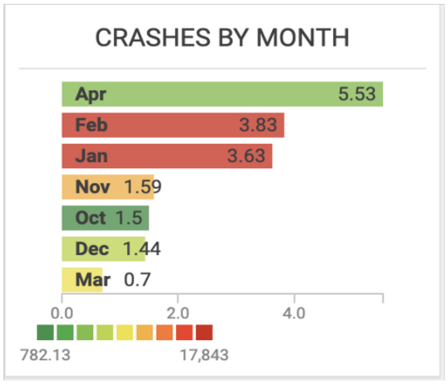
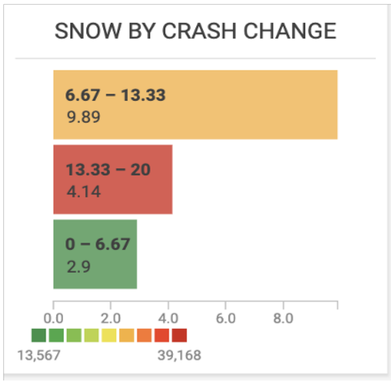
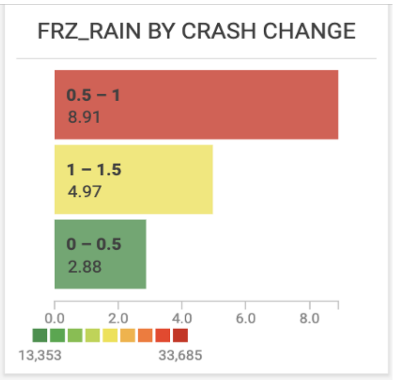
Development of a Surface Transportation Impact Factor for Winter Severity Indices







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16. Abstract

The State of Missouri is a diverse state in terms of winter weather patterns, population distribution and traffic patterns. Winter weather ranges from severe ice storms to high accumulation snow events to typical events with mixed precipitation types and amounts with a wide range of impacts across the state. Missouri has areas ranging from sparsely populated rural to congested urban areas. With this diversity in mind and the data-driven culture of the Department, the MoDOT Winter Severity Index process developed in this research effort provides a tool to accurately compare response practices, winter weather management, and performance across the various diverse regions of Missouri.

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Acronyms and Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACS	American Community Survey
ACIS	Applied Climate Information System
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
AWSSI	Accumulated Winter Season Severity Index
CWD	Clear Weather Day
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPU	Graphical Processing Unit
LE	Law Enforcement
METAR	Meteorological Terminal Air Report
NWS	National Weather Service
Org	Organization
RITIS	Regional Integrated Transportation Information System
RWIS	Road Weather Information Systems
S-HAL	Safety Handbook for Locals
SHRP	Strategic Highway Research Program
TMS	MoDOT Transportation Management System
USDOT	United States Department of Transportation
VMT	Vehicle Miles Travelled
WSI	Winter Severity Index
WSI_wx	Weather-Based Winter Severity Index

Executive Summary

MoDOT is a data driven Department of Transportation, as represented by the MoDOT Tracker (https://www.modot.org/tracker-measures-departmental-performance) and numerous internal efforts to use data to improve the overall organization. MoDOT's winter weather response is no exception and the need for a Winter Severity Index (WSI) process that will capture the impacts to the travelling public and MoDOT was identified.

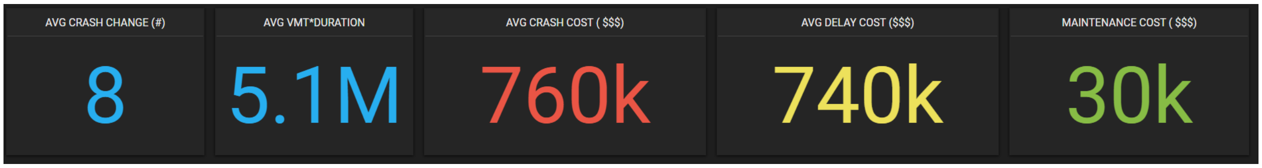
While most WSI systems across the US and Canada are based on the significant weather variables influencing winter season severity, the MoDOT WSI developed in this research effort develops a tool that tells the broader story of winter weather impacts in Missouri. The centerpiece of the MoDOT WSI is a dashboard that provides visual analytics with the impacts of winter weather across the state that can be easily filtered to display broad impacts over several years to the impacts of specific storms and specific MoDOT maintenance areas.

For instance, the dashboard tells us that over the years of 2017 to 2019, winter weather related crashes increased on the average per maintenance area by three, average crash costs were $660,000, average delay costs were $430,000 and average MoDOT maintenance costs were $14,000 as shown in Figure 1.

AVG CRASH CHANGE (#)	AVG VMT*DURATION	AVG CRASH COST ($$$)	AVG DELAY COST ($$$)	MAINTENANCE COST ($$$)
3	3.6M	660k	430k	14k

Figure 1. Overall average winter weather impacts across 2017 to 2019

If we look specifically at a severe storm that occurred on January 11, 2019, the winter weather related crashes increased on the average per maintenance area by five, average crash costs were $760,000, average delay costs were $740,000 and average MoDOT maintenance costs were $30,000 as shown in Figure 2.



AVG CRASH CHANGE (#)	AVG VMT*DURATION	AVG CRASH COST ($$$)	AVG DELAY COST ($$$)	MAINTENANCE COST ($$$)
8	5.1M	760k	740k	30k

Figure 2. Average winter weather impacts of the January 11, 2019 storm

And to look even more specifically at the Hampton maintenance area (in St. Louis County) during the January 11, 2019, storm, the storm related crashes increased by 33, crash costs were $2,500,000, delay costs were $4,200,000 and MoDOT maintenance costs were $44,000 as shown in Figure 3.

AVG CRASH CHANGE (#)	AVG VMT*DURATION	AVG CRASH COST ($$$)	AVG DELAY COST ($$$)	MAINTENANCE COST ($$$)
33	13M	2.5M	4.2M	44k

Figure 3. Winter weather impacts specific to the Hampton maintenance area of the January 11, 2019 storm

While this analysis is valuable, a key objective of the MoDOT WSI is also to develop a normalized picture of the winter weather impacts so that an accurate comparison can be made across maintenance areas and districts in different regions of Missouri that does not skew the impacts to the heavily travelled and highly impacted urban areas. This will allow MoDOT to better compare response practices, winter weather management, and performance across the various diverse regions of Missouri. An example of the complete normalized dashboard for 2017 to 2019 is shown in Figure 4.

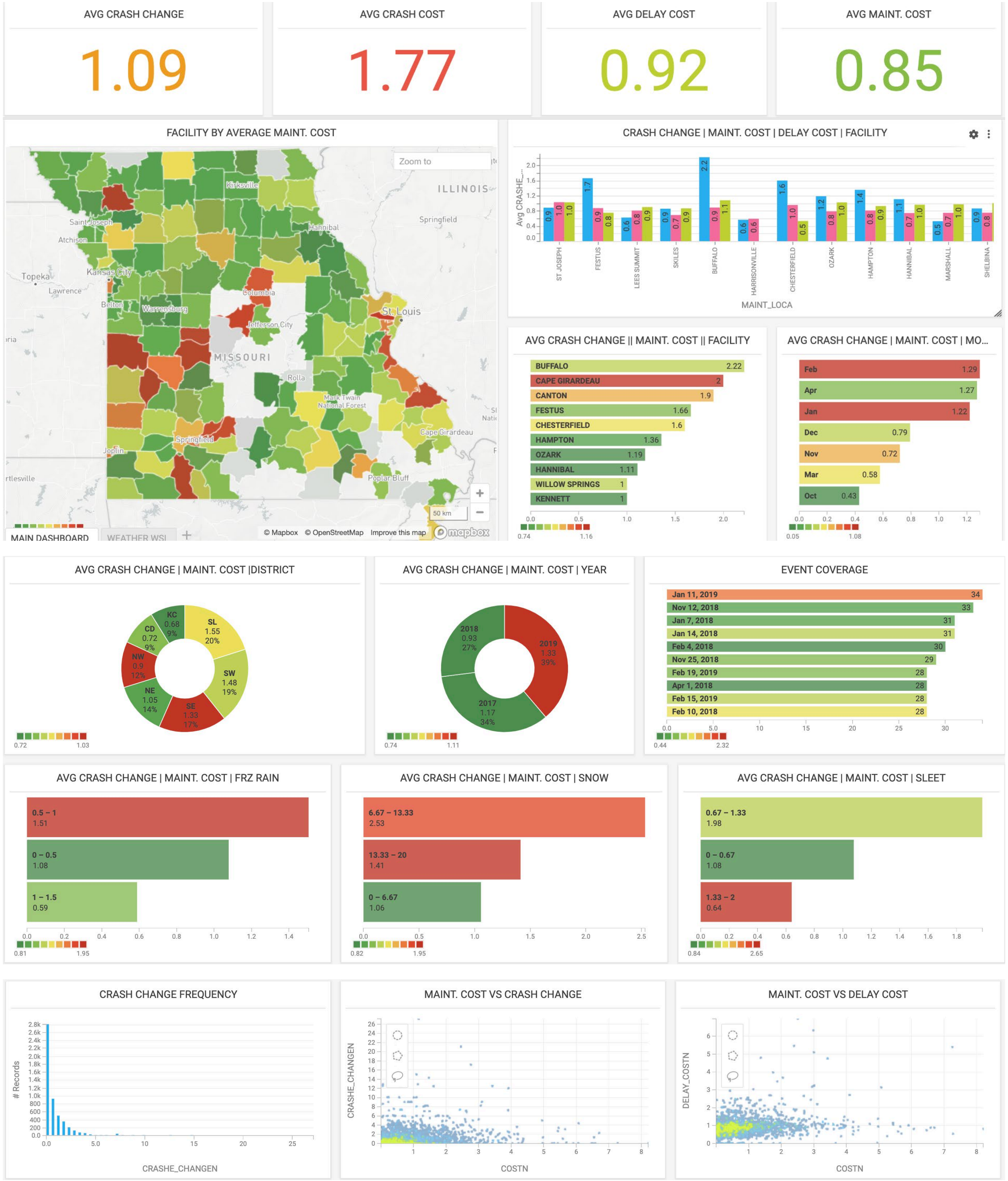


Figure 4. Missouri Winter Severity Dashboard showing normalized data for 2017 to 2019

Chapter 1 Introduction

A number of WSIs have been developed across the United States and Canada. The development of WSIs by different states and provinces is based mostly on the significant weather variables influencing winter season severity as described in the Literature Review Chapter.

The primary goal of this research effort is to develop an expanded WSI for Missouri to include broader impacts to both MoDOT and the Missouri travelling public. Weather factors alone do not tell the entire story. The total impacts of a given weather event that occurs in a very rural area versus a similar event that strikes during the peak hour in an urban area can be magnitudes different.

The State of Missouri is diverse, ranging from rural and sparsely populated areas such as Worth County in northern Missouri, Reynolds County in southern Missouri and Maries County in central Missouri to congested urban areas such as St. Louis County, part of the St. Louis Metropolitan Area and Jackson County, part of the Kansas City Metropolitan Area. In addition, Missouri has diverse winter weather. Southern Missouri winter weather can resemble southern US weather patterns with a tendency to icy storms and daily freeze-thaw cycles. Northern Missouri winter weather can represent northern US weather patterns with larger snow accumulations and extended cold weather. The central part of Missouri can take on northern or southern winter weather tendencies or a mix of both. It is not uncommon for Missouri to experience snow accumulations over 12 inches and disabling ice storms that require weeks of recovery, and at times even the southern and northern tiers of the State can experience any of these types of extreme winter weather.

Considering this diversity, this WSI effort provides a tool that tells the broader story with visualized data that includes impacts to the travelling public such as the cost of crashes and travel delay, and the tangible cost to MoDOT to respond to the winter weather events. These impacts are displayed in a dashboard that can be filtered by locations, dates, and types of events. These impacts are also offered in a manner that normalizes them to assist in the review and analysis of each storm for use by MoDOT to manage their winter maintenance and develop lessons learned and best practices.

The research team explored and evaluated many data elements which are detailed in the Measures and Factors Chapter. The data elements selected to support the MoDOT WSI are those that provide the best picture of the impacts of winter weather events to the Missouri highway system. The geographic unit areas for the data processing were selected as the MoDOT maintenance area boundaries, which allow integration of data from all contributing sources including data from MoDOT and external sources.

In summary, the MoDOT WSI development is not solely focused on a traditional WSI, rather a holistic system for assessing the impacts of winter weather events in a broader sense that captures costs and other impacts taking into account the timing, location and other underlying effects.

Chapter 2 Literature Review

The United States Department of Transportation (USDOT) Federal Highway Administration (FHWA) estimates that during the 10-year average (2007-2016) there have been nearly 1,235,000 weather-related crashes per year, which accounts for 21% of vehicle crashes per year (5,891,000), resulting in 16% (5376) of crash fatalities and 19% (418,005) of crash injuries. While weather can have a significant impact on safety, mobility is also impacted, and its effectiveness is reduced as presented in Table 1 from FHWA [1].

Table 1. Weather-impacted freeway traffic flow reductions

Weather Conditions	Freeway Traffic Flow Reductions			
	Average Speed	Free-Flow Speed	Volume	Capacity
Light Rain/Snow	3% - 13%	2% - 13%	5% - 10%	4% - 11%
Heavy Rain	3% - 16%	6% - 17%	14%	10% - 30%
Heavy Snow	5% - 40%	5% - 64%	30% - 44%	12% - 27%
Low Visibility	10% - 12%			12%

In North America, the average air temperature has been increasing from 1955 to 2005 with greatest increases occurring in the winter season. Simulations for future weather changes have indicated intensifying patterns. [2] In Missouri, [3] they studied the parameters that correspond to dabbling-duck abundance during autumn-winter, 1995-2005. The data used was waterfowl survey data adopted from Missouri conservation areas and the weather parameters considered were adopted from the Historical Climatology Network. The parameters that were considered are: Temperature (daily average and consecutive days with an average <= 0 degrees Celsius), snow depth and consecutive days of snow cover >= 2.54cm. The duration of these occurrences had the greatest impact on the ability of ducks to feed and rest. The calculated sector-specific indices can be helpful in specific sectors when determining potential changes in autumn-winter distributions of waterfowl given climate change projections, but their applicability to other sectors is inadequate.

A lot of variables should be considered when examining the winter severity index in the context of climatological values for a site. An accumulated winter season severity index (AWSSI) was created in [4] to accumulate historical context of winter impacts and site-to-site comparisons. The authors developed a concise index which captures the impacts of the winter season at sites with intervening warm seasons by using a site-specific threshold-based score of severity. Daily temperature (maximum, minimum and average), precipitation and snow (depth and fall) were collected from an Applied Climate Information System (ACIS) to compute the AWSSI. Limitations to this method includes the missing winter weather parameters such as freezing rain, wind and blowing snow.

The variability of weather conditions calls for a WSI to assess seasonal severity. Out of the 50 states in the United States, 19 states have some type of referenced WSI as presented (colored) in Figure 5. The figure is a summary of states with documented WSI. Each color reflects differences in approach (considered variables). The description of variables used, and limitations of each approach is presented in Table 2, along with information about the framework developer, author, considered variables, and limitations. Similarly colored groups reflect states with similar approaches or considered variables.

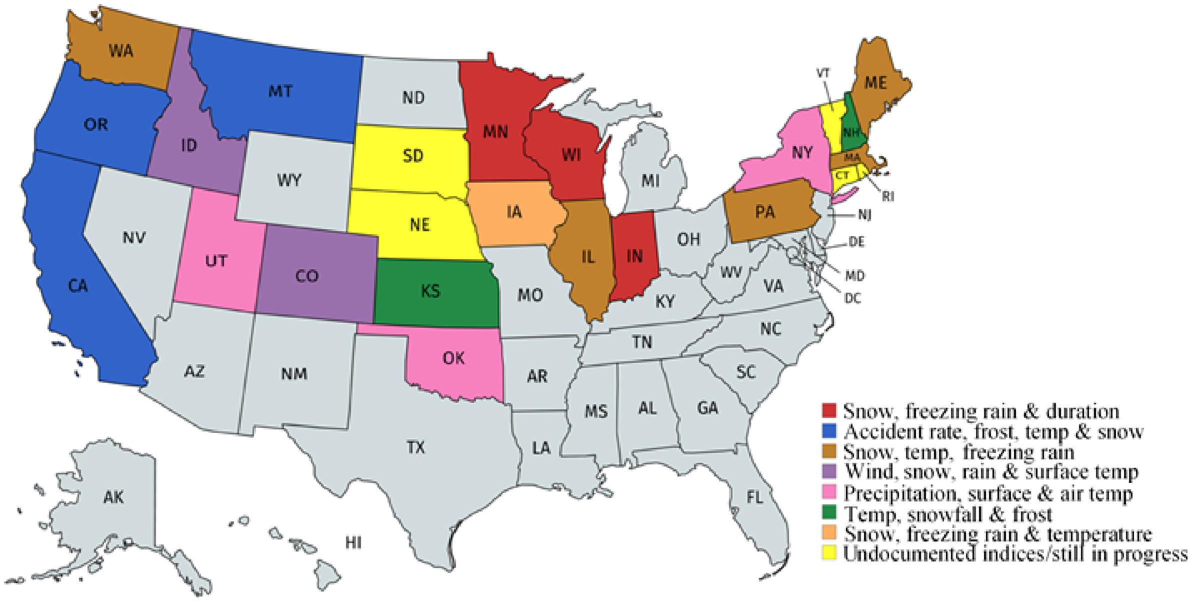


Figure 5. US states with and without a documented process for WSI. Colors represents states with similar indices

The states of Kansas and New Hampshire have a similar WSI as described in the RWIS Volume 1: Research Report [5]: the developers used data from the NWS and found the contributing variables to weather severity includes temperature index, daily snowfall accumulation, freezing days, and the range between the mean monthly maximum and minimum air temperatures. The variables considered in this index is unique to the states involved and may not be transferable to other states with different weather patterns. In the second group, for the states of Wisconsin, Minnesota and Indiana, the developers accounted for weather variability across county and districts within the state and used variables such as number of snow and freezing rain events, snow amount, storm durations, and incidents (road maintenance) [6,7,8]. The WSI developed by these states is unique, in that it considers weather-related cost factors, which allows for consideration of localized impact of winter events. The WSI developed by Illinois, Pennsylvania, Maine, Washington, and Massachusetts focused on snowfall and temperature only [6,8], so they exhibit much less variables than the afore-mentioned groups. Washington and Massachusetts have an even simpler WSI, calculated by using temperature observations in Washington, while Massachusetts monitors salt usage throughout the state. The simplicity in this group's framework speeds up the computational process, which comes at a cost of eliminating impacted cost and mobility.

Another unique approach was implemented by the states of New York, Oklahoma, and Utah, considering both surface and air temperature and also making a distinction between precipitation and non-precipitation variables. Iowa is worth mentioning in a group by itself since it is considered in literature to have a well-documented WSI. Their index captures conditions before, during, and after a storm event. However, it lacks the inclusion of impacted cost. California, Montana, and Oregon are grouped together based on their similarity in calculating an index at a state and county level. This group is also unique in being the only one that calculates its index using crash rates to incorporate a direct transportation safety variable. The last documented WSI group is Colorado and Idaho: in addition to using variables such as rain, snow, and surface temperature, this group also considers grip-based mobility parameters such as layer thickness. While all the grouped frameworks covered most of the critical factors impacting WSI in their calculation, there seems to be a gap in the fact that none of these states consider all factors at the same time. There is also no consideration or process for including intangible weather impacts such as delay and safety into the WSI. The current study develops a methodology that overcomes these limitations while developing a WSI for the state of Missouri, which by our knowledge does not have a documented WSI.

Table 2. Literature review of developed indices

State	Developer	Author	Variables	Limitations
Kansas, New Hampshire	Strategic Highway Research	[5] Boselly et al. (1993)	Temperature index, daily snowfall, daily	Developed for both states so ignores unique

	Program (SHRP)		freezing, and temperature range	characteristics, excludes effect on cost and mobility
Wisconsin	Wisconsin DOT	[6] Cohen (1981); [7] McCullouch et al. (2004); [8] Strong et al. (2005)	Snow events, freezing rain, maintenance events (incidents)	Excludes air temperature, effect on mobility
Minnesota	Minnesota DOT	[8] Strong et al. (2005)	Snow events & freezing rain	Excludes air temperature, effect on mobility
Indiana	Indiana DOT	[8] Strong et al. (2005)	Snow events, freezing rain, duration & average temperature	Computational challenge with the number of variables
Illinois, Pennsylvania, Maine	Illinois State Water Survey, Pennsylvania DOT, Maine DOT	[6] Cohen (1981); [8] Strong et al. (2005)	Snowfall & temperature	Excludes effect on cost and mobility
Washington	Washington State DOT	[9] Boon and Cluett (2002)	Temperature	Excludes many winter variables, effect on cost and mobility
Massachusetts	Massachusetts DOT	[9] Boon and Cluett (2002)	Salt usage	Excludes many winter variables, effect on cost and mobility
New York	New York State DOT	[10] Chien et al. (2014)	Snow, rain & temperature	Excludes effect on cost and mobility
Oklahoma	Oklahoma DOT	[11] Balasundaram et al. (2012)	Snow & rain	Excludes temperature, effect on cost and mobility
Utah	Utah DOT	De Pondeca et al. (2011); [12] Farr and Sturges (2012)	Snow, rain & state topography	Excludes temperature, effect on cost and mobility
Iowa	Iowa DOT	[13] Walsh (2016)	Storm-based events	Excludes effect on cost and mobility
California	California DOT	[8] Strong et al. (2005)	Snow, frost & temperature	Excludes effect on mobility
Montana	Montana DOT	[8] Strong et al. (2005)	Snow, rain, frost, temperature & wind	Excludes effect on mobility
Oregon	Oregon DOT	[8] Strong et al. (2005)	Snow, frost, temperature & wind	Excludes effect on mobility

Colorado	Colorado DOT	[13] Walsh (2016)	Wind, snow & rain	Excludes effect on cost
Idaho	Idaho DOT	[13] Walsh (2016)	Wind, snow & rain	Excludes effect on cost

Clear Roads Project 18-03 Evaluation of SSI and WSI Variables

The Clear Roads Project 18-03 is a key resource for this project. The following provides a brief summary of the Clear Roads project as it relates to MoDOT.

- Clear Roads reviewed 10 of the top WSI systems in USA and Canada (Wood uses the Mathews Canadian model for Ministry of Transportation, Ontario, and Alberta Transportation).
- Current WSI systems work with weather and recommend traffic for future work.
- Top weather variables used:
    - Air Temperature.
    - Wind Speed (for blowing snow).
    - Pavement temperature.
    - Pavement condition / Precipitation type.
    - Snow accumulation (hard to get accurately).
- RWIS and national data are the strongest inputs.
- Data QA/QC is critical and ranges from daily, hourly, real time.
- Use agency owned data first before relying on others that you do not have control over the quality.
- Suggested to start with a simple WSI and building in complexity as necessary for individual organizations, always work in progress. Start with an existing WSI, modify as needed to meet local conditions, develop into unique index as needed.
- Transferable WSI should start with Matthews, (built to be transferrable), others with universal indices AWSSI, Boselly and Walker. Could input data and compare models.
- Calibrate WSI based on severity scale thresholds of winter operations standards.
- Freezing rain, blowing snow and widespread frost hardest to factor.

- Most organizations outputs are in spreadsheet and / or automated dashboard.

Chapter 3 Data, Measures and Factors

A large number of data sets were reviewed for consideration in the MoDOT WSI. Table 3 shows all of the data, measures and factors considered for the WSI and how they apply to the WSI. Note that a number of data elements were not used, if they either did not produce valuable information related to the needs of the WSI or were not available at the time of this study. In particular, the RWIS data would be of value for future enhancements of the WSI. A complete matrix showing the full analysis of the data elements is found in Appendix B.

The following provides a guide to the matrix.

Data Source. While much of the data is provided by MoDOT; there are other sources as well. Source details are found below in References.

Data Field(s). These are generally specific information fields; however, some of the data element fields are combined for brevity.

Description and Method of Measurement. Where applicable, the method used to measure the element is provided or a more detailed data source that would describe the measurement details.

Applicability to MoDOT WSI. This column provides a brief description of the manner that the data element is used in the WSI tool. For example, the data element may be applied directly to a WSI calculation, may be combined with other data elements, and applied to a WSI calculation, may be used to verify or adjust other data, may be used to process or convert other data or may not apply to the WSI.

Table 3. Matrix of data, measures and factors

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
MoDOT Roadway Data and Information	Major/Minor Routes [14]	MoDOT roadway classification by Major and Minor types	Used as a reference for route types. Major routes are approximately the same as MoDOT "continuous operation routes"
	Roadway Functional Classification [15]	MoDOT roadway functional classification following FHWA functional classification	Not used
	Average Annual Daily Traffic (AADT) - Daily/Hourly [16]	AADT route data collected by MoDOT Planning including hourly traffic breakdown	Hourly AADT values used to calculate delay impacts
	Roadway Geodata*	Used to convert MoDOT County/Route/Log Mile to Latitude/Longitude	Used to tie together MoDOT data that is based on MoDOT log mile system with data that is latitude/longitude based
	Vehicle Miles Traveled (VMT)	Calculated from AADT data and roadway segment lengths	Use in calculation of delay impacts
MoDOT Maintenance Area Information	Maintenance Area Boundaries*	Geographic boundaries for MoDOT Maintenance Areas	Geographic unit areas for WSI modelling
	Maintenance Area Organization (Org) Codes*	MoDOT Org codes for maintenance areas, typically representative of a maintenance building	Used to connect financial data with Maintenance Areas
MoDOT Traveler Information Map - From Transportation Management System (TMS)	Incidents - Type/Location/Date/Time/ Duration*	Roadway incidents reported to MoDOT that are displayed on the Traveler Information (TI) map. These can be anything that impacts traffic, traffic crashes, flooded roads, road damage, debris on roadway, etc.	Can be used to verify event date/times
	Road Conditions - Condition/Location/Date/ Time*	Road conditions reported during winter events by MoDOT field staff for display on the TI map.	Can be used to verify event date/times

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
Regional Integrated Transportation Information System (RITIS) Data [17]	Real time speeds	Speeds recorded by RITIS system based on probe data capturing speed changes.	Speed decreases will be filtered to correspond with winter weather events. Used to calculate delay impacts.
	Real time speed event date/time/location	Date/time/location of speed changes.	Used to tie impacts to weather events
MoDOT Crash Data (TMS)	Crash type*	Crash type derived from Law Enforcement (LE) statewide crash reporting system, Property Damage Only, etc.	Used to calculate crash costs
	Crash Location/Date/Time*	Crash date/time derived from LE statewide crash reporting system.	Used to tie crashes to winter weather events, filtered to crashes occurring during winter weather event determined from other data
	Crash Reports - Road Conditions*	Road conditions recorded by Law Enforcement on crash report forms.	Road conditions from crash reports are categorized differently than the MoDOT TI Map road conditions. Can be used for data verification, but not used directly in the WSI.
MoDOT Winter Events Database (Maintenance Division)	Event date/time*	Reported/recorded by MoDOT District and Central Office staff.	Used in conjunction with other data to determine timing of winter weather events
	Event Building (Org)*	Reported/recorded by MoDOT District and Central Office staff. These will correspond with the financial org codes.	Used in conjunction with other data to determine location of winter weather events by org code
	Event Type and Amount*	Reported/recorded by MoDOT District and Central Office staff.	Used to determine event types.

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
	Major and Minor Times*	Reported/recorded by MoDOT District and Central Office staff. Major time is the days to meet MoDOT snow/ice objectives. Minor time is the days until the event response is complete.	Used in conjunction with other data to determine timing of winter weather events. This information can be used to verify the start and end time of events since pre-treatment would start early and cleanup will typically last past the end of the actual weather event.
	Comment field*	Reported/recorded by MoDOT District and Central Office staff.	Not directly used
RWIS Data	Road Conditions - RWIS	Road surface condition detected by RWIS system.	Not used due to lack of availability
	Air Temperature	Air temperature at RWIS location.	Not used due to lack of availability
	Relative Humidity	Relative Humidity at RWIS.	Not used due to lack of availability
	Dew Point	Dew point at RWIS site.	Not used due to lack of availability
	Wind Speed and Direction	Wind speed at RWIS site.	Not used due to lack of availability
	Wind Direction	Wind Direction at RWIS site.	Not used due to lack of availability
	Wind Gusts	Wind gusts and related information recorded at RWIS site.	Not used due to lack of availability
	Barometric Pressure	Barometric pressure at RWIS site.	Not used due to lack of availability
	Visibility	Visibility at RWIS site.	Not used due to lack of availability
	Precipitation Amount	Measured rainfall at RWIS site, may not be collected when freezing.	Not used due to lack of availability
	Precipitation Situation	Yes/No report from rain gauge.	Not used due to lack of availability

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
RWIS Data (Cont.)	Snow Depth	Estimated from precipitation amounts.	Not used due to lack of availability
	Pavement Freeze Point	Calculated from RWIS puck readings (temperature and salinity).	Not used due to lack of availability
	Pavement Water Level/Ice Level	Calculated from various sensor inputs.	Not used due to lack of availability
	Pavement Temperature	Pavement temperature from RWIS pucks.	Not used due to lack of availability
	Subsurface Temperature	Subsurface temperature from RWIS sensor.	Not used due to lack of availability
	Bridge temperature	Bridge deck temperature from RWIS bridge pucks where available.	Not used due to lack of availability
	Grip	Gives an indication of surface friction between 0 - 1, calculated from RWIS sensors.	Not used due to lack of availability
	Salinity	Gives an indication of road/bridge chemical level detected by RWIS pucks.	Not used due to lack of availability
NWS Data [18]	Missouri Automated Surface Observing System (ASOS) Metadata	Locations of Missouri sites and other information.	Geographic reference to locations of ASOS data to associate with nearest areas
	Air Temperature	Air temperature at ASOS site.	Used to determine event types
	Relative Humidity	Relative Humidity at ASOS site.	Not used
	Dewpoint	Dewpoint at ASOS site.	Not used
	Wind Speed	Wind speed at ASOS site.	Used to determine event types
	Wind Direction	Wind Direction at ASOS site.	Not used
	Wind Gusts, Timing, Directional Gusts	Wind gusts and related information recorded at ASOS site.	Not used
	Barometric Pressure	Barometric Pressure at ASOS site.	Not used

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
	Visibility	Visibility at ASOS site.	Used to determine event types
	Precipitation Amount	Precipitation Amounts recorded at ASOS site.	Not used
	Cloud Amount	Amount in octans recorded at ASOS site.	Not used
	Cloud Base Height	Cloud Height from ceilometer at ASOS site.	Not used
	Weather Type	Type of precipitation (showers, snow, sleet, etc.) observed at ASOS site.	Used to determine event types
	Ice Accumulation	Ice Accumulation at ASOS site.	Not directly used
MoDOT Financial Data	R913 - Snow and Ice Response*	The time and expenses incurred related to snow and ice operations.	Used for calculation of MoDOT event tangible costs
	R914 - Snow & Ice Preparedness, Prevention and Clean-up*	The time and expenses incurred related to snow and ice prevention and clean-up and includes purchasing of tools and equipment, purchasing/receiving salt or other winter materials, debris/tree removal associated with snow or ice storms.	Used for calculation of MoDOT event tangible costs
Road User Costs	Crash costs [19, 20]	Derived from AASHTO "User and Non-User Benefit Analysis for Highways" or MoDOT "Safety Handbook for Locals" (S-HAL).	Used to calculate crash costs

Data Source	Data Field(s)	Description and Method of Measurement	Applicability to MoDOT WSI
	Delay costs [19]	Derived from AASHTO "User and Non-User Benefit Analysis for Highways".	Used to calculate delay costs
Socioeconomic Data	Population Density	Population density based on census tracts or other geographic boundaries.	Not used
	Urban/rural boundaries	Established urban/rural boundaries used by planning agencies.	Not used

*Data not available publicly and provided directly by MoDOT

Chapter 4 Weather Based WSI Methodology

Weather plays a major role in traffic crashes and user impacts. The weather role is present all year round, but it is prominent in the winter season. The State of Missouri geographically lies in a region that enables it to witness multiple weather changes as it lies in a competition area between two distinct air masses: the cold and dry Arctic air from the north and the hot and moist air from the south.

During the winter season, the different regions of Missouri experience different weather conditions and precipitation types that can affect highway traffic. To understand the effect of such adverse weather on traffic, data was collected from different ASOS within the State of Missouri. Figure 6 shows the location of the ASOS. The data is in hourly and sub-hourly temporal resolution based on adverse weather. The data is reported in Meteorological Terminal Air Report (METAR) format and was obtained for the period January 2015 to the end of December 2020.

Precipitation accumulations were obtained from the ASOS data such as snowfall (in), sleet (in), and freezing rain (in). Furthermore, air temperature (F), visibility (mi), and wind gust (mph) were obtained to analyze and develop the weather based WSI.

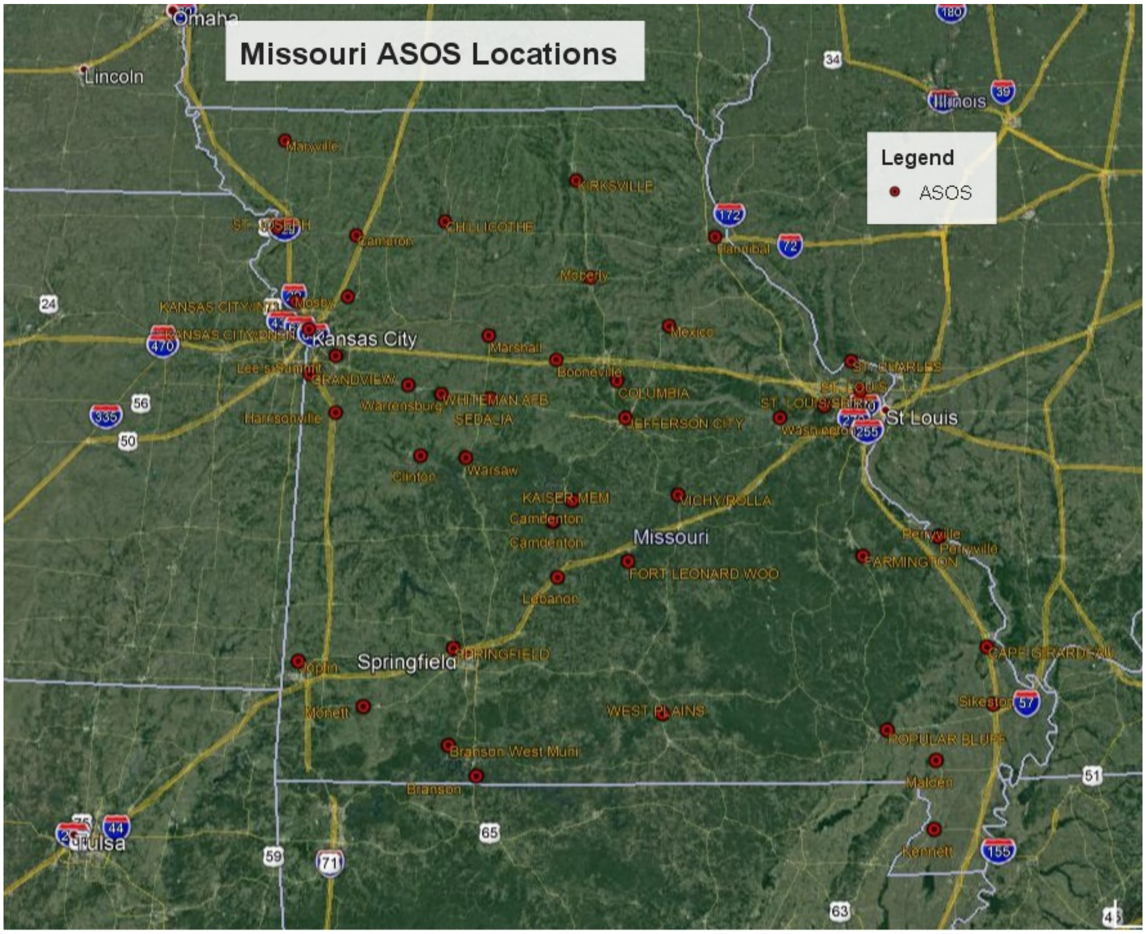


Figure 6. Missouri ASOS locations

Freezing Rain Events

The ASOS freezing rain event was analyzed across the different districts and their associated crash and delay costs. Freezing rain occurs with the presence of a deep warm layer aloft and extending to near-surface, with near-surface temperature at or below freezing. These events usually occur along a warm front. Figure 7 shows that the majority of the freezing rain events across MO are likely to cost between $900 to $21,000. Nevertheless, there was a single freezing rain event that occurred in February 2019 in the NE district has cost MoDOT near $109,000.

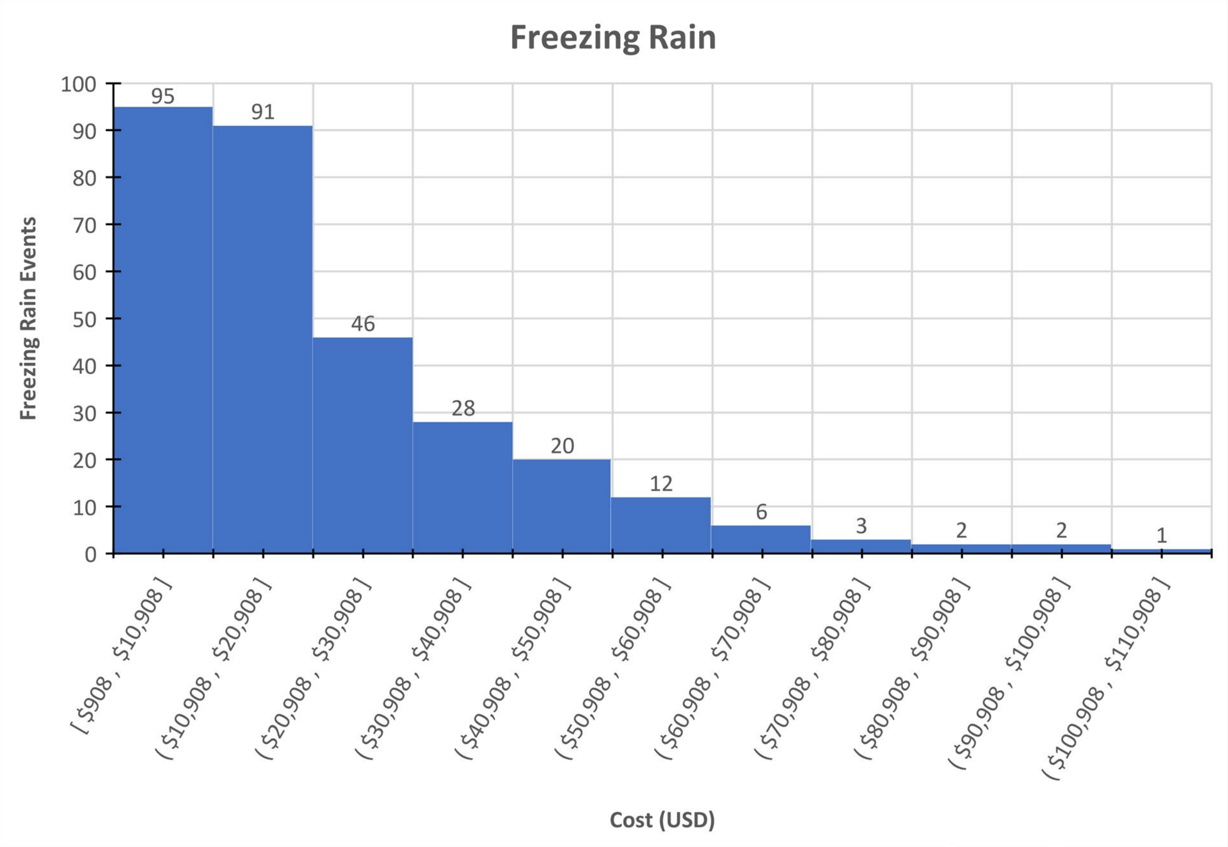


Figure 7. Freezing rain events vs associated cost (traffic and crashes)

Figure 8 shows that freezing rain events are affecting all the districts, but these events exhibit different cost patterns across MO. The Southwest (SW) district has incurred the highest freezing rain cost (~ $1,900,000), while the Southeast (SE) district has incurred less than $400,000 over the past five years. It is worth mentioning that 50% of the five-years total cost has been incurred in the SW and Northeast (NE) districts. The figure also shows that Kansas City (KC), St. Louis (SL) approximately shares a similar cost (~ $980,000 to $1,200,000) over the past five years. The Central District (CD) and the SE share similar costs ($380,000 to $460,000) of the same period.

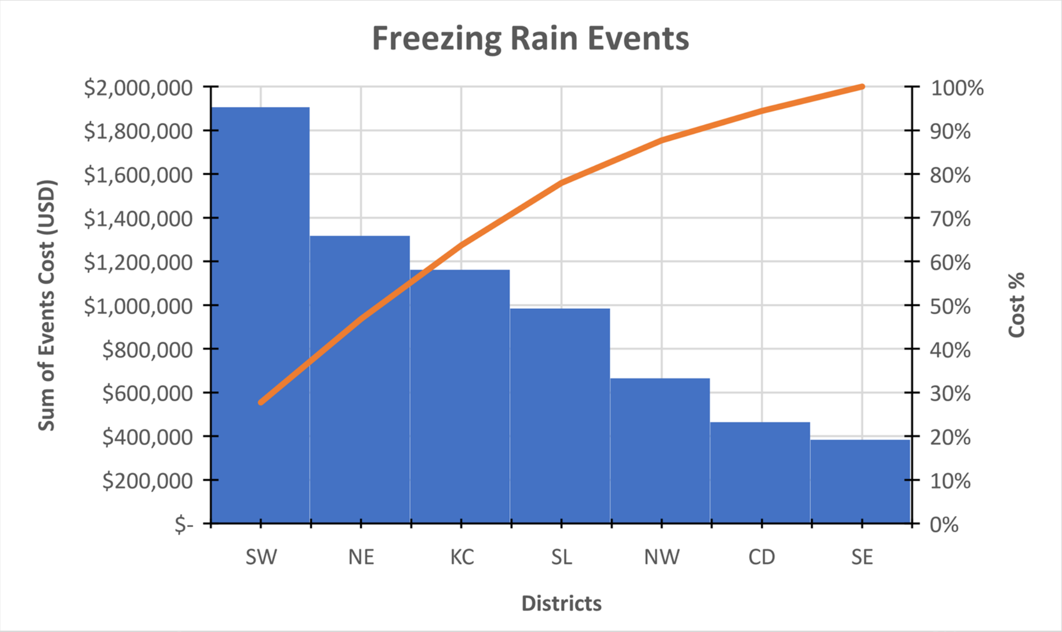


Figure 8. Freezing rain events associated cost (traffic and crashes) per district

Sleet Events

The ASOS data were filtered to show the cost of the sleet events. Sleet is a special type of precipitation that happens during a shallow warm (above freezing) layer aloft with a deep subfreezing layer below it. This type of precipitation is usually associated with warm fronts and can be considered a transitional type as the warm front tracks through an area. Figure 9 shows that majority of the sleet events can approximately cause $2,000 to $12,000. Meanwhile, there was a single event that occurred in February 2019 in the NW district that cost MoDOT up to $74,000.

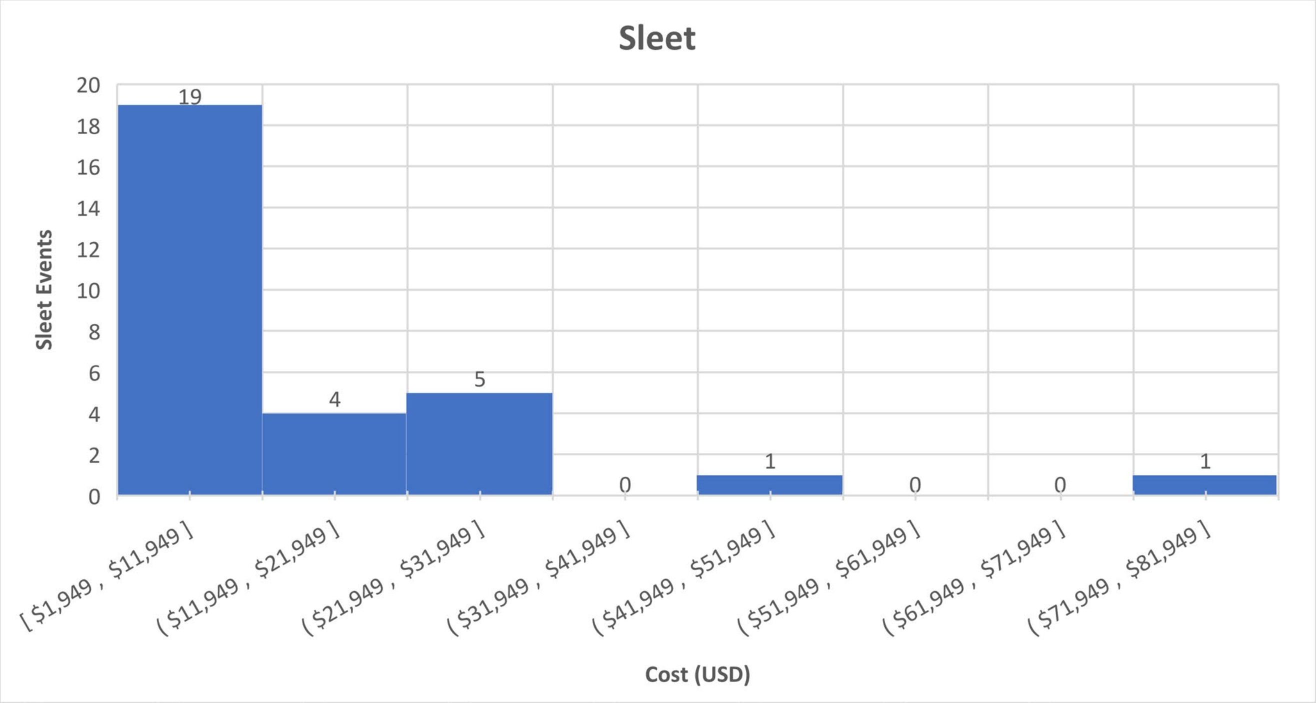


Figure 9. Sleet events vs associated cost (traffic and crashes)

The events cost per district is given in Figure 10. It is evident that the SW has incurred the highest cost during sleet events ($115,000). Meanwhile, the NE district has incurred the lowest cost ($3,800). The figure also shows that 50% of the total 5 years cost is shared between the SW and NW districts.

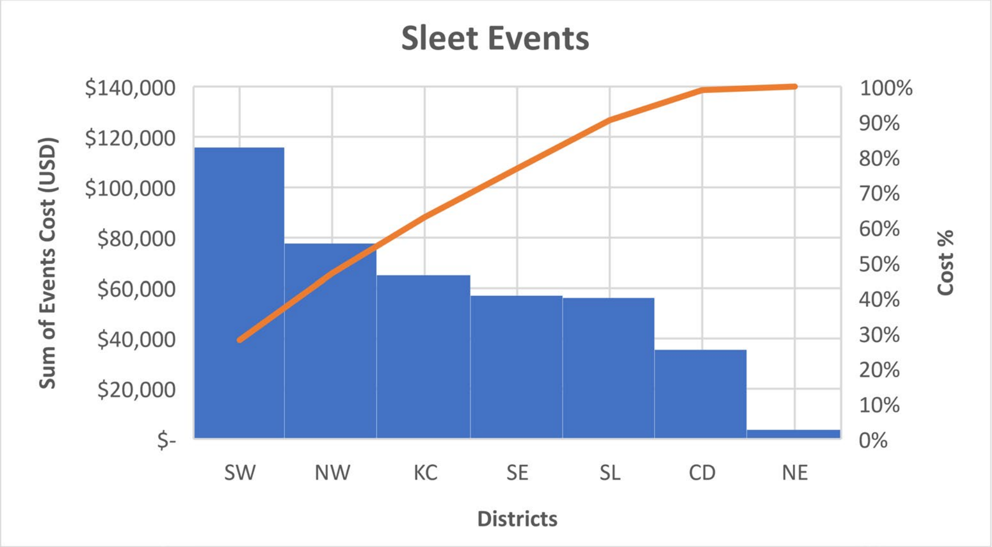


Figure 10. Sleet events associated cost (traffic and crashes) per district

Snow Events

Snow events are more common than freezing rain or sleet and usually can last longer. Figure 11 shows that the majority of the snow events (>300 events) cost MoDOT up to $20,000. Four snow events cost MoDOT $75,000 to $80,000. Comparing this figure to Figure 7 reveals that although snow events are more common than freezing rain events, severe freezing rain events can be costlier.

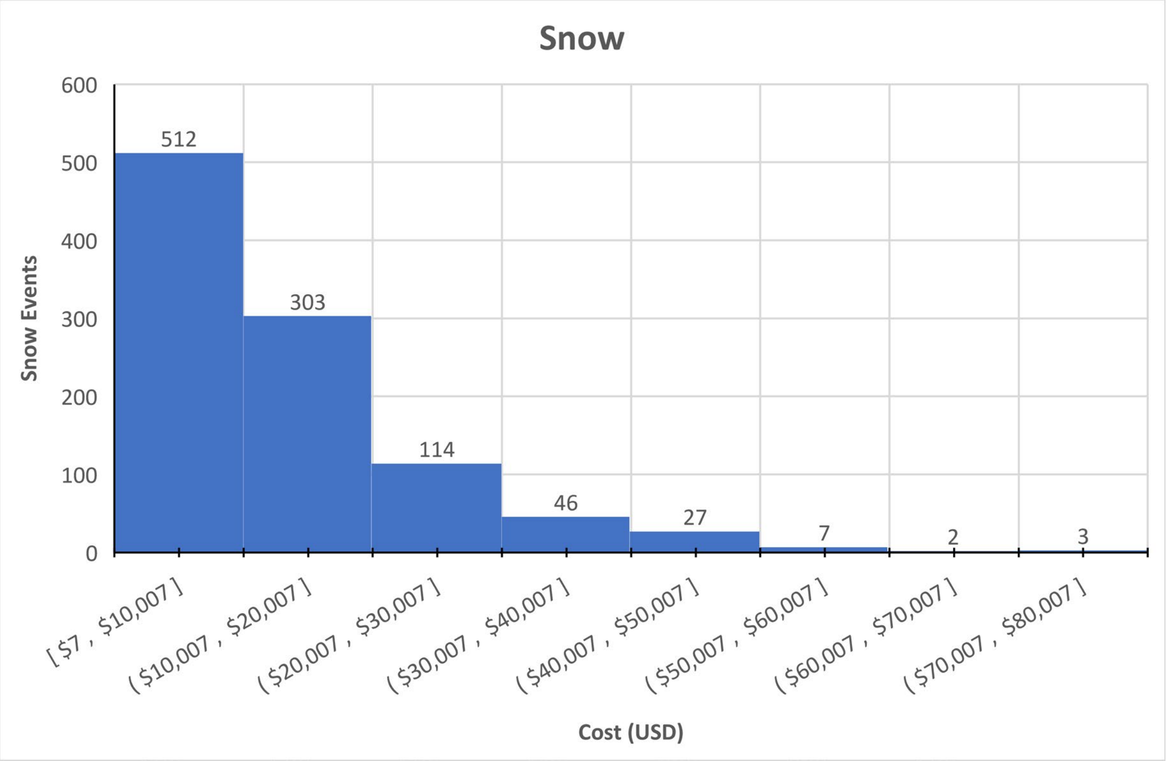


Figure 11. Snow vs associated cost (traffic and crashes)

Figure 12 shows that the SL, NW, and SW districts exhibit the highest traffic and crash costs ($2,800,000 to $2,300,000) each during snow events over the last five years. This also represents 50% of the total cost incurred during the last five years. The figure also shows that the SE district has incurred the least cost over the same period.

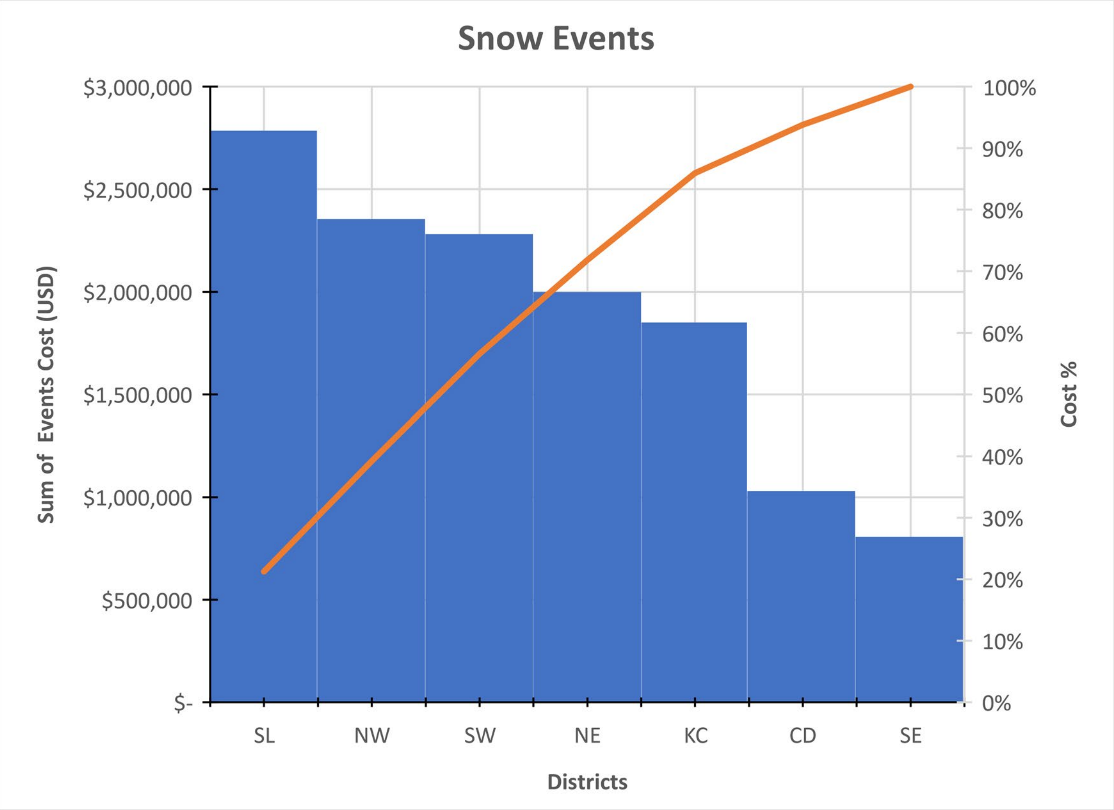


Figure 12. Snow events associated cost (traffic and crashes) per district

Multi-Precipitation Events

It is worth considering events with all three precipitation types recorded (snow, sleet, and freezing rain). Figure 13 shows that majority of such events have approximately cost MoDOT between $2,000 to $22,000, individually. It is worth noting that a single event that occurred in February 2019 in the KC district has cost MoDOT $80,773.

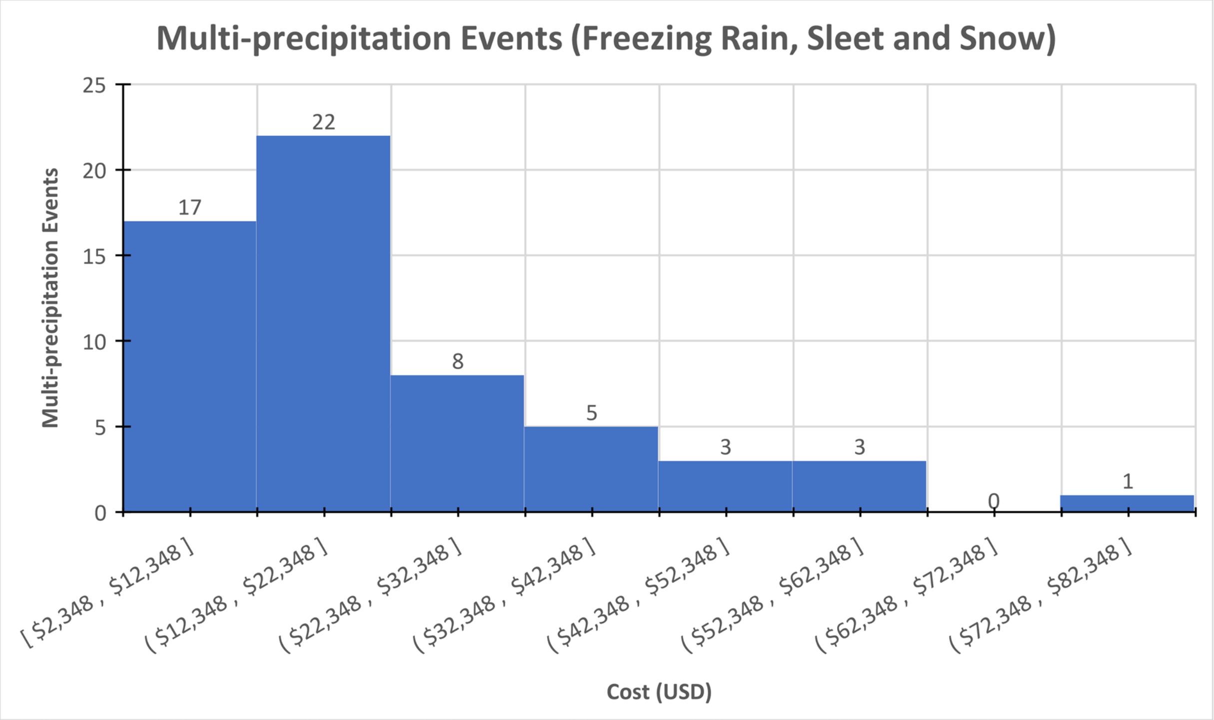


Figure 13. Multi-precipitation events vs associated cost (traffic and crashes)

Figure 14 shows that the NE district accounts for the highest cost during such events and the combination of the NE and KC districts accounts for 50% of the total cost over the last five years. The figure also shows that the SL district incurred the least cost under the multi-precipitation conditions over the same period.

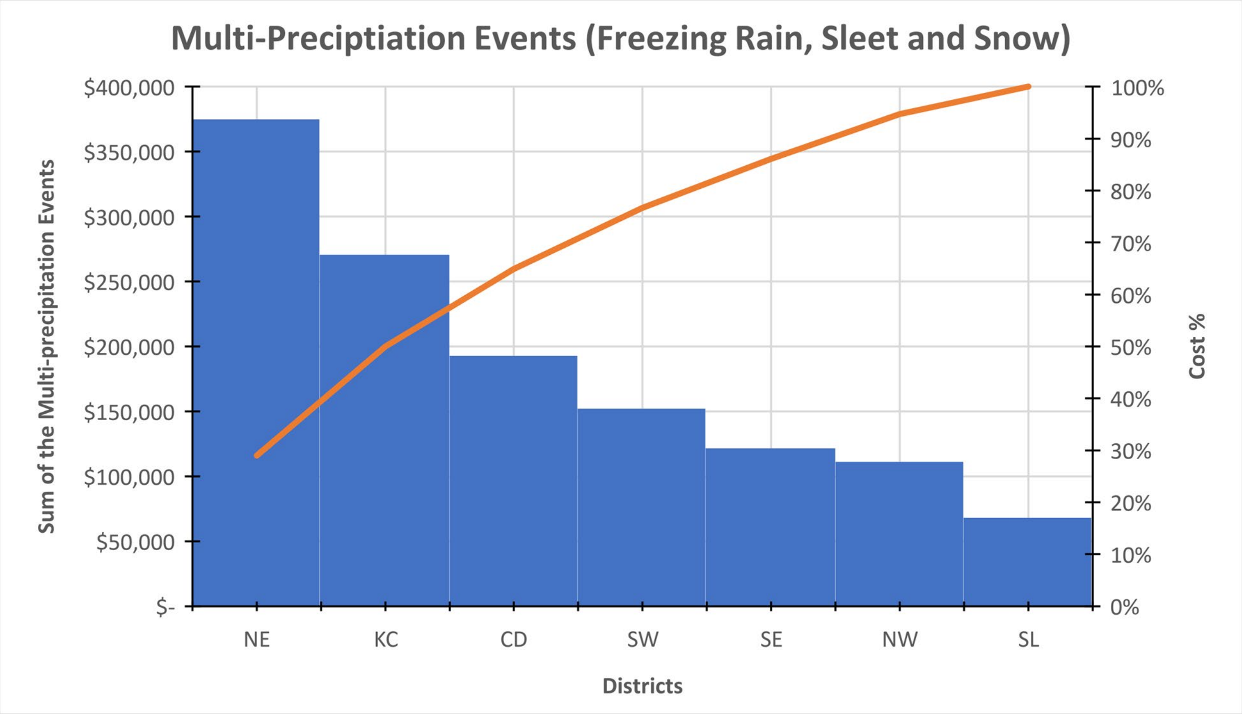


Figure 14. Multi-precipitation events associated cost (traffic and crashes) per district

Non-Precipitation Events

To understand the relationship between crashes and air temperature, wind gust, and visibility, the five years data were filtered for crashes with no precipitation. The sections below discuss each weather parameter.

Visibility

Low visibility accounts for vehicle crashes and crashes every year. Low visibility can be associated with precipitation or precipitation events accompanied by winds. Low visibility can also occur due to non-precipitation events, such as mist, fog, and freezing fog. The data were analyzed for non-precipitation events and visibility less or equal to 0.25 miles. The visibility threshold was based on [19].

The data shows three of such events as seen in Figure 15. Two of the events incurred less than $2,000 each. Nevertheless, a single event occurs in February 2018 has cost MoDOT $25,452.

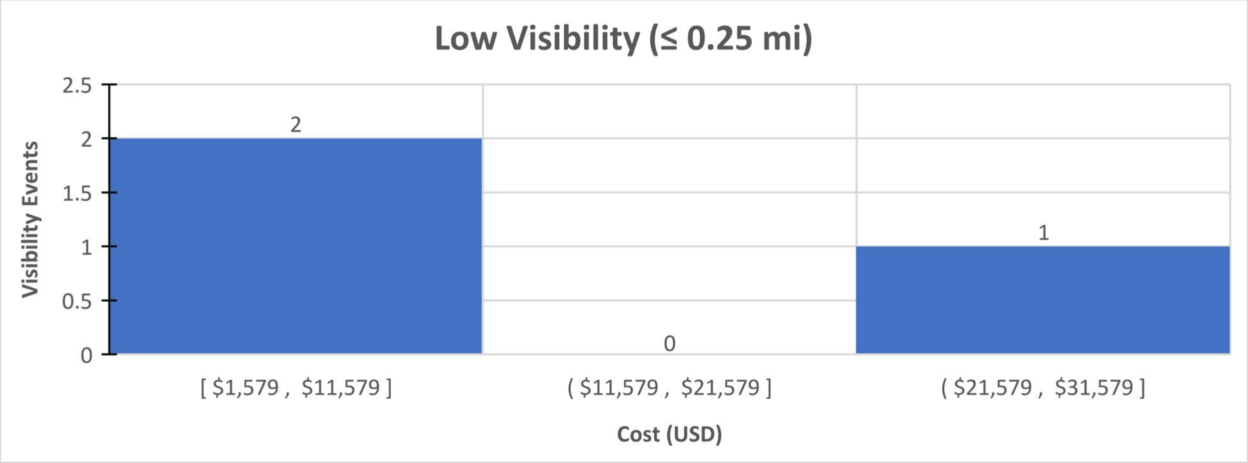


Figure 15. Low visibility (0.25 mi) events with no precipitation vs associated cost (traffic and crashes)

Figure 16 shows that the two fog events occurred in the NE district adding up to nearly 90% of the total cost of such events. The events occurred in January and February 2018. A single event occurred in the KC district.

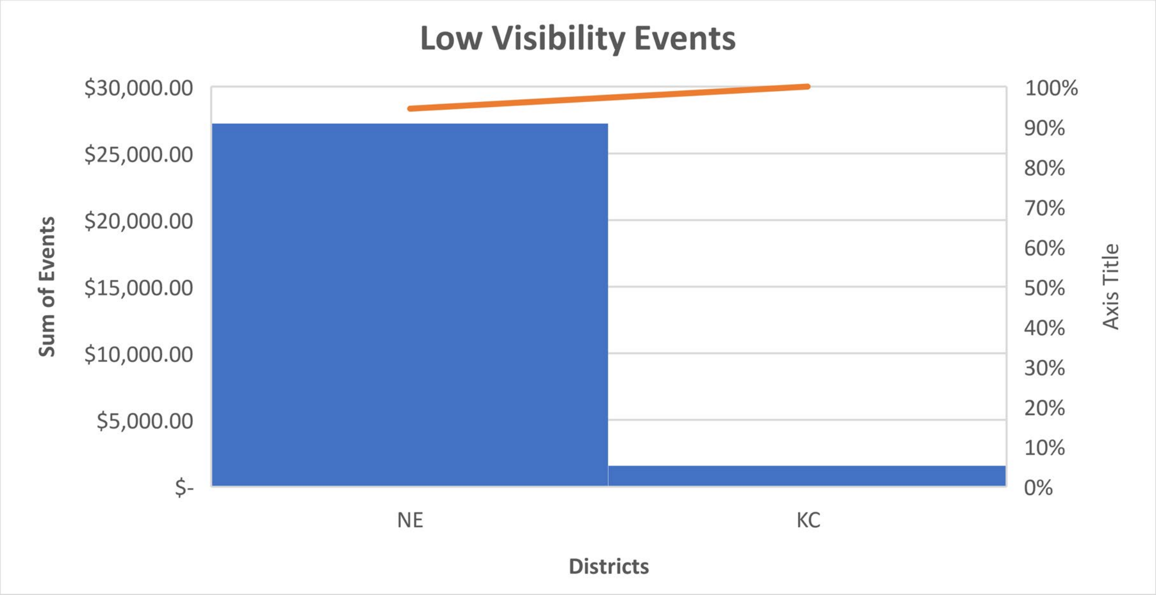


Figure 16. Low visibility events associated cost (traffic and crashes) per district

Wind and Near to Below Freezing Air Temperature

Windy conditions can have an impact on driving behavior and can lead to crashes especially at a certain location where the wind gust maximizes due to topography and terrain. To study the effect of windy events, the data were filtered for winds greater or equal to 30 mph based on [19]. The events occurred near freezing or below freezing air temperatures. Figure 17 shows that the majority of the events cost MoDOT up to $10,000 while a couple of events incurred $22,000 to $26,000 each.

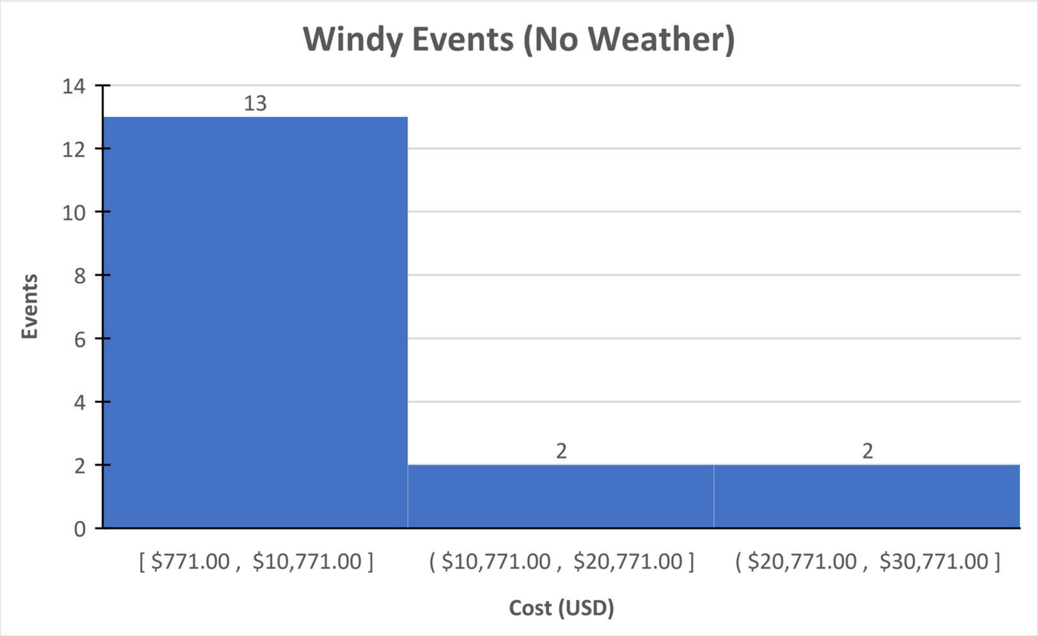


Figure 17. Windy conditions (≥ 30 mph) events with no precipitation vs associated cost (traffic and crashes)

Figure 18 shows that the NE district has incurred the most crash cost under windy conditions. The figure also shows that 80% of the total five years cost was incurred at the NE, SW, and NW districts.

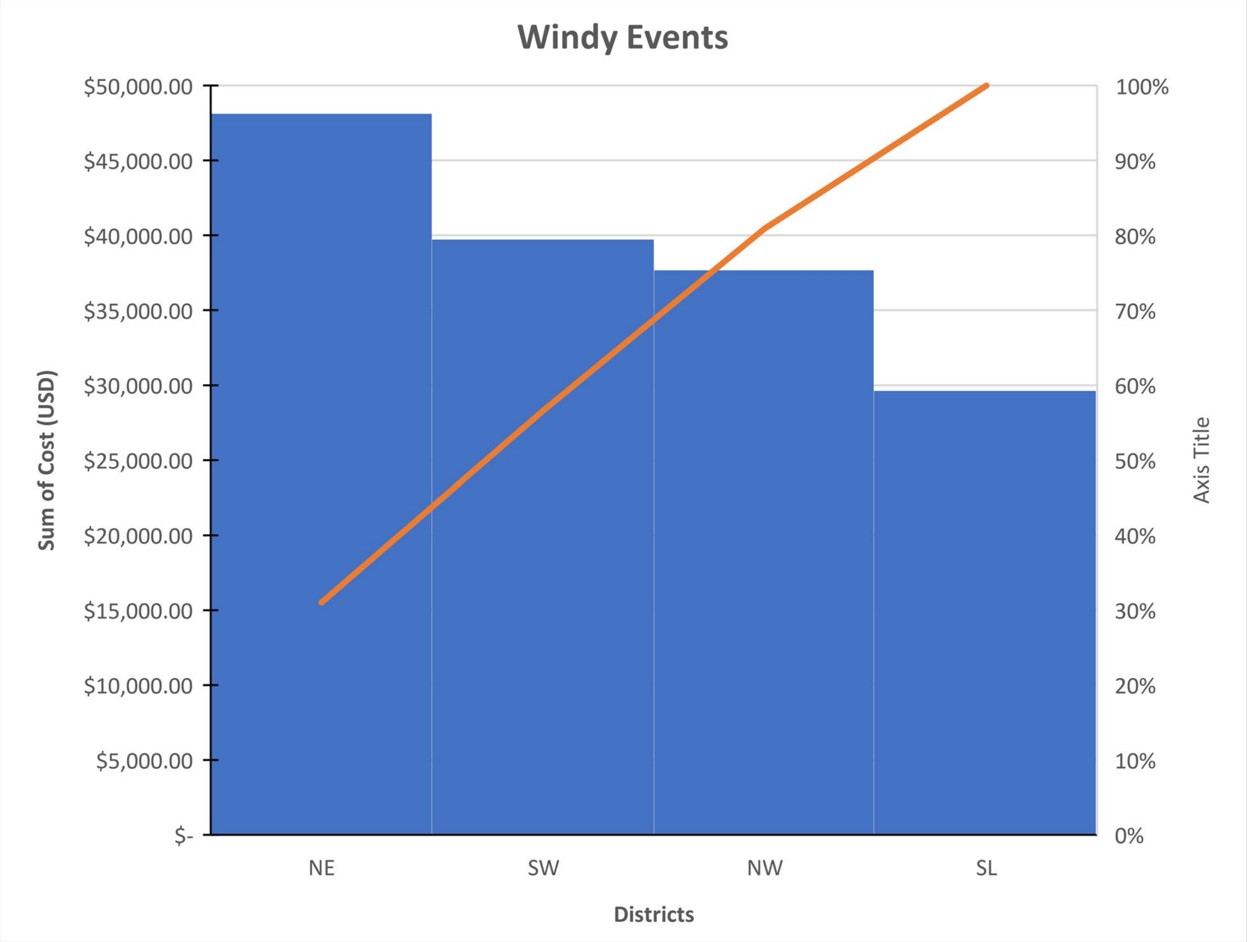


Figure 18. Windy events associated cost (traffic and crashes) per district

Weather-Based Winter Severity Index (WSI_wx)

The weather-based Winter Severity Index (WSI_wx) was computed while accounting for the freezing rain, sleet, snow, windy conditions, and low visibility events. To account for the low visibility induced by precipitation, the wind parameter was incorporated in the precipitation events. Meanwhile, the visibility-based WSI was calculated during non-precipitation events. It is worth noting that the wind gust was converted to a percentage before being incorporated in the WSI formulas. The Final WSI is calculated by summing all the WSIs in Table 4. It is also worth noting that the snowfall events contribute the most to the WSI. The second highest contributor is the freezing rain followed by sleet. The windy conditions can contribute to WSI calculated from a weather event and this contribution can be feeble or essential at times. The Visibility WSI is only calculated when no precipitation is present, and the visibility is less or equal to 0.25 miles.

Table 4. Weather-based WSI formulas and calculated WSI_wx

	Associated Windy Conditions	**Non-windy conditions**
Freezing Rain (FZRN)	$FZRN_{WSI} = \frac{FZRN(in)}{\sum (FZRN, IP, SN, Wind)}$	$ZRN_{WSI} = \frac{FZRN(in)}{\sum (FZRN, IP, SN)}$
Sleet (IP)	$IP_{WSI} = \frac{IP(in)}{\sum (FZRN, IP, SN, Wind)}$	$IP_{WSI} = \frac{IP(in)}{\sum (FZRN, IP, SN)}$
Snow (SN)	$SN_{WSI} = \frac{SN(in)}{\sum (FZRN, IP, SN, Wind)}$	$SN_{WSI} = \frac{SN(in)}{\sum (FZRN, IP, SN)}$
Windy (≥30 mph)	$Wind_{WSI} = \frac{Wind(mph)}{\sum (FZRN, IP, SN, Wind)}$	
Visibility (≤0.25 mi)		$Vis_{WSI} = 1$
Final WSI	$WSI_{Wx} = \sum (FZRN_{WSI}, IP_{WSI}, SN_{WSI}, Wind_{WSI}, Vis\_WSI)$	

Figure 19 shows a summary of cost by type of event for all types of events. Figure 20 shows the WSI_wx for the three most frequent type of winter weather events, snow, freezing rain and sleet calculated using the above formulas.

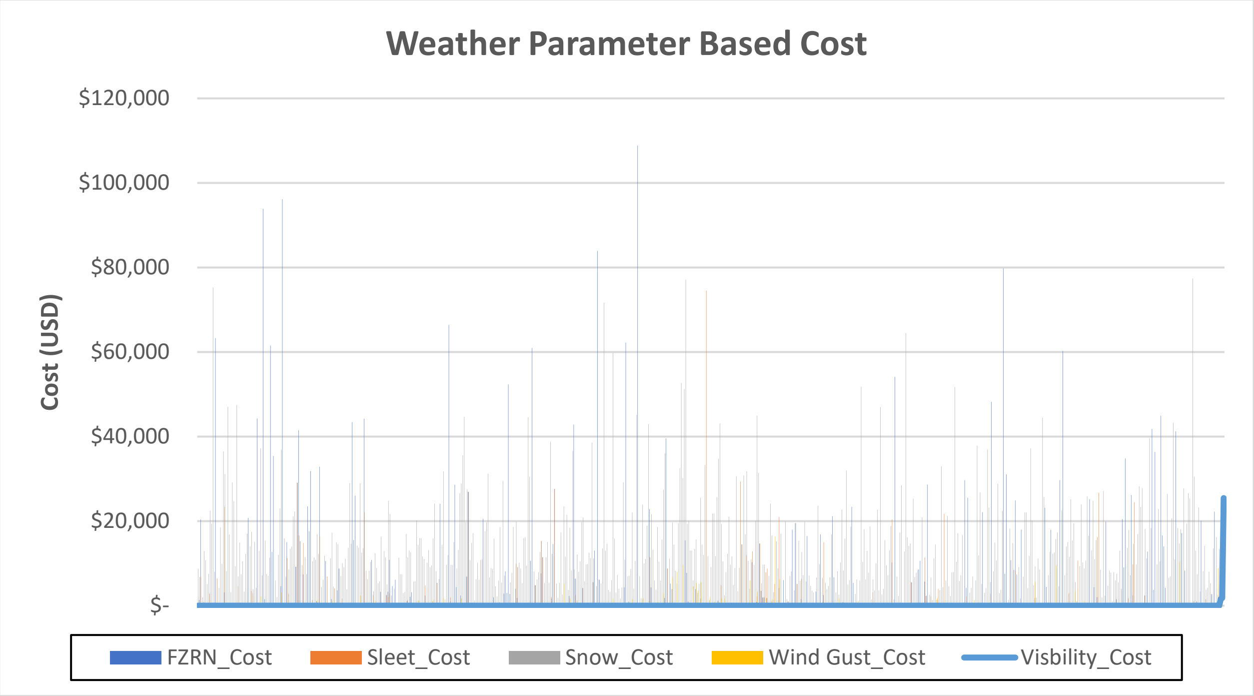


Figure 19. Summary of MoDOT costs by type of event

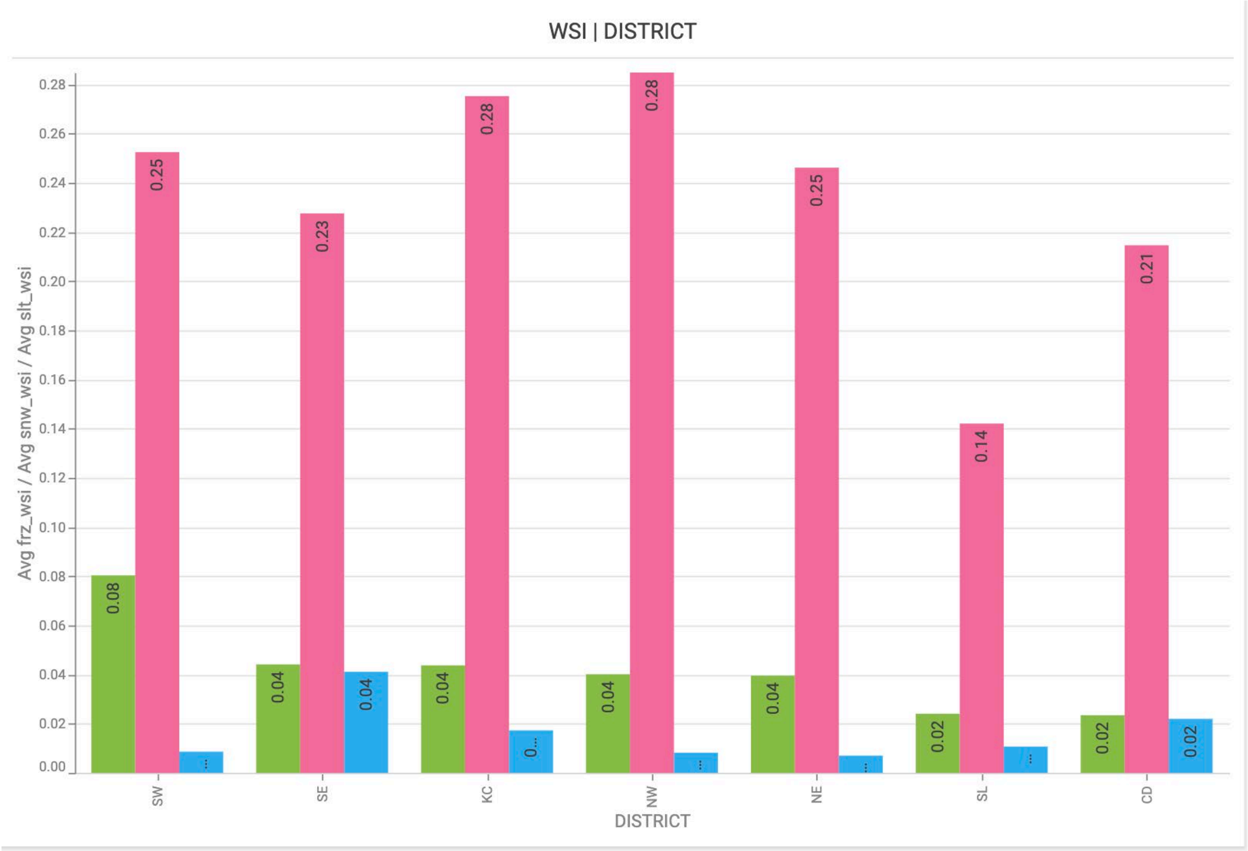


Figure 20. WSI_wx for snow, freezing rain and sleet by district

Chapter 5 Data Extraction and Conflation

Data was collected during the winter months in Missouri: October, November, December, January, February, March, and April for 2017, 2018 and 2019. Six main sources of data were used to develop the methodology for the unified winter severity index. They include *Winter events database* – which captures the start and end time for each event, the maintenance facility responsible for responding to the event, and other weather variables such as snow accumulation, freezing rain and sleet. *Crash database* – a collection of crash information extracted from police reports which captures the severity, location, time, and road condition under-which the crash occurred. *Traffic volumes* – road segment level hourly traffic counts. *Weather data* – additional weather variables such as temperature, wind gust and visibility collected from ASOS stations [22]. *Financial database* - records costs incurred during winter event response. *Probe database* - high-resolution, segment-level travel time and speed data were collated from probes. *Maintenance Facility Database* – geographic boundaries of approximately 136 maintenance facilities in the state of Missouri.

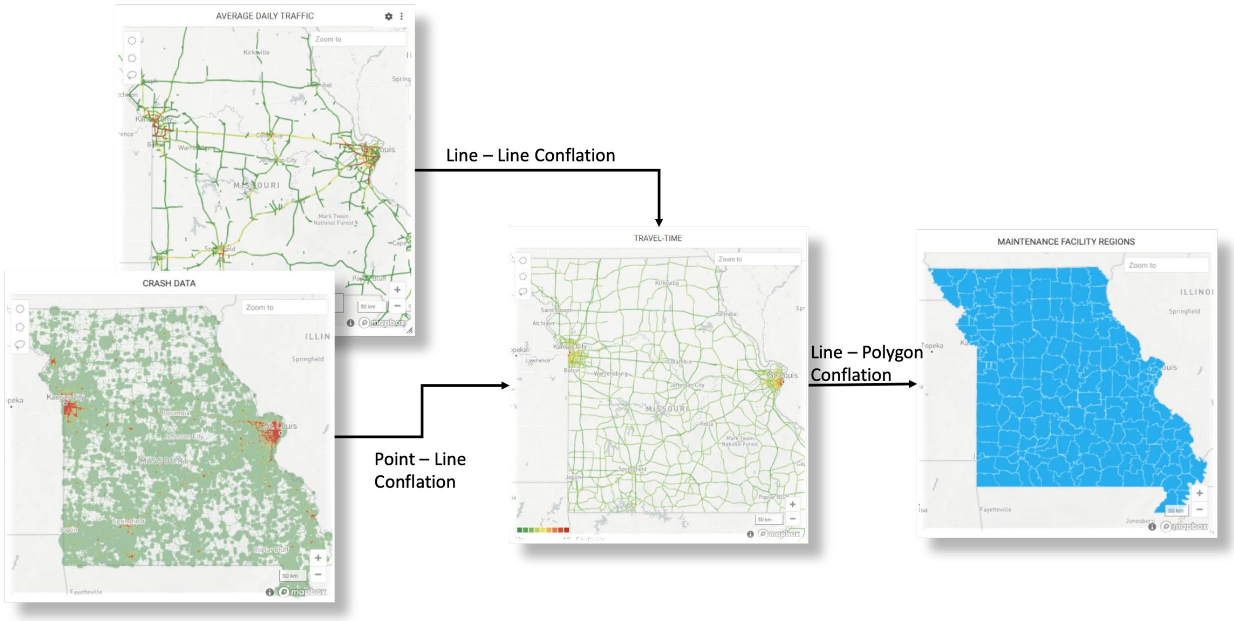
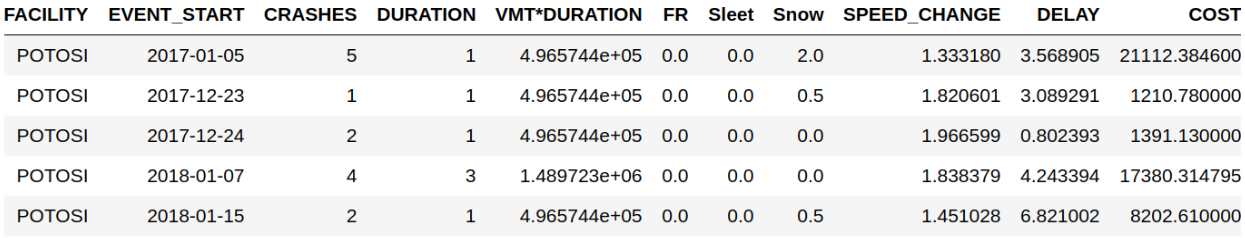


Figure 21. Conflation pipeline: Variety of data sources and the conflation types used

Data extraction is followed by a conflation pipeline that is used to integrate the different data layers into a standardized, unified data layer or table as illustrated in Figure 21. The conflation process begins by mapping all point layers to line data layers. For example, ASOS weather stations (point layers) are mapped to traffic volume and probe segments (line layers) by using a buffer radius around the points; all line layers which lie with the buffer are assigned to the weather station. This mapping is necessary to compute the impact of weather on traffic volume and speeds. The next step in the conflation process is to map all line-to-line data layers. This mapping is carried out by using proximity analysis and other variables such as the direction of line segments and road names. By mapping line-to-line layers (i.e., traffic volume to travel time data), we are able to compute the total delay during an event. The final step of data conflation is to map all points and line layers to polygon layers. The current study had only one polygon layer which is the geographic boundary of all maintenance facilities. A geo-spatial intersection of point and line layers with polygon layers was used to carry out this final step of the conflation process. Table 5 shows a snapshot of the table generated after the conflation process. As shown, the conflation process enables us to obtain additional columns such as the product of vehicle miles traveled and duration of winter event, delay, and the final cost for responding to the event. With all the different sources of data integrated, the impact of each weather event on factors such as mobility, safety, etc., can be calculated.

Table 5. Conflated data layers



FACILITY	EVENT_START	CRASHES	DURATION	VMT*DURATION	FR	Sleet	Snow	SPEED_CHANGE	DELAY	COST
POTOSI	2017-01-05	5	1	4.965744e+05	0.0	0.0	2.0	1.333180	3.568905	21112.384600
POTOSI	2017-12-23	1	1	4.965744e+05	0.0	0.0	0.5	1.820601	3.089291	1210.780000
POTOSI	2017-12-24	2	1	4.965744e+05	0.0	0.0	0.0	1.966599	0.802393	1391.130000
POTOSI	2018-01-07	4	3	1.489723e+06	0.0	0.0	0.0	1.838379	4.243394	17380.314795
POTOSI	2018-01-15	2	1	4.965744e+05	0.0	0.0	0.5	1.451028	6.821002	8202.610000

Baseline Winter Event and Cost Estimation

The impact of a winter event is estimated based on three cost variables: maintenance cost, crash cost and delay cost. The maintenance costs are tangible costs that were administered to clear a winter event. These costs were provided by the various maintenance facilities for each winter event. They included costs such as fringes, equipment costs and other expenditures as shown in Table 6 below. The distribution of maintenance costs by different types of weather events is shown in figure 22. The average cost per event per maintenance facility ranged between about $5,000 and

$80,000. The costs were highest (as shown in Figure 22) when the event consisted of both snow and freezing rain.

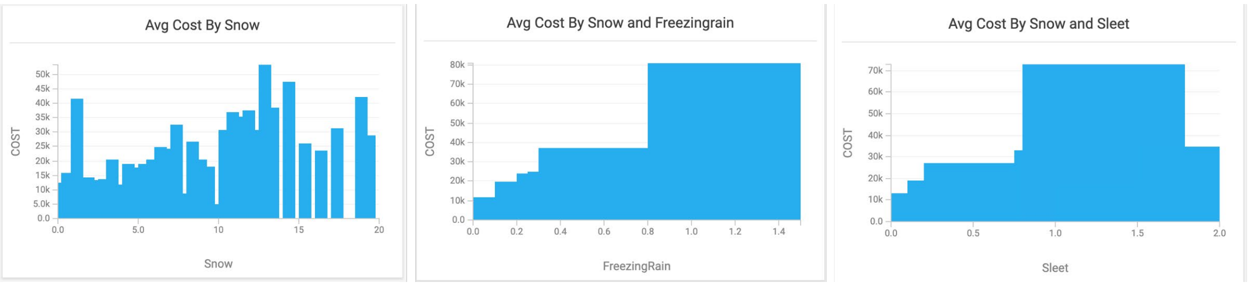


Figure 22. Average maintenance cost per incident, per maintenance facility for different amounts of snow, freezing rain and sleet

Crash Cost Estimation

The safety impact of an event is captured by estimating the change in the number of crashes during the event. The change in the number of crashes is calculated relative to a baseline event.

<u>*Baseline event*</u>: In the current study, the baseline event for crash costs is assumed to be a clear weather day (CWD) within one week from the occurrence of the event. If there were no clear weather days within one week, the closest CWD over the same duration of the event is used. Table 6 is a snapshot showing different winter events and the dates for their corresponding baselines.

Table 6. Summary of processed winter events data

	event_start	event_end	maintenance_bldg	event_duration	event_baseline_start	event_baseline_end	district
718	2017-01-05	2017-01-05	POTOSI	1	2016-12-29	2016-12-29	CD
719	2017-01-04	2017-01-05	VERSAILLES	2	2016-12-28	2016-12-29	CD
720	2017-01-05	2017-01-05	CALIFORNIA	1	2016-12-29	2016-12-29	CD
721	2017-01-05	2017-01-05	CUBA	1	2016-12-29	2016-12-29	CD
722	2017-01-05	2017-01-05	ST ROBERT	1	2016-12-29	2016-12-29	CD

These crash frequency changes were monetized to enable economic comparisons to other tangible costs. The study adopted FHWA's comprehensive crash unit costs [23] to monetize the change in crashes based on the severity of the crash. Table 7 shows the unit costs that were used to estimate crash costs during a winter event. The crash costs during a winter event are calculated by totaling the unit costs (comprehensive) based on crash severity. From Figure 23, each winter event on average increased the number of crashes by three, at a total cost of about $660,000. The costs were significantly higher in districts around St. Louis and Kansas City but also in some rural districts in the northeast and southeast of Missouri. The top ten facilities by crash costs are shown in Figure 23 as well.

Table 7. HSM crash unit costs (2016 dollars) [14]

Crash Severity	Economic Crash Unit Cost	QALY Crash Unit Cost	Comprehensive Crash Unit Cost
Fatal (K)	1,688,100	4,052,000	5,740,100
Disabling Injury (A)	151,000	153,400	304,400
Evident Injury (B)	56,800	54,400	111,200
Possible Injury (C)	38,500	24,200	62,700
PDO (O)	8,700	1,400	10,100

Delay Cost Estimation

The impact of a winter event on mobility is estimated by monetizing the total delay over the entire duration of the event. The total delay is computed by subtracting the delay during an event from the delay during a baseline event.

Baseline Event: For delay cost estimation, the baseline travel time for each road segment, which is assumed to be the 85th percentile of travel time for all times is used. The average travel time during the event is subtracted from the baseline travel time and then multiplied by the traffic volume and duration of the event to obtain the total delay.

To monetize the mobility impact, we multiply the total delay by the value of time per person. The value of time estimates is based on USDOT guidance on value of time for surface mode travel. The recommended values are shown in table 8 below. In the current research, we used $20 (an average of hourly rate for passenger car drivers and truckers) as the value of time. Figure 24 shows the delay costs across different maintenance facilities per winter event. The estimated delay cost per event per maintenance facility is approximately $430,000.

Table 8. Recommended hourly values of travel time savings (2012 U.S. $ per person-hour)

Category	**Surface Modes (except High-Speed Rail)**	**Air and High-Speed Rail Travel**
Local Travel-		
Personal	$12.30	
Business	$24.10	
All Purposes	$12.80	
Intercity Travel-		
Personal	$17.20	$32.60
Business	$24.10	$60.00
All Purposes	$18.70	$43.70

A visualization of the different costs per facility is shown in Figure 24. It can be noted that the impact of an event varies across the different impact factors. For example, although crash costs in the KC district is high, the maintenance costs are relatively lower compared to other districts.

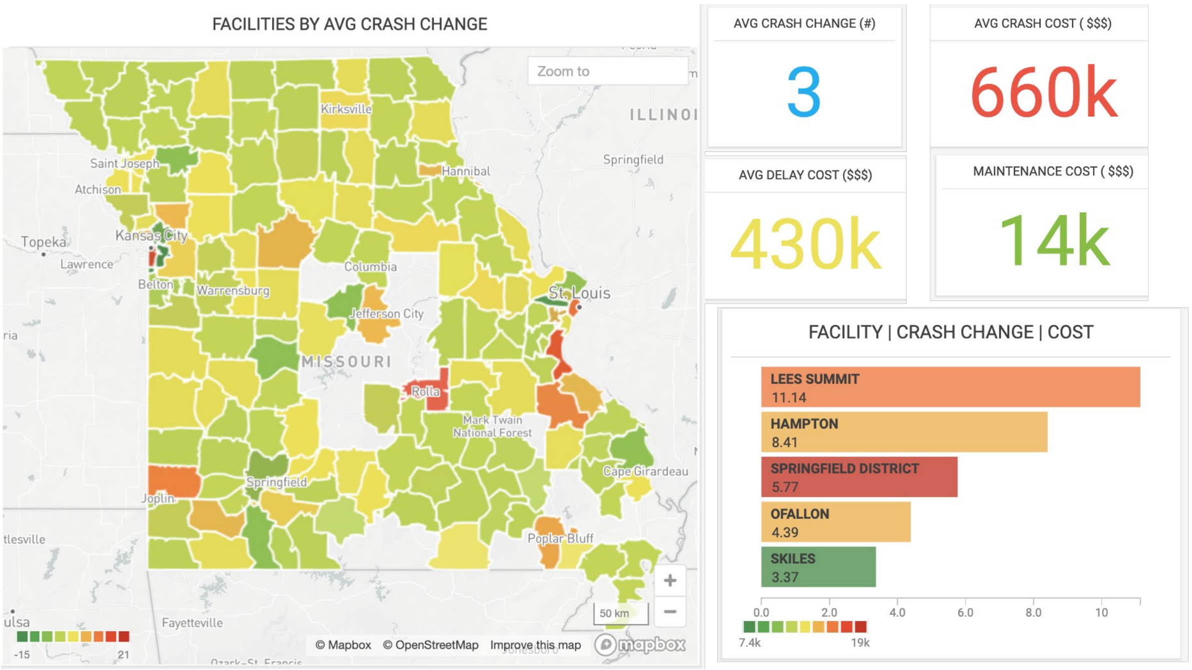


Figure 23. Average maintenance, crash, and delay cost per event per facility

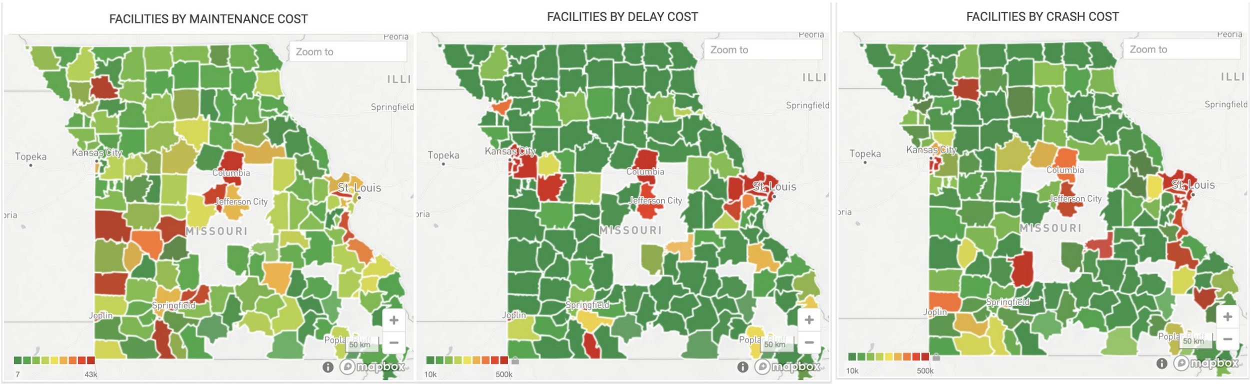
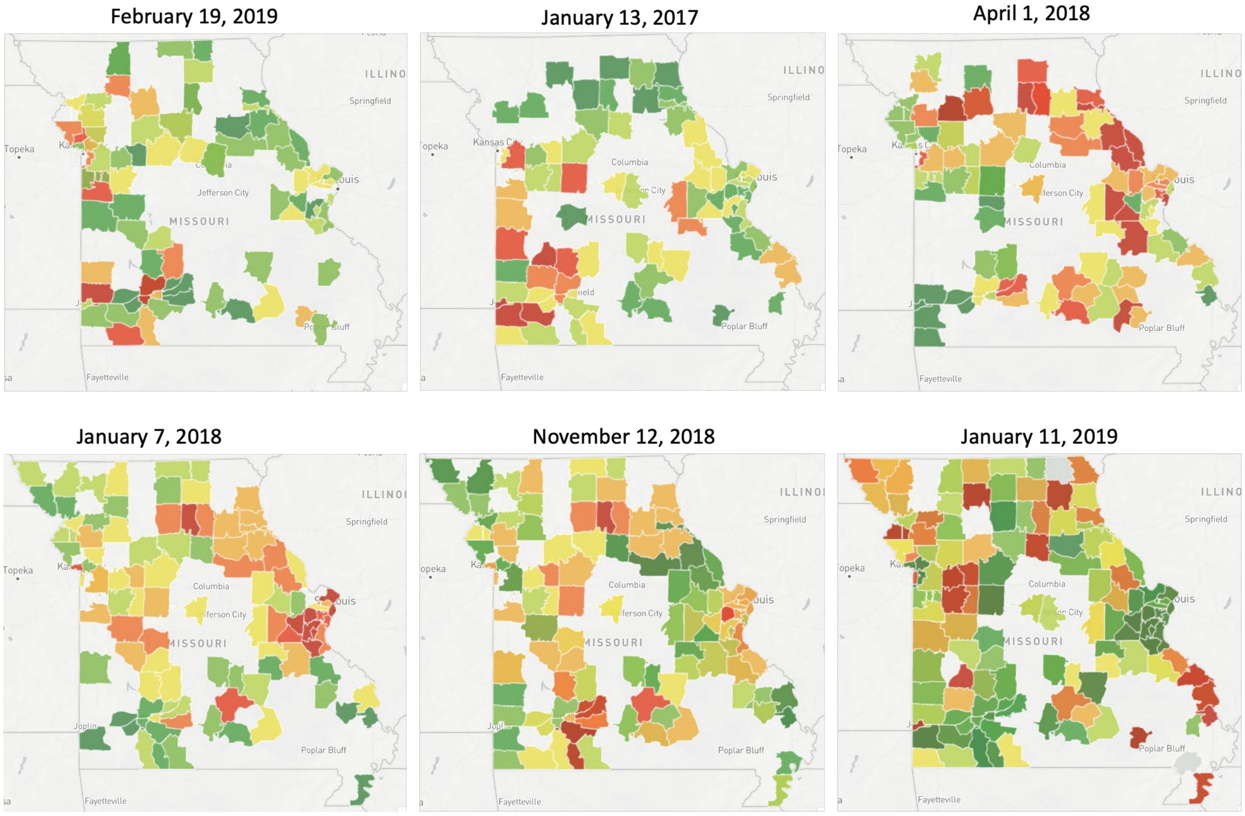


Figure 24. Average tangible (maintenance) and intangible (delay and crash) costs over the analysis period (2017 – 2019)

Chapter 6 Data Normalization

The impact of each winter event on safety, delay and maintenance costs were normalized by comparing each event to a high impact event obtained by averaging the top six winter events since January 2017 (shown in Figure 25). For example, to normalize crash costs, the crash cost for an event is divided by the average crash cost during the six major events. Similar computations are completed for delay costs and maintenance costs.


February 19, 2019

January 13, 2017

April 1, 2018

January 7, 2018

November 12, 2018

January 11, 2019

Figure 25. Major winter events used for normalizing maintenance, crash, and delay costs

Chapter 7 Visual Analytics of Weather Impacts

To understand the relationship between different weather variables and their impact on both tangible and intangible costs, a web-based visualization tool was developed [24]. The tool is interactive; enabling multi-dimensional views to be visualized and analyzed simultaneously. It uses REACT JavaScript library for front-end development, D3 and DC library for graphing and cross filtering, and a graphical processing unit (GPU) database for data storage and rendering. A snapshot of the tool is shown in Figure 26. The ability to use cross filtering to view different dimensions of the data is useful for understanding the impacts of different variables.

Figure 26 shows that the average maintenance cost per event is about 85% the cost of a major winter event. The average delay cost only drops by 8% compared to the delay cost during a major winter event. Crash costs and average change in crashes are however higher compared to the major events, 77% and 9% respectively.

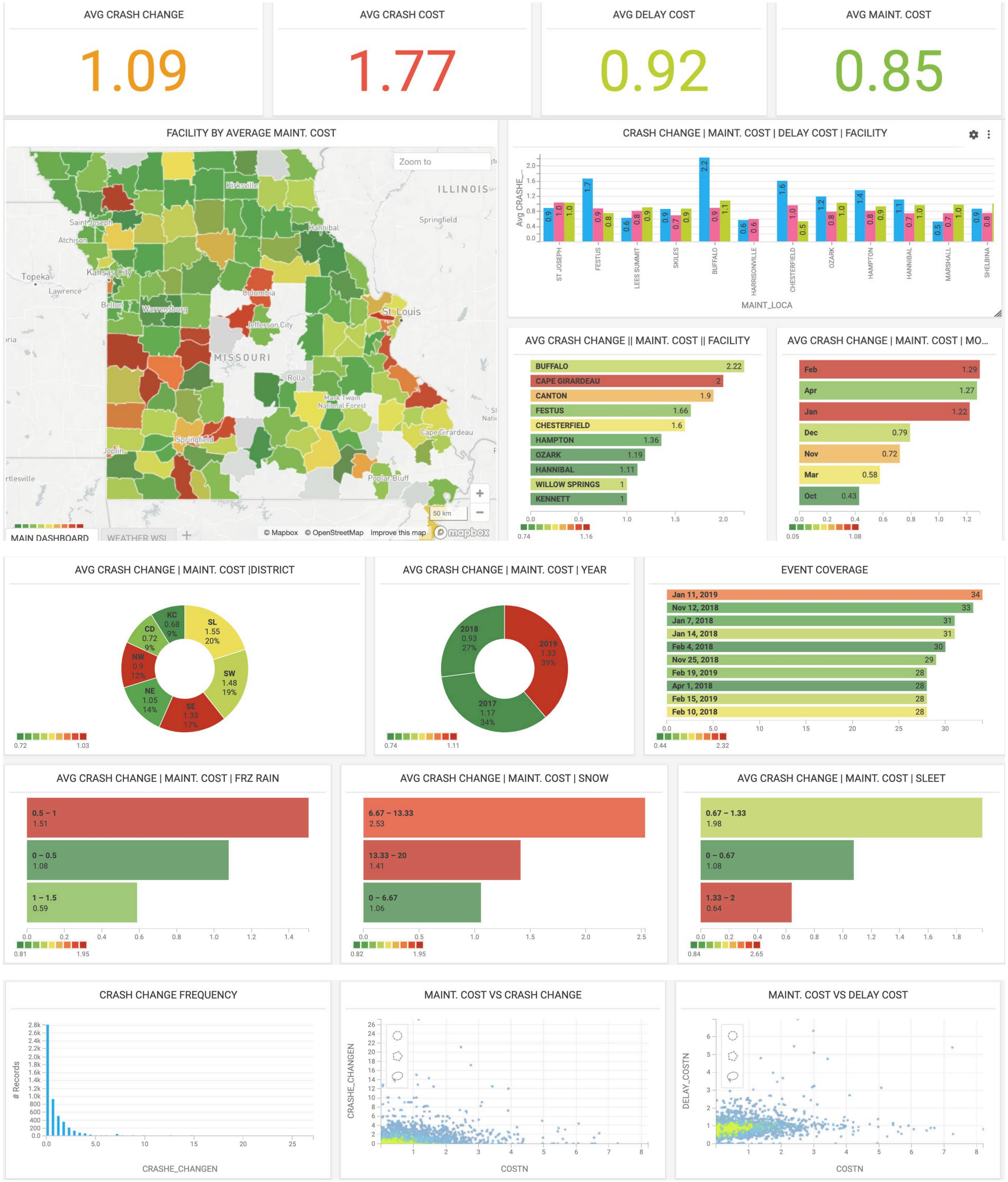


Figure 26. Missouri Winter Severity Dashboard: Showing impact of winter events between 2017 and 2019, across multiple facilities

General Trends of Missouri Winter Weather

A summary of general trends observed through the visual analytics tool are discussed as follows:

1. Compared to baseline crash numbers, winter events generally lead to about 8% increase in crash rate (or three crashes per winter event – from figure 27 below). However, the distribution of crash changes from Figure 27 show that the opposite is also true for some maintenance facility centers – winter events result in a reduction in the number of crashes, perhaps due to a reduction in VMT and/or lower operating speeds during the event.

Figure 27. Crash changes by day of week and distribution

2. Events during the last month of the winter season (April) have the highest impact in terms of the change in the number crashes. Events during January and February however have much higher delay costs (as shown by the colors in the row chart below).

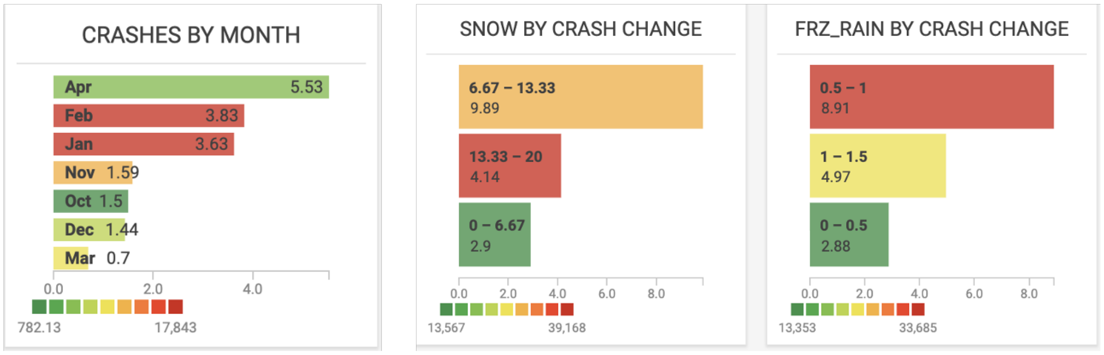


Figure 28. Bar charts for crashes by month, snow, and freezing rain by crash changes

Both delay and crash costs are highest when snow depths are between 7 – 14 inches. Traffic volume reduces drastically beyond 14 inches of snow and hence a reduction in the total delay. A similar trend is observed for freezing rain conditions as shown in the figure above.

Crash-Prone Facilities: Figure 29 shows regions that are likely to see increased crash costs during a winter event. Buffalo for instance records more than twice the number of crashes during a winter event as compared to a high impact event. The color of the row bar chart and the map shows the average maintenance costs for responding to events. Cape Girardeau for example shows high maintenance costs and crash change, whereas Festus has high crash change but low maintenance cost.

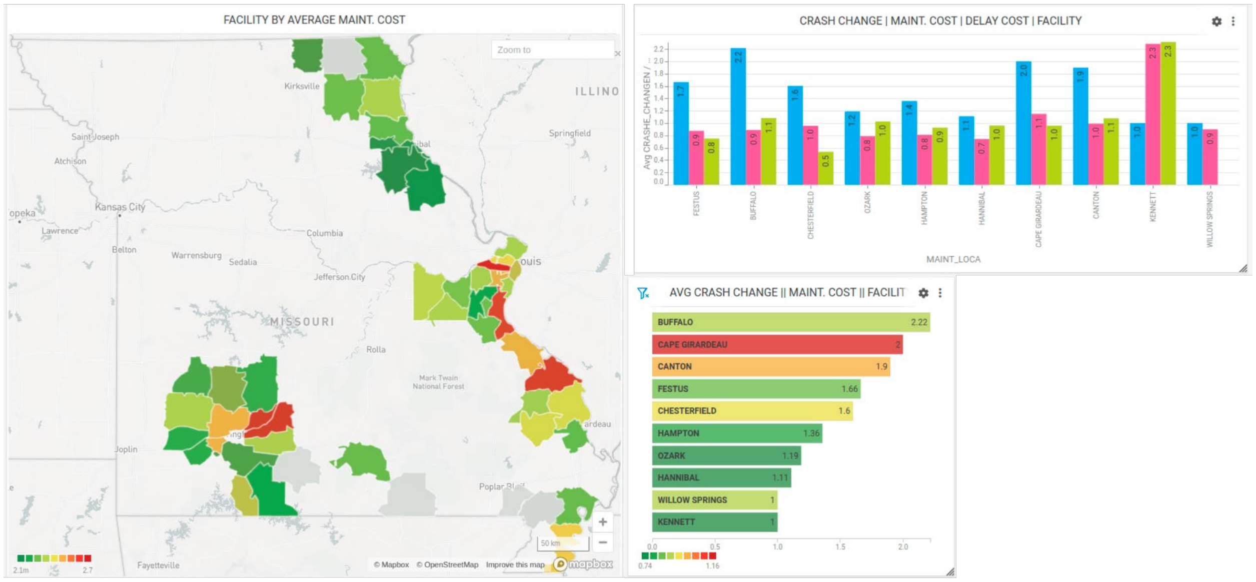


Figure 29. Top ten crash-prone facilities during winter events

In Figure 30, we compare the average crash change and maintenance costs per event by district. In general, about 40% of the increase in crash numbers due to a winter event occurred in the SL and SW districts. The average maintenance costs in these two districts were however 13% lower than the cost to a high impact event in these districts. Although the NW and SE districts have relatively lower crash costs, their maintenance costs are about 4% higher than the cost incurred during a major event in these two districts. Figure 28 also captures February, April, and January as the most crash-prone during winter events. A large proportion of maintenance costs were however incurred in February and January.

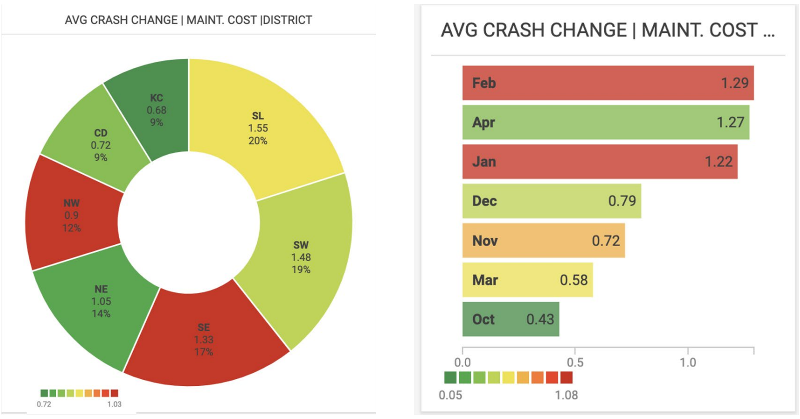


Figure 30. Winter event impact by district and month

Chapter 8 Conclusion

This research effort has developed a process and a tool for a MoDOT WSI that goes beyond the traditional WSI that is only based on winter weather season severity. The MoDOT WSI provides a comprehensive view of the impacts of winter weather events, impacts to the travelling public and to MoDOT.

The diversity of Missouri, both from a winter weather perspective as well as population densities, makes winter weather particularly challenging for MoDOT. In addition to capturing the impacts of winter weather events, the MoDOT WSI also develops a normalized picture of the winter weather impacts so that an accurate comparison can be made across maintenance areas and districts in different regions of Missouri that does not skew the impacts to the heavily travelled and highly impacted urban areas. This will allow MoDOT to better compare response practices, winter weather management, and performance across the various diverse regions of Missouri.

Considering the needs of MoDOT, this WSI effort provides a tool that tells the broader story with visualized data that includes impacts to the travelling public such as the cost of crashes and travel delay, and the tangible cost to MoDOT to respond to the winter weather events. These impacts are displayed in a dashboard that can be filtered by locations, dates, and types of events as well as in a normalized manner.

In summary, a MoDOT WSI has been developed that is not solely focused on a traditional WSI, but rather a holistic system for assessing the impacts of winter weather events in a broader sense that capture costs and other impacts taking into account the timing, location and other underlying effects.

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Appendix A ─ Detailed Analysis of Existing WSI

Table A-1 provides a detailed review of existing WSI by State. Refer to Figure 5 in Chapter 2 for color coding.

The development of WSI by different states depends mostly on the significant weather variables influencing winter season severity. To study the WSI model developed by each state and the different variables that were included, not included, and considered, Table A-2 provides a summary within the primary weather variables (temperature, snow, wind, and rain).

Table A-1: Detailed analysis of existing WSI

Location	**Developed by**	**Author**	**Approach/Variables**	**Data Source**	**Limitations**
Kansas, New Hampshire	Strategic Highway Research Program (SHRP)	Boselly et al., 1993	Safety assessment of weather impacts for highway agencies to efficiently allocate their resources.	Daily records from the National Weather Service. Assuming that the impact of temperature, snowfall, and likelihood of frost on maintenance costs are 35%, 35% and 30%, respectively.	Developed for all states so eliminates unique local characteristics to state.

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

Tindex: temperature index (which is equal to 0 if the minimum air temperature is above 32° F; 1, if the maximum air temperature is above 32° F while the minimum air temperature is below 32° F; and 2, if the maximum air temperature is at or below 32° F)

Sdaily: mean daily value of snowfall (millimeters)

dfreez: mean daily values of the number of days with minimum air temperature at or below 32° F ($0 \leq dfreez \leq 1$)

Trange: is mean monthly maximum air temperature minus the mean monthly minimum air temperature

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td>Wisconsin</td><td>Wisconsin DOT</td><td>(Cohen, 1981; McCullouch et al., 2004; Strong et al., 2005)</td><td>Number of snow events, the number of freezing rain events, the number of incidents (drifting snow, cleanup, and frost mitigation) *investigated but not included in final model: wind speed/direction and pavement temperature</td><td>Daily records from the National Weather Service (NWS). Assuming that the impact of temperature, snowfall, and likelihood of frost on maintenance costs are 35%, 35% and 30%, respectively.</td><td>Does not consider air temperature. Used for a whole season rather than unique events so unable to assess particular events impact.</td></tr>
<tr><td colspan="6">$$WI_{Wisconsin} = 0.16 \times D_{Snowevent} + 0.28 \times D_{frrain} + 0.03 \times D_{snowamount} + 0.01 \times D_{duration} + 0.18 \times D_{incident}$$
DSnowevent: number of snow events
Dfrrain: number of freezing rain events
Dsnowamount: snow amount in inches
Dduration: total storm duration in hours
Dincident: number of incidents (drifting snow, cleanup, and frost mitigation)</td></tr>
<tr><td>Minnesota</td><td>Minnesota DOT</td><td>Strong et al., 2005</td><td>Similar approach to Wisconsin but removed number of incidents</td><td></td><td>Does not consider air temperature. Used for a whole season rather than unique events so unable to assess particular events impact.</td></tr>
</table>

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td colspan="6">

$$WI_{Minnesota} = 0.18 \times D_{Snowevent} + 0.31 \times D_{frrain} + 0.08 \times D_{snowamount} + 0.32 \times D_{duration}$$

DSnowevent: number of snow events
Dfrrain: number of freezing rain events
Dsnowamount: snow amount in inches
Dduration: total storm duration in hours
Dincident: number of incidents (drifting snow, cleanup, and frost mitigation)

</td></tr>
</table>

Location	**Developed by**	**Author**	**Approach/Variables**	**Data Source**	**Limitations**
Indiana	Indiana DOT	Strong et al., 2005	Similar to Wisconsin but included: snow depth, storm density (storm duration), and average temperature, as well as separate equations for each state climate zone which means derives a unique WSI for each of the state's climate regions		The amount of meteorological data brings a computational challenge but is accurate with WSI for each location.

$$WI_{Indiana} = a_1 \times D_{frost} + a_2 \times D_{frrain} + a_3 \times D_{drift} + a_4 \times D_{snowevent} + a_5 \times S_{depth} + a_6 \times H_{storm} + a_7 \times T_{avg}$$

Dfrost: number of frost days (i.e., minimum temperature is at or below 32° F and minimum dew point is at or below 32° F)
Dfrrain: number of freezing-rain days (i.e., number of days with freezing rain and/or drizzle and a minimum temperature at or below 32° F)
Ddrift: number of drifting days (i.e., the number of days with wind speeds >15 mph and either snow on the ground or a snow event)
Dsnowevent: number of snow-event days, where a snow event day is defined as the number of days with minimum temperature at or below 32° F multiplied by the snowfall intensity and divided by the average temperature during the event
S*depth* is the snow depth
H*storm:* is the storm intensity
T*avg*: average temperature
To estimate parameters (ai) in the winter severity equation, Indiana DOT officials calculated the correlation between the winter severity index and snow removal costs using a multiple regression analysis of regional weather data.

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td>Illinois</td><td>Illinois State Water Survey</td><td>(Cohen, 1981; Strong et al., 2005)</td><td>Daily snowfall and temperature variables which is similar to WSI for Ontario, Canada.</td><td></td><td></td></tr>
<tr><td colspan="6">

$$WI_{Illinois} = D_{Snow} + D_{cold}$$

DSnow: number of days in which the daily snowfall accumulation is greater than or equal to 0.5 in (1.3 cm)
Dcold: number of days where mean daily temperature is between 15° and 30° F (−9° to −1 °C)</td></tr>
<tr><td>Pennsylvania</td><td>Pennsylvania DOT</td><td>(Strong et al., 2005)</td><td>Similar to Illinois but with additional meteorological variables</td><td></td><td></td></tr>
<tr><td colspan="6">

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

Sseason: total inches of snowfall in the period
Dmed: number of days with snowfall between 1 and 6 in.
Dhvy: number of days with snowfall > 6 in.
Dfrost: number of days with a maximum temperature above 32° F and a minimum temperature below 32° F
Dfreeze: number of days with temperature below 32° F
Hsi: total hours in the period when snow or ice occurs
The Pennsylvania index is unique because it has separate variables for different snow amounts or intensities</td></tr>
</table>

Location	Developed by	Author	Approach/Variables	Data Source	Limitations
Maine	Maine DOT	(Maine DOT, 2009)	Regionally computed WSI		

No corresponding statewide value. Maine's severity index assigns various point values to different weather conditions or derived parameters. The first derived parameter is the “freezing rain equivalent,” defined by:

$$FZRA\ Equiv = \frac{30}{30+DeltaT^2} \\ +[Daily\ Precip\ Total - Daily\ Snfl(10:1\,ratio)\ Equiv\ Precip]$$

DeltaT: maximum temperature less thirty (Tmax – 30)

The second derived parameter is the “modified daily snowfall,”:

$$Mod\ \ Daily\ Snfl = (Est\ \ Daily\ Snfl\ (ratio) - Measured\ Daily\ Snfl) * 1.25 \\ + Measured\ Daily\ Snfl$$

This formula converts the total daily liquid precipitation into a snowfall amount for freezing rain computations. The estimated ratio is obtained from knowledge about temperature ranges and average snow-to-liquid ratios.

Location	**Developed by**	**Author**	**Approach/Variables**	**Data Source**	**Limitations**
Washington	Washington State DOT		Documented Simpler WSI		Unavailable specific equation
Winter frost index is calculated from NWS temperature observations. however, its specific equation is not available					
Massachusetts	Massachusetts's DOT	Massachusetts DOT, 2012	Documented Simpler WSI using slat usage in-state.		Unavailable specific equation
Does not have robust documentation regarding the parameters of its index, though the state's agency acknowledges the existence of an index. Massachusetts uses the severity index to measure performance by comparing winter severity to salt usage throughout the state.					
New York	New York State DOT	Chien et al., 2014	Surface, air temperature, precipitation, and non-precipitation parameters.		Unavailable specific equation
Oklahoma	Oklahoma DOT	Balasundaram et al., 2012	Precipitation and non-precipitation events		Unavailable specific equation
Utah		De Pondeca et al., 2011; Farr and Sturges, 2012	Similar to New York and Oklahoma but considers the states complex topography		Unavailable specific equation

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td>Iowa</td><td>Iowa DOT</td><td>Walsh, 2016</td><td colspan="2">Storm-based event index, rather than monthly or seasonal. Also, considered the best documented WSI.</td><td></td></tr>
<tr><td colspan="6">

$$SSI_{Iowa} = \sqrt{\frac{1}{b}[(E_{storm} \times T_{roadduring} \times W_{during}) + B_{before} + T_{roadafter} + W_{after} - a]}$$

SSIowa: storm severity index
Estorm: storm type (i.e., 1 = freezing rain, 2 = light snow, 3 = medium snow, 4 = heavy snow)
Troadduring: in-storm road surface temperature (cooling, consistent, or warming)
Wduring: in-storm wind condition
Bbefore: early storm behavior (i.e., rain or no rain)
Troadafter: post-storm temperature (cooling, consistent, or warming)
Wafter: post-storm wind condition; and *a, b* are parameters to normalize the index from 0 to 1.
</td></tr>
<tr><td>California</td><td>California DOT</td><td>Strong et al., 2005</td><td>Identifying weather conditions causing road crashes</td><td></td><td></td></tr>
<tr><td colspan="6">

$$AccRate_{\text{California}} = a_0 + a_1 \times Frost + a_2 \times TMIN + a_3 \times Nsnow + a_4 \times TMAX$$

Frost: equals 1 if the maximum daily air temperature is >32° F and the minimum daily air temperature is <32° F and equals 0 otherwise
TMIN: minimum daily air temperature
Nsnow: number of days in a month with snowfall
TMAX: maximum daily air temperature.
</td></tr>
<tr><td>Montana</td><td>Montana DOT</td><td></td><td>Identifying weather conditions causing road crashes</td><td></td><td></td></tr>
</table>

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td colspan="6">$$AccRate_{\text{Montana}} = a_0 + a_1 \times SnowFreq + a_2 \times Frost + a_3 \times TMAX + a_4 \times DewPtTemp + a_5 \times Rain + a_6 \times Snow + a_7 \times WindSpdAvg$$
SnowFreq: frequency of snowfall during the day
Frost: equals 1 if the maximum daily air temperature is >32° F and the minimum daily air temperature is <32° F and equals 0 otherwise
TMAX: maximum daily air temperature
DewPtTemp: average daily dew point temperature
Rain: average rate of rainfall during the day
Snow: average rate of snowfall during the day
WindSpdAvg: average wind speed</td></tr>
</table>

<table>
<tr><th>Location</th><th>Developed by</th><th>Author</th><th>Approach/Variables</th><th>Data Source</th><th>Limitations</th></tr>
<tr><td>Oregon</td><td>Oregon DOT</td><td></td><td>Identifying weather conditions causing road crashes</td><td></td><td></td></tr>
<tr><td colspan="6">

$$AccRate_{\text{Oregon}} = a_0 + a_1 \times TMIN + a_2 \times WindSpdAvg + a_3 \times Snow + a_4 \times Frost + a_5 \times SnowFreq + a_6 \times TMAX + a_7 \times Templow$$

TMIN: minimum daily air temperature
WindSpdAvg: average wind speed
Snow: average rate of snowfall during the day
Frost: equals 1 if the maximum daily air temperature is >32° F and the minimum daily air temperature is <32° F and equals 0 otherwise
SnowFreq: frequency of snowfall during the day
TMAX: maximum daily air temperature
Templow: is 1 if the temperature remains below the freezing point through the day</td></tr>
<tr><td>Colorado, Idaho</td><td>Colorado DOT, Idaho Transportation Department</td><td>Walsh, 2016</td><td colspan="2">Event-based variables and specific points along road segments.</td><td></td></tr>
<tr><td colspan="6">

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

MaxLayerThickness(*mm*): Road surface precipitation accumulation defined by:

$$MaxLayerThickness(mm) = max(IceLayer, SnowLayer, WaterLayer)$$

</td></tr>
</table>

Table A-2: Weather-related variables to develop WSI

		Temperature										Snow							Wind				Rain					
State	Papers	Air/surface								Road		Daily amt.	Event amt.	Intensity/ rate	Duration	Days	Depth/ cover	other	Speed	Direction	Drift	Gust	Number of event	Duration	Number of days	Storm Type	Temperature	Accum.
		Obs.	Max.	Min.	Ave.	Obs. Dew Point	Dew Pt. Ave.	T threshold	Days with $T < 32°$	Obs.	Min.																	
CA	1	🟥	🟩	🟩				🟩				🟥				🟩	🟥											
CO	2									🟩	🟩		🟩				🟩		🟩									🟩
ID	3									🟩	🟩		🟩				🟩		🟩									🟩
IL	4				🟥			🟩				🟥				🟩												
IN	5			🟥	🟩	🟥		🟩	🟩					🟩		🟩	🟩	🟩	🟥		🟩		🟥		🟩			
IA	6	🟥	🟥	🟥	🟥					🟩			🟥	🟥			🟥	🟥	🟩	🟩	🟩	🟩				🟩	🟩	
KS	7		🟥	🟥	🟥			🟩	🟥			🟩																
ME	8		🟥					🟩				🟩	🟥					🟥										🟩
MA	9		🟩	🟩													🟩	🟩	🟥									
MT	10	🟥	🟩	🟩		🟥	🟩	🟩		🟥		🟥		🟩				🟩	🟩	🟥		🟥		🟥				
NH	11		🟥	🟥	🟥			🟩	🟥			🟩																
NY	12				🟩			🟩									🟩							🟩				
OK	13	🟩						🟩					🟩	🟩				🟩	🟩	🟥		🟥						🟩
OR	14	🟥	🟩	🟩	🟥			🟩						🟩				🟩	🟩	🟥		🟥						
PA	15		🟥	🟥				🟩	🟩			🟥	🟥	🟥	🟩	🟩	🟩											
UT	16									🟥				🟥				🟥	🟥									
WA	17	🟥																										
MN	18														🟩		🟩						🟩	🟩				
WI	19														🟩		🟩	🟩					🟩	🟩				

☐	Not used
🟥	Considered/used but not included
🟩	Included in final model

Appendix B ─ Full Matrix of Data, Measures and Factors

The full matrix of Data, Measures and Factors is shown in Table C-1. The following provides a guide to the matrix.

Data Source. While much of the data is provided by MoDOT, there are other sources as well. Source details are found below in the Data Sources List.

Data Field(s). Some of the data element fields are combined for brevity, but each applicable data field will be broken out as needed in the future development steps.

Description and Method of Measurement. Where applicable, the method used to measure the element is provided or a more detailed data source that would describe the measurement details.

Initial Applicability to MoDOT WSI. This column provides a brief description of the anticipated manner that the data element might be used in the WSI tool. For example, the data element may be applied directly to a WSI calculation, may be combined with other data elements, and applied to a WSI calculation, may be used to verify or adjust other data, may be used to process or convert other data or may not apply to the WSI.

Duplication/Complement/Conflict. One of the issues that is addressed in the WSI tool development is duplicate data sources that may either complement each other or provide conflicting information. The duplication/complement/conflict column identifies the nature of the duplication and a brief explanation. Note that a number of elements simply provide additional geographic data points to provide more granular coverage.

Availability of Information. The availability of information column provides an assessment of the information availability. Information that is not available or inconsistently available will not be used in the WSI tool.

Viability for WSI (None/Low/Medium/High). This column provides a level of viability recommended by the research team.

Table C-1. Matrix of Data, Measures and Factors

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
MoDOT Roadway Data and Information	Major/Minor Routes [14]	MoDOT roadway classification by Major and Minor types	May be used as part of a WSI weighting factor, higher value to Major routes. Major routes are approximately the same as MoDOT "continuous operation routes".	Unique	Readily available, essentially static data	High
	Roadway Functional Classification [15]	MoDOT roadway functional classification following FHWA functional classification	Could be used as part of a WSI weighting factor, higher value to higher type functional classification routes. However, other factors may be a better fit for WSI weighting.	Unique	Readily available, essentially static data	Low
	AADT - Daily/Hourly [16]	AADT route data collected by MoDOT Planning including hourly traffic breakdown	May be used by itself or part of VMT calculation as part of a WSI weighting factor, higher value for higher AADT or higher peak hour traffic	Unique	readily available, varies annually	High
	Roadway Geodata*	Used to convert MoDOT County/Route/Log Mile to Latitude/Longitude	Used to tie together MoDOT data that is based on MoDOT log mile system with data that is latitude/longitude based.	Unique	Readily available, essentially static data	High
	Vehicle Miles Traveled (VMT)	Calculated from AADT data and roadway segment lengths	Normalizing factor. May be used as part of a WSI weighting factor, higher value to higher VMT.	Unique	Readily available, essentially static data	High
MoDOT Maintenance Area Information	Maintenance Area Boundaries*	Geographic boundaries for MoDOT Maintenance Areas	Will probably be used as the geographic unit areas for WSI modelling	Unique	Readily available, essentially static data	High
	Maintenance Area Org Codes*	MoDOT organization codes for maintenance areas, typically representative of a maintenance building.	Used to connect financial data with other factors	Unique	Readily available, essentially static data	High
MoDOT Traveler Information Map (TMS)	Incidents - Type/Location/Date/Time/ Duration*	Roadway incidents reported to MoDOT that are displayed on the Traveler Information (TI) map. These can be anything that impacts traffic; traffic crashes, flooded roads, road damage, debris on roadway, etc.	Will only use traffic crashes. Will probably be used as part of a WSI weighting factor.	Similar duplicate data from crash reports. May require some deconflicting.	Readily available from MoDOT TMS	High
	Road Conditions - Condition/Location/Date/Time*	Road conditions reported during winter events by MoDOT field staff for display on the TI map	Locations, start, end times will be used for WSI modelling to tie crashes to a winter weather event	Similar duplicate data from crash reports, RWIS data, NWS data. May require some deconflicting.	Readily available from MoDOT TMS	High

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
RITIS Data	Real time speeds [17]	Speeds recorded by RITIS system based on probe data capturing speed changes.	Speed decreases will be filtered to correspond with winter weather events. May be used as part of a WSI weighting factor.	Unique	Available with a RITIS account	High
	Real time speed event date/time/location [17]	Date/time/location of speed changes	Time/date/location of speed decreases will be used to help identify start and end times of events. For instance, traffic impact could continue well past the end of a storm event.	Unique	Available with a RITIS account	High
MoDOT Crash Data (TMS)	Crash type*	Crash type derived from Law Enforcement (LE) statewide crash reporting system, Property Damage Only, etc.	May be used as part of a WSI weighting factor	Similar duplicate data from MoDOT TI map incidents. May require some deconflicting.	Readily available from MoDOT TMS	High
	Crash Location/Date/Time*	Crash date/time derived from LE statewide crash reporting system	Used to tie crashes to winter weather events, will be filtered to crashes occurring during winter weather event determined from other data	Similar duplicate data from MoDOT TI map incidents. May require some deconflicting. There will be more LE reported crashes than those found in the MoDOT TI map data.	Readily available from MoDOT TMS	High
	Crash Reports - Road Conditions*	Road conditions recorded by Law Enforcement on crash report forms	Road conditions from crash reports are categorized differently than the MoDOT TI Map road conditions. May be used for data verification, but probably not used directly in the WSI.	Similar duplicate data from MoDOT TI map road conditions. May require some deconflicting. May provide some information not found in MoDOT TI map data.	Readily available from MoDOT TMS	Low
MoDOT Winter Events Database (Maintenance Division)	Event Date/Time*	Reported/recorded by MoDOT District and Central Office staff	Used in conjunction with other data to determine timing of winter weather events	Used in conjunction with other sources to fine tune event timing	Readily available from MoDOT staff	High
	Event Building (Org)*	Reported/recorded by MoDOT District and Central Office staff. These will correspond with the financial org codes	Used in conjunction with other data to determine location of winter weather events by org code	Used in conjunction with other sources to fine tune event location	Readily available from MoDOT staff	High
	Event Type and Amount*	Reported/recorded by MoDOT District and Central Office staff	May be used in conjunction with other data as part of a WSI weighting factor. This information may be used for data verification, but probably not used directly in the WSI.	Similar duplicate data to TI map and NWS data. May require some deconflicting. This source probably is a lower confidence factor than others.	Readily available from MoDOT staff	Medium

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
MoDOT Winter Events Database (Maintenance Division)	Major and Minor Times*	Reported/recorded by MoDOT District and Central Office staff. Major time is the days to meet MoDOT snow/ice objectives. Minor time is the days until the event response is complete.	Used in conjunction with other data to determine timing of winter weather events. This information may be used to verify the start and end time of events since pre-treatment would start early and cleanup will typically last past the end of the actual weather event.	Similar duplicate data to various other sources. May require some deconflicting.	Readily available from MoDOT staff	Medium
	Comment Field*	Reported/recorded by MoDOT District and Central Office staff	May provide additional information for various factors but will probably not be used directly in the WSI	Unique	Readily available from MoDOT staff	Low
RWIS Data	Road Conditions - RWIS	Road surface condition detected by RWIS system	Could be used in conjunction with other road condition data to determine timing of winter weather events. Could be used to rate event severity as part of a WSI weighting factor.	Similar duplicate data from MoDOT TI map road conditions. May require some deconflicting. May provide some information not found in other data sources.	Not available at this time	None (due to lack of availability)
	Air Temperature	Air temperature at RWIS location	Could be used in conjunction with other road condition data to determine timing of winter weather events	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Relative Humidity	Relative Humidity at RWIS	Probably not used for WSI	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Dew Point	Dew point at RWIS site	Probably not used for WSI	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Wind Speed and Direction	Wind speed at RWIS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Wind Direction	Wind Direction at RWIS site	Probably not used for WSI	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Wind Gusts	Wind gusts and related information recorded at RWIS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Barometric Pressure	Barometric pressure at RWIS site	Probably not used for WSI	Provides additional geographic data points	Not available at this time	None (due to lack of availability)

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
RWIS Data	Visibility	Visibility at RWIS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Precipitation Amount	Measured rainfall at RWIS site, may not be collected when freezing	Could be used for precipitation data verification, but probably not used directly in the WSI	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Precipitation Situation	Yes/No report from rain gauge	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Snow Depth	Estimated from precipitation amounts	Could be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Not available at this time	None (due to lack of availability)
	Pavement Freeze Point	Calculated from RWIS puck readings (temperature and salinity)	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Unique	Not available at this time	None (due to lack of availability)
	Pavement Water Level/Ice Level	Calculated from various sensor inputs	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Unique	Not available at this time	None (due to lack of availability)
	Pavement Temperature	Pavement temperature from RWIS pucks	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Unique	Not available at this time	None (due to lack of availability)
	Subsurface Temperature	Subsurface temperature from RWIS sensor	Probably not used for WSI	Unique	Not available at this time	None (due to lack of availability)
	Bridge Temperature	Bridge deck temperature from RWIS bridge pucks where available	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Unique	Not available at this time	None (due to lack of availability)
	Grip	Gives an indication of surface friction between 0 - 1, calculated from RWIS sensors	Could be used in conjunction with other road condition data to determine timing of winter weather events.	Unique	Not available at this time	None (due to lack of availability)
	Salinity	Gives an indication of road/bridge chemical level detected by RWIS pucks	Could be used in conjunction with other road condition data to determine timing of winter weather events. May be helpful to identify frost on bridge events and other types of events that are difficult to identify from other data.	Unique	Not available at this time	None (due to lack of availability)

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
National Weather Service (NWS) Data [18]	Missouri ASOS Metadata	Locations of Missouri sites and other information	Geographic locations of ASOS data to associate with nearest roadway segments.	Unique	Readily available from NWS	High
	Air Temperature	Air temperature at AWOS/ASOS site	May be used in conjunction with other road condition data to determine timing of winter weather events.	Provides additional geographic data points	Readily available from NWS	Medium
	Relative Humidity	Relative Humidity at AWOS/ASOS site	Probably not used for WSI	Provides additional geographic data points	Readily available from NWS	None
	Dewpoint	Dewpoint at AWOS/ASOS site	Probably not used for WSI	Provides additional geographic data points	Readily available from NWS	None
	Wind Speed	Wind speed at AWOS/ASOS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Readily available from NWS	Medium
	Wind Direction	Wind Direction at AWOS/ASOS site	Probably not used for WSI	Provides additional geographic data points	Readily available from NWS	None
	Wind Gusts, Timing, Directional Gusts	Wind gusts and related information recorded at AWOS/ASOS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Readily available from NWS	Medium
	Barometric Pressure	Barometric Pressure at AWOS/ASOS site	Probably not used for WSI	Provides additional geographic data points	Not available at all sites	None
	Visibility	Visibility at AWOS/ASOS site	May be used in conjunction with other road condition data to determine timing of winter weather events. May be used to rate event severity as part of a WSI weighting factor.	Provides additional geographic data points	Readily available from NWS	Medium
	Precipitation Amount	Precipitation Amounts recorded at AWOS/ASOS site	Could be used for precipitation data verification, but probably not used directly in the WSI	Provides additional geographic data points	Not available at all sites	Low
	Cloud Amount	Amount in octans recorded at AWOS/ASOS site	Probably not used for WSI	Unique	Readily available from NWS	None
	Cloud Base Height	Cloud Height from ceilometer at AWOS/ASOS site	Probably not used for WSI	Unique	Not available at all sites	None

Data Source	Data Field(s)	Description and Method of Measurement	Initial Applicability to MoDOT WSI	Duplication/Complement/Conflict	Availability of Information	Viability for MoDOT WSI (None/Low/ Medium/High)
National Weather Service (NWS) Data [18]	Weather Type	Type of precipitation (showers, snow, sleet, etc.) observed at AWOS/ASOS site	May be used in conjunction with other data to determine type and timing of winter weather events. Used to correlate with crash data to decide inclusion of crash into the winter weather event.	Provides additional geographic data points	Readily available from NWS	High
	Ice Accumulation	Ice Accumulation at AWOS/ASOS site	May be used for event timing data verification, but probably not used directly in the WSI	Provides additional geographic data points	Not available at all sites	Low
MoDOT Financial Data	R913 - Snow and Ice Response*	The time and expenses incurred related to snow and ice operations.	Used for calculation of MoDOT event tangible costs	Unique	Readily available from Missouri SAMII system	High
	R914 - Snow & Ice Preparedness, Prevention and Clean-up*	The time and expenses incurred related to snow and ice prevention and clean-up and includes purchasing of tools and equipment, purchasing/receiving salt or other winter materials, debris/tree removal associated with snow or ice storms.	Used for calculation of MoDOT event tangible costs	Unique	Readily available from Missouri SAMII system	High
Road User Costs	Crash Costs [19, 20]	Derived from AASHTO "User and Non-User Benefit Analysis for Highways" or MoDOT "Safety Handbook for Locals" (S-HAL)	With appropriate categorization, may be able to develop crash costs for winter events. May be used as part of a WSI weighting factor.	Unique	Readily available from the listed documents.	Medium
	Delay Costs [19]	Derived from AASHTO "User and Non-User Benefit Analysis for Highways"	Probably not used for WSI	Unique	May be difficult to develop consistently at a high level for this project based on the statewide scope of the project.	None
Socioeconomic Data	Population Density	Population density based on census tracts or other geographic boundaries	May be used as part of a WSI weighting factor	Unique	Readily available from Census or ACS	Medium
	Urban/Rural Boundaries	Established urban/rural boundaries used by planning agencies	May be used as part of a WSI weighting factor	Unique	Readily available from Census or ACS, essentially static data.	Medium

* Data not available publicly and provided directly by MoDOT