Evaluation of Direct Liquid Application of Salt Brine vs Granular Salt as Measured Through Various Performance and Safety Metrics

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With the increasing adoption of direct liquid application (DLA) of salt brine in roadway winter maintenance, limited field-based evidence exists comparing its performance with conventional granular salt. Previous studies suggest that salt brine applications reduce salt usage, shortens time to bare/wet, and improves roadway friction; however, results were based on limited datasets and treatments involving prewet salt or blends. To address this gap, this study synthesized existing literature, surveyed current practices, developed a field data collection protocol, and conducted field testing to evaluate the operational and safety performance of salt brine DLA versus granular salt. Field protocols were implemented in Jefferson and Sheboