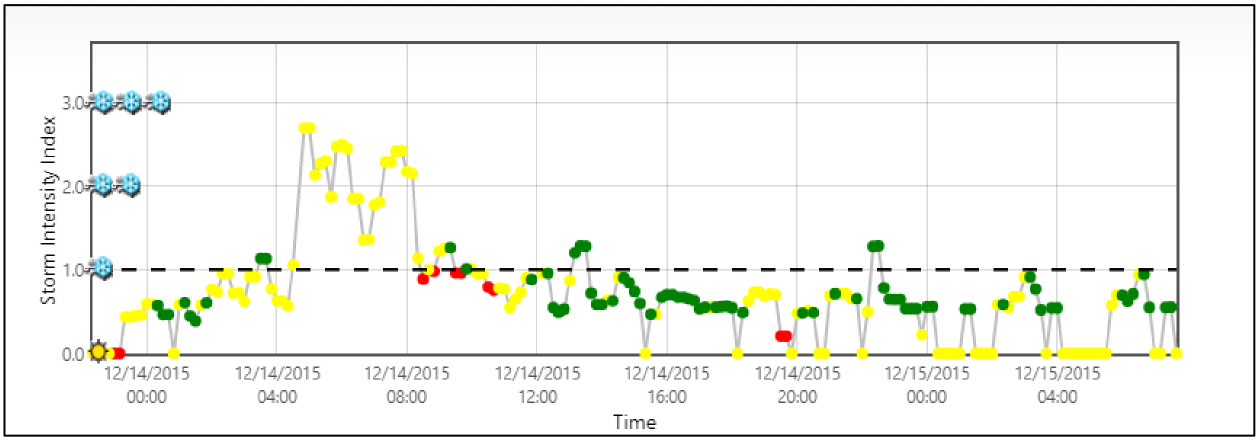

Figure 27: UDOT's real-time Storm Intensity Index charted over time at an RWIS location.

An example of real-time index and performance measurement calculations is shown in Figure 28. Included are index-relevant variables and their current values and calculated index values (refer to Utah Method for definitions).

RWIS Variable	740 MST	750 MST	Worst Condition	WRWI Variable	
IceSight Grip	0.15	0.15	0.15	RCV	1.200
Precipitation Detected	Yes	Yes	Yes		
Visibility (mi)	0.23	0.35	0.23		
Snowfall Rate (in/hr)	1.42	2.17	2.17	SRV	0.585
Road Temperature (°F)	26.96	26.96	26.96	RTV	0.063
Wet-bulb temperature (°F)	26.1	26.4	26.1	BSV	0.061
Wind gust (mph)	0*	0*	0*	FRV	0.000
				WRWI	1.909
				SII	2.419
				S&I PM	Acceptable

Figure 28: An example snapshot of index-relevant data, the WRWI/SII calculation results, and the snow and ice performance measure (S&I PM) result (Oppermann and Williams, 2018).

There are common themes found throughout SSI/WSI visualization tools, including using color coding to easily view the severity, maps to show SSI/WSI spatially, or graphs to show SSI/WSI over time. It is recommended that you familiarize yourself with SSI/WSI visualization tools and pick out the aspects of each that you like best. Then as you work through the SSI/WSI process, work with your IT and GIS staff, or a contractor, to develop a visualization tool that best suits your needs. Practically speaking, the simpler the SSI/WSI visualization tool is to understand, the more likely it will be used.

Identify key departmental areas you want to apply the SSI/WSI results. Examples are provided in Table 6.

Table 6: Examples of Actions to Take from SSI/WSI Results

SSI/WSI Finding	**Application / Action**
•Districts or regions are identified as consistently having higher SSI/WSI.	Specific equipment reallocation Approved new equipment purchase Approved increased material use Approved overtime, extra shifts
•One specific district, shed/garage shows higher material use than expected based on SSI/WSI and what you see from other sheds statewide. •Or one specific district, shed/garage shows lower than average material use, but higher SSI/WSI.	This is an opportunity to assess practices and LOS being provided in their area Identify training needs and conduct training This is an opportunity to learn and share what this group is doing that is working so well.
•The most recent season ranks as highly severe compared to prior seasons.	Identify the climatological specifics that contributed to the severe season; keep an eye on those climatological markers in climate forecasts Use this season as a performance assessment and learning tool—these are the seasons in which maintenance efficiency must be maximized Use the season as an opportunity to communicate the complicated nature of winter maintenance operations and how this intersects with driver expectations.

6. Evaluate the Results and/or Improve SSI/WSI

Implementing the index may be an iterative process at your agency. There may be a testing phase that merges into the live, active-use phase. There may be a singular region the index is tested in before it is expanded statewide. Even after the go-live date, it is reasonable to expect that adjustments will need to be made. Reiterating the example from above about ITD: They started out with a basic index that they tested in a single district. After that proved successful, the index went live statewide. Then, over time, it became more complex, with additional variables that helped with their severity assessment and with practical user interfaces.

Develop ways to monitor the data and the results. Someone should always be looking at both the data and the results. As a standard operating procedure, the data should be quality assured regularly (i.e., a human should have eyes on the data weekly, if not daily). Create a formalized means of logging and addressing errors noted. As noted in Step 3, in regard to data QA/QC, this evaluation step is time intensive and requires someone with training or experience.

The index results should be shared with upper management and operators alike. In order to get the most out of your index, be open to feedback and willing to make changes. Even after 14 years, thanks to continued close monitoring and evaluation, Iowa DOT is still making changes to their SSI/WSI. (A summary of this evolution is provided in Appendix G.) The changes are subtle, and have historically served the purpose of fixing errors in the human-reported data (e.g., falsifying in order to make the weather look harsher) or unusual weather that might cause the index to respond inappropriately (e.g., a fix was added to keep the index from going negative—a rare mild storm could trigger a negative result).

Thus, one can reasonably assume that the implemented index is not fixed in time but will undergo subtle changes that will only improve it over the years. That being said, in the long term, it is important to maintain some amount of consistency in methodology for the purpose of historical comparisons and for preserving context.

Lessons Learned
A human should be keeping an eye on the data and alerting the appropriate parties when something is reporting erroneously, or not at all.
A human should be making notes about the current storm versus what the results are revealing.
Formalize the process of checking, logging, and addressing the results of the index calculation in regular intervals.
Manually checking the incoming data and outgoing results is time intensive and requires a trained eye.

Calibrating your SSI/WSI

Calibrating the SSI/WSI you have developed is a critically important step to ensure that the values being reported represent the conditions that are present. It might be helpful to compare current storms with how you would have expected them to be rated or ranked (i.e., the severity) with what the tool is showing. The SSI/WSI calibration process takes time.

For example:

- ITD took about 1 year to calibration their “basic” SSI/WSI.

- Iowa DOT: "*In the beginning, there were challenges, until it gained some context and it was explained more. You have to get a feel for it until it means something.*" And now, after at least a decade of running it, it is understood and valued from operator to upper management.
- Ontario Ministry of Transportation: "*When the index results were given to regional maintenance engineers, they couldn't determine how right it seemed. There was, as of yet, no context for its values.*"

The results should be consistent with what your agency set out for it to look like. Now is the time to test your tool, run it up, down, and across the agency. Ask for and encourage feedback. Do not lose hope if there is some initial confusion among the ranks. It may take time for the index values to mean something. Even within the first season you can start comparing index values calculated from day to day or storm to storm. Then, in subsequent years, seasonal comparisons can be made. Because it is an index, it is unitless and must rely on context for meaning.

There is no right or wrong number when it comes to an index. (For example, in the Utah method, an instantaneous WRWI value might be calculated as a "3," and in the Idaho method, a storm might be calculated as a "400.") As mentioned above, it will need some context to make sense. You may choose to calibrate your index using historical data, if available, as this will add years of context to your initial go-live storms. After having run it for over 14 years now, Iowa's index has a strong history to provide context (see Figure 29).

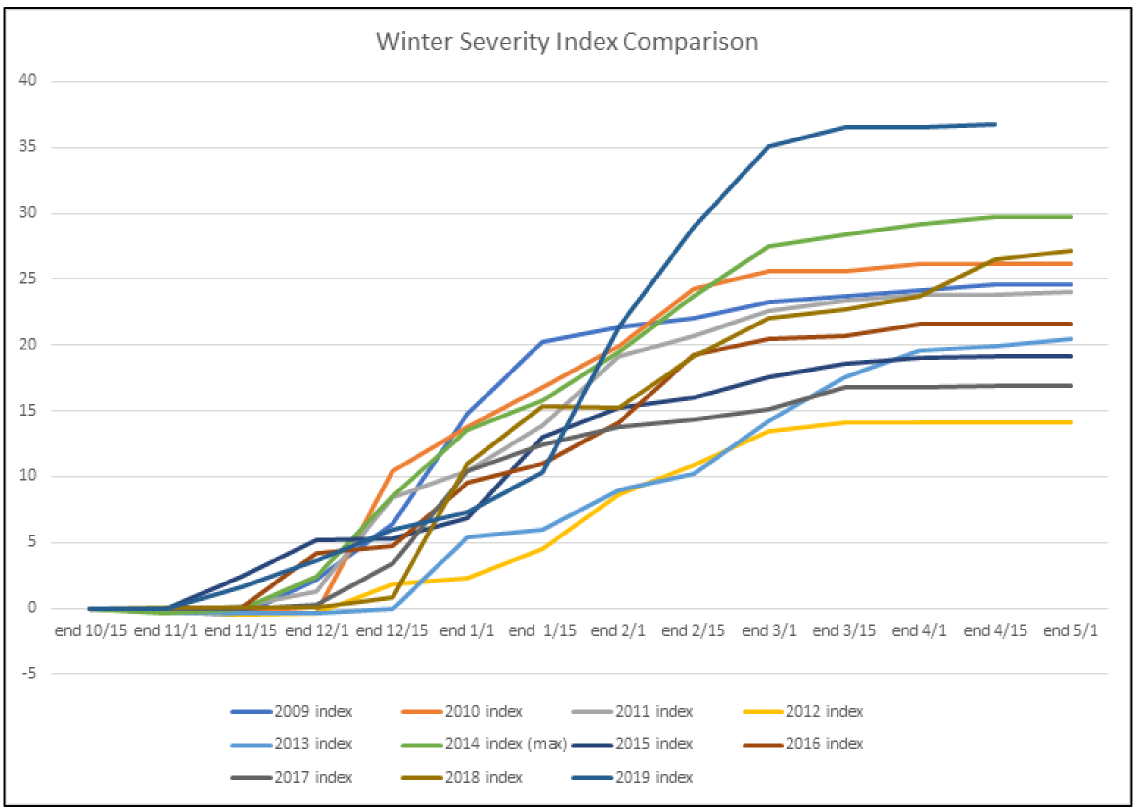

Figure 29: Cumulative WSI over each winter season since 2008/2009. The y-axis shows the unitless WSI value, and the x-axis is dates over the winter season. Source: Iowa DOT.

When Your SSI/WSI Comes Up Short

You may find after your first few storms, or after years of applying your SSI/WSI that is not as accurate as you would like, or that it is not picking up specific phenomena—for example blowing snow or freezing rain. If this occurs, investigate how others have addressed or handled what you have identified. It may help to work with an academic partner or meteorological consultant to assist in this step. Then work to apply and test the updated/modified SSI/WSI using this new information.

Lessons Learned
The tool will gain more meaning over time, so be patient and watch the ways in which it translates data into "severity" over a number of storms and seasons.
Look to others—other agencies, trusted meteorologists, or research organizations—for guidance on how your index might be improved.
While consistency is key in year-to-year analyses, it is always possible, and never too late, to make improvements to your index.

Recommendations Guide Summary

Chapter 1 described ten methods. These methods were chosen because they represented a wide range of approaches—each used different variables, combinations of variables, data sources, combinations of data sources, and inventive calculations—and they also represented DOTs across the country—from the mountains to the plains to the coast. What was strikingly evident was the wealth of work that has gone into the development of each index, and the degree to which partnerships have been utilized for sharing information and skillsets. Indeed, this is a subject matter that only benefits from openness and sharing.

In this report, an effort was made to compare and contrast each index to the others, in order to reduce the effort of teasing out some of the more critical details that could promote easier and more effective dialogue and decision making for interested parties.

SSI/WSI variables and data sources were also detailed in Chapter 1. Where possible, some of the science behind how the variables are measured was included to clarify aspects of the reliability discussion. Comments on the quality of the data offered by each data source were also included.

Chapter 2 introduced six steps an interested agency could follow to develop or improve their index. They are:

1. Identify goals for SSI/WSI use.
2. Identify who should be at the table from your agency.
3. Identify variables and data source(s).
4. Develop or identify SSI/WSI method to be applied.
5. Identify SSI/WSI application and how it will be utilized.
6. Evaluate the results and/or improve SSI/WSI.

Some of the steps describe major considerations one should make throughout the process, such as:

- Performing data QA/QC
- Weighting variables
- Making geographic and climatological considerations
- Evaluating how simple or complicated your index should be
- Determining the resolution of your index
- Incorporating storm changes over time
- Calibrating the index

Each section or subsection also has a summary of lessons learned during communications with the agencies and entities running these indices. A summary of key lessons learned from Chapter 2 is presented below.

Lessons Learned
Creating an SSI/WSI program with top-down and bottom-up support will create the most successful program.
Bring everyone to the table: Meteorologists, technology/software personnel, field personnel (operators), upper management, and trusted consultants, contractors or academic partners.

Frequent communication (e.g., monthly) is highly encouraged to maintain momentum, create an opportunity for frequent dialog, to ask questions, and to gather feedback from users.
The SSI/WSI needs a singular champion: a position whose assigned responsibility is to oversee the management and operation of the SSI/WSI.
Develop a written description of the data sources, where the data is located and accessed, the database architecture and nomenclature, how the data was processed, what data was lost (or not used) and why, additional data sources used, and the final database storage location.
Remember that reports from the field (operator logs) can be a valuable data source. They provide ground truthing of automated data, nuanced descriptions of weather that automated sources cannot provide, and at a fairly high spatial resolution (i.e., all along a road segment or at the worst weather spot).
Mobile observations are an enticing future option for improving resolution of SSIs/WSIs. Work is still needed to understand how the information will best be collected and incorporated in the methodologies.
Every state is unique based on climate, weather, topography/complexity of terrain, LOS guidelines, driver expectations, maintenance capabilities, location of urban versus rural populations, and unique weather phenomena. For these reasons it is highly recommended each state, or region, develop an SSI/WSI to address their specific needs.
Once developed, whether basic or advanced, SSIs/WSIs take time to test, and they will evolve. Index development is an iterative process and you should accept that it will change over time.
Having the most comprehensive and detailed SSI/WSI calculation method that uses complex models or atmospheric physics, may be the right choice for your agency, but do not overlook a more simplistic method simply because it is just that —simplistic. A more basic SSI/WSI can still give you useful information for comparing storms, seasons, maintenance garages' performance, resource expenditures, etc.
A human should be keeping an eye on the data and alerting the appropriate parties when something is reporting erroneously, or not at all. This step is can be time intensive and should be performed by trained or experienced personnel.
A human should be making notes about the current storm versus what the results are revealing.
Gain trust in the tool through education and input. Gather feedback openly.
The tool will gain more meaning over time, so be patient and watch the ways in which it translates data into "severity" over a number of storms and seasons.
Look to others—other agencies, trusted meteorologists, or research organizations—for guidance on how your index might be improved.
While consistency is key in year-to-year analyses, it is always possible, and never too late, to make improvements to your index.

Task 6: Agency Follow-up

The research team distributed the Task 5 Recommendations Guide to the agencies and personnel that had assisted by providing survey and interview responses, and asked for their review of it for information presented in Task 5 Chapters 1 and 2. Feedback received was used to improve the usability of information provided in this report.

Task 7: Spreadsheet Tool

Background

The research team distilled the information available in the Recommendations Guide into a simple tool that walks a user through possible variables and methods to be used to calculate severity for specific weather patterns. Questions that were considered in the development process included:

1. What data does the agency have available?
2. What is the quality of the available data?
3. What are the key parameters needed to calculate severity?

From the answers to these initial questions, a flowchart was developed to guide the agencies toward a given calculation method, using a flow of information illustrated in the example shown in Figure 30.

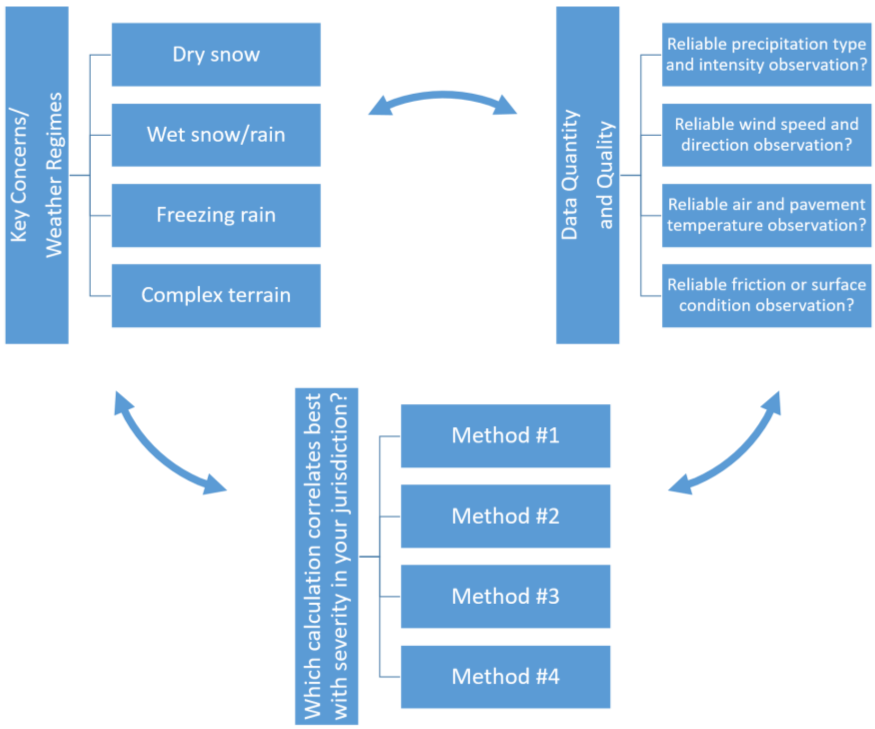

Figure 30: Example information or thought flow for guiding agencies to adopt a given SSI/WSI methodology.

A multi-step flowchart tool was created allowing users to select variables that are used to identify key weather patterns or directly represent key conditions. Once selected (boxes checked) the SSI/WSI methods that use the same variables will be highlighted. The user can then review in the Final Report document each of the highlighted SSI/WSI methods to determine whether:

1. One of the SSI/WSI methods could be used for their purposes,
2. A combination or modification of SSI/WSI methods could be used for their purposes, or
3. An original, new SSI/WSI should be developed to best address their needs.

Results

A flowchart tool has been created in Excel to support identification of SSIs/WSIs that may work for your agency based on weather patterns you would like to see included and variables of interest or data elements that you have available to you. The spreadsheet is meant to be used in tandem with the information provided in the Recommendations Guide.

How to Use the Flowchart Tool

The flowchart tool is an Excel-based tool with logic build into it. We recommend reading the Recommendations Guide and this How to Use the Flowchart Tool document in their entirety prior to using the tool to make any decisions about SSIs/WSIs to be used by your agency.

When you open the Excel based tool you will see Steps 1-3 (Figure 31):

Step 1. Weather Patterns/Key Concerns

Step 2. Select Variable of Interest or Available

Step 3. SSI/WSI Methods and Variables Used

Step 1 **Weather Pattern/Key Concerns**		**Step 2** **Select Variables of Interest or Available**		**Step 3** **WSI/SSI Methods and Variables Used**
☐ Snow	FALSE	***Atmospheric Variables***		**AWSSI (National)**
☐ Freezing Rain	FALSE	☐ Air Temperature	FALSE	Air Temperature
☐ Widespread Frost	FALSE	☐ Wet-Bulb Temperature, Relative Humidity	FALSE	Snow Accumulation
☐ Blowing Snow	FALSE	☐ Wind Speed	FALSE	Snow Depth
		☐ Wind Gust Speed	FALSE	
		☐ Wind Direction	FALSE	**Boselly (Massachusetts, Washington)**
		☐ Vertical Temperature Profile	FALSE	Air Temperature
		☐ Atmospheric Pressure*	FALSE	Snow Accumulation
		Pavement Variables		
		☐ Road Temperature	FALSE	**Idaho**
		☐ Surface State/Condition	FALSE	Wind Speed
		☐ Friction	FALSE	Layer Thickness [Water, ice, snow?]
		☐ Water or Ice Layer Thickness	FALSE	Road Temperature
		Precipitation Variables		
		☐ Precipitation Occurrence**	FALSE	**Iowa**
		☐ Precipitation Type	FALSE	Number of Snow and Freezing Rain Events
		☐ Snow Accumulation	FALSE	Snowfall Accumulation
		☐ Snow Depth	FALSE	Snowfall Duration
		☐ Snowfall Rate	FALSE	Freezing Rain Duration
		☐ Blowing Snow	FALSE	Blowing Snow Duration
		☐ Freezing Rain Occurrence	FALSE	Sleet Duration
		☐ Freezing Rain Accumulation	FALSE	Precipitation Type
		☐ Visibility***	FALSE	Road Temperature
		Radiation Variables		
		☐ Shortwave and Longwave Radiation	FALSE	**Matthews (Alberta, Ontario, Canada)**
		☐ Sensible and Latent Heat Fluxes	FALSE	Snow Accumulation
		Temporal Variables		Pavement Condition [Surface State/Condition]
		☐ Frequency of Events	FALSE	Precipitation Type
		☐ Duration of Events	FALSE	Air Temperature
		Geographic Variables		Wind Speed
		☐ Climate Zone/Region within a State	FALSE	

Figure 31: Steps 1,2, and 3 of flowchart tool.

Each step is explained following.

Step 1. Weather Patterns/Key Concerns

Starting at Step 1 Weather Patterns/Key Concerns, select the weather patterns or key concerns that you would like for an SSI/WSI to consider. The four weather pattern options to select are:

- ☐ Snow
- ☐ Freezing Rain
- ☐ Widespread Frost
- ☐ Blowing Snow

Information on each weather pattern can be found in the Special Weather Scenarios section. Note that Freezing Rain and Widespread Frost imply ice presence, so if you are interested in an ice event weather pattern select one or both of these, depending on the usual cause of icing in your jurisdiction. Selecting a weather pattern can be done by clicking your mouse on box to the left of the weather pattern of interest. Figure 32 provides a visual for Step 1 in the flowchart tool, showing both Snow and Widespread Frost have been selected in this example.

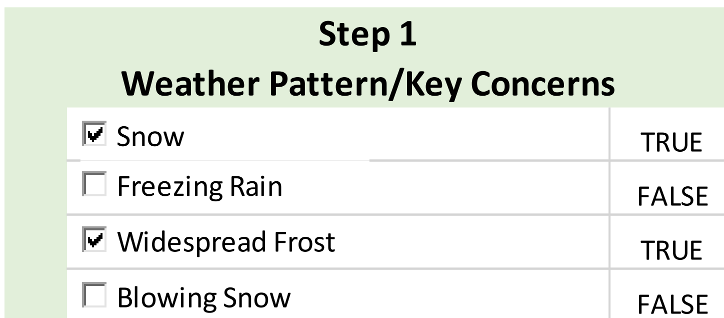

Figure 32. Step 1 from the flowchart tool.

As you select a weather pattern, the variables used to capture that weather pattern are highlighted in yellow under the Variables of Interest in Step 2.

Step 2. Select Variables of Interest or Available

Based on what you selected in Step 1 some of variables should be highlighted yellow already (Figure 33). Read through the list of variables and select the data variables you have available to use or are interested in using. The variables include:

Atmospheric Variables

- ☐ Air Temperature
- ☐ Wet-Bulb Temperature, Relative Humidity
- ☐ Wind Speed
- ☐ Wind Gust Speed
- ☐ Wind Direction
- ☐ Vertical Temperature Profile
- ☐ Atmospheric Pressure

Pavement Variables

- ☐ Road Temperature
- ☐ Surface State/Condition

- Friction
- Water or Ice Layer Thickness

Precipitation Variables

- Precipitation Occurrence
- Precipitation Type
- Snow Accumulation
- Snow Depth
- Snowfall Rate
- Blowing Snow
- Freezing Rain Occurrence
- Freezing Rain Accumulation
- Visibility

Radiation Variables

- Shortwave and Longwave Radiation
- Sensible and Latent Heat Fluxes

Temporal Variables

- Frequency of Events
- Duration of Events

Geographic Variables

- Climate Zone, Region within a state

Information on each variable can be found in the Variable Breakdown section.

Variables in step two will already be highlighted based on the weather pattern(s) you selected in Step 1. You can select additional variables that are not highlighted. As you select the variables you will see that the variables listed under each SSI/WSI in Step 3 will become highlighted in yellow.

Figure 33 provides a visual for Step 2 in the flowchart tool, showing what Variables are highlighted yellow when both Snow and Widespread Frost weather patterns have been selected in this example.

Step 2 Select Variables of Interest or Available	
Atmospheric Variables	
Air Temperature	FALSE
Wet-Bulb Temperature, Relative Humidity	FALSE
Wind Speed	FALSE
Wind Gust Speed	FALSE
Wind Direction	FALSE
Vertical Temperature Profile	FALSE
Atmospheric Pressure*	FALSE
Pavement Variables	
Road Temperature	FALSE
Surface State/Condition	FALSE
Friction	FALSE
Water or Ice Layer Thickness	FALSE
Precipitation Variables	
Precipitation Occurrence**	FALSE
Precipitation Type	FALSE
Snow Accumulation	FALSE
Snow Depth	FALSE
Snowfall Rate	FALSE
Blowing Snow	FALSE
Freezing Rain Occurrence	FALSE
Freezing Rain Accumulation	FALSE
Visibility***	FALSE
Radiation Variables	
Shortwave and Longwave Radiation	FALSE
Sensible and Latent Heat Fluxes	FALSE
Temporal Variables	
Frequency of Events	FALSE
Duration of Events	FALSE
Geographic Variables	
Climate Zone/Region within a State	FALSE

Step 2 Select Variables of Interest or Available	
Atmospheric Variables	
☑ Air Temperature	TRUE
☑ Wet-Bulb Temperature, Relative Humidity	TRUE
Wind Speed	FALSE
Wind Gust Speed	FALSE
Wind Direction	FALSE
☑ Vertical Temperature Profile	TRUE
Atmospheric Pressure*	FALSE
Pavement Variables	
☑ Road Temperature	TRUE
☑ Surface State/Condition	TRUE
☑ Friction	TRUE
☑ Water or Ice Layer Thickness	TRUE
Precipitation Variables	
Precipitation Occurrence**	FALSE
☑ Precipitation Type	TRUE
☑ Snow Accumulation	TRUE
☑ Snow Depth	TRUE
☑ Snowfall Rate	TRUE
Blowing Snow	FALSE
Freezing Rain Occurrence	FALSE
Freezing Rain Accumulation	FALSE
Visibility***	FALSE
Radiation Variables	
☑ Shortwave and Longwave Radiation	TRUE
☑ Sensible and Latent Heat Fluxes	TRUE
Temporal Variables	
☑ Frequency of Events	TRUE
☑ Duration of Events	TRUE
Geographic Variables	
Climate Zone/Region within a State	FALSE

Figure 33: Step 2 from the flowchart tool. The image on the left shows what Step 2 looks like following Step 1 selection of Snow and Widespread Frost weather patterns. The image on the right shows Step 2 following selection of the variables that are highlighted yellow.

Step 3. SSI/WSI Methods and Variables Used

As you move to Step 3 you will see headings for each SSI/WSI followed by a list of variables used in each, as is shown below.

AWSSI (New York—modified, MT, others) Air Temperature Snow Accumulation Snow Depth **Boselly (Massachusetts, Washington)** Air Temperature Snow Accumulation **Idaho** Wind Speed Layer Thickness Road Temperature **Iowa** Number of Snow and Freezing Rain Events Snowfall Accumulation Snowfall Duration Freezing Rain Duration Blowing Snow Duration Sleet Duration Precipitation Type Road Temperature **Matthews (Alberta and Ontario, Canada)** Snow Accumulation Pavement Condition [Surface State/ Condition] Precipitation Type Air Temperature Wind Speed **Minnesota** Air Temperature Road Temperature Dew Point/Relative Humidity Frost/Black Ice Occurrence Wind Speed Wind Gust Speed Wind Direction Precipitation Type Precipitation Duration Precipitation Amount [Accumulation] Cloud Cover [Short- and Longwave Radiation] Atmospheric Pressure Blowing Snow **Pennsylvania** Snow Accumulation Freezing Rain Accumulation Precipitation Duration Air Temperature	**RWSBEE2 (Indiana)** Roughness length [Friction] Air Temperature Wind Speed Road Temperature Short- and Longwave Radiation Sensible and Latent Heat Fluxes Vertical Temperature Profile Precipitation Type Visibility Wind Gust Speed Snow Depth Precipitation Accumulation **Utah** Road Condition Friction Snowfall Rate [Visibility] Road Temperature Wet-bulb Temperature Wind Gust Speed Precipitation Occurrence **Walker (Nebraska, Colorado--modified)** Snowfall Total [Accumulation] Snowfall Rate Wind Speed Air Temperature District Area [Region within a State] Visibility Duration **Maryland** Air Temperature Surface Temperature Precipitation Occurrence Wind Speed Storm Duration Climate Zone **Maine** Air Temperature Snow Accumulation Precipitation Amount Precipitation Type Freezing Rain Accumulation **Other/Develop Your Own**

Note that the location where the SSI/WSI is used is listed as its name or next to the name – for example, RWSBEE2 (Indiana).

Based on the variables selected in Step 2, the variables used in each SSI/WSI are highlighted in yellow under Step 3 (Figure 34). You can then easily identify the SSIs/WSIs that have used variables that you indicated are important. To find detailed information on each SSI/WSI see the Method Breakdown section.

Note that there is an option called **Other/Develop Your Own SSI/WSI**. This option is discussed at length in Chapter 2: Recommendations for Developing or Improving Your SSI/WSI. This SSI/WSI is always highlighted in Step 3 because it is always an option, as it can be tailored to fit your weather patterns and variables of interest.

With the information provided by you and the flowchart tool, your agency can look at the feasibly of using an SSI/WSI that already exists or whether developing your own SSI/WSI is the right option for you.

Step 3
WSI/SSI Methods and Variables Used

AWSSI (National)

Air Temperature
Snow Accumulation
Snow Depth

Boselly (Massachusetts, Washington)

Air Temperature
Snow Accumulation

Idaho

Wind Speed
Layer Thickness [Water, ice, snow?]
Road Temperature

Iowa

Number of Snow and Freezing Rain Events
Snowfall Accumulation
Snowfall Duration
Freezing Rain Duration
Blowing Snow Duration
Sleet Duration
Precipitation Type
Road Temperature

Matthews (Alberta, Ontario, Canada)

Snow Accumulation
Pavement Condition [Surface State/Condition]
Precipitation Type
Air Temperature
Wind Speed

Minnesota*

Air Temperature
Road Temperature
Dew Point/Relative Humidity
Frost/Black Ice Occurrence
Wind Speed
Wind Gust Speed
Wind Direction
Precipitation Type
Precipitation Duration
Precipitation Amount [Accumulation]
Cloud Cover [Short- and Longwave Radiation]
Atmospheric Pressure
Blowing Snow

RWSBEE2 (Indiana)*

Roughness Length [Friction]
Air Temperature
Wind Speed
Road Temperature
Short and Longwave Radiation
Sensible and Latent Heat Fluxes
Vertical Temperature Profile
Precipitation Type
Visibility
Wind Gust Speed
Snow Depth
Precipitation Accumulation [Snow, Ice, other?]

Utah

Road Condition
Friction
Snowfall Rate, Visibility
Road Temperature
Wet-bulb Temperature
Wind Gust Speed
Precipitation Occurrence

Walker Method (Nebraska and modified and used in Colorado)

Snowfall Total [Accumulation]
Snowfall Rate
Wind Speed
Air Temperature
District Area
Visibility
Duration

Maryland

Air Temperature
Surface Temperature
Precipitation Occurrence
Wind Speed
Storm Duration
Location Variable

Maine Method

Air Temperature
Snow Accumulation
Precipitation Amount
Precipitation Type
Freezing Rain Accumulation

Other/Develop Your Own

Figure 34: Step 3 from the flowchart tool, showing variables used in each SSI/WSI that were selected based on weather patterns in Step 1 and variables in Step 2.

Project Conclusions

This project arose out of a need to make sense of the wide variety of SSI and WSI methods in use by agencies across North America and the world. One desired goal was to establish an optimal methodology from the evaluation of all of the methods. ***A key conclusion from this research was that agency capabilities, access to data, goals, partnerships, climates, etc. are different enough that a singular optimal SSI/WSI methodology would be unwise or impossible to recommend.*** Instead, there are examples of success found in each of the methods described in the Recommendations Guide, and interested parties are encouraged to utilize the synthesis of information here, as well as contact colleagues at other agencies, to decide which path their SSI/WSI will take.

Again, it must be noted that the significant contributions of agency personnel, consultants, and research bodies that have been working on SSI/WSI development for, in many cases, decades. Each is recognized in Acknowledgements.

Several ideas for future work arose from this project, including:

- Comparing index outputs from different methods at the same location and perform a critical investigation of the differences.[38] For example, compare AWSSI and NEWINS outputs at Omaha, Nebraska, or Boselly and Iowa outputs at Des Moines, Iowa.
- Cataloging methods of performance measurement-specific severity indices, examining the intersection between the road weather index and the performance index, and providing recommendations for best practices thereof.
- Examining the intersection(s) between maintenance-based severity indices and societal impact-based severity indices.
- Evaluating ways to incorporate mobile observations into SSI/WSI.
- Examining whether or how to include traffic data in SSI/WSI.
- Evaluating methods to include special weather scenarios—freezing rain, blowing snow, and widespread frost—in SSI/WSI.
- Identify the specific threat to transportation agencies caused by freezing drizzle and investigate the degree to which its specific inclusion in SSI/WSI is warranted.
- Evaluate the degree to which dual-polarization radars provide accurate enough estimates of precipitation type and accumulation to be useful in SSI/WSI applications.

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[38] Complements to Curtis Walker.

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Lead state:

Minnesota Department of Transportation
Research Services
395 John Ireland Blvd.
St. Paul, MN 55155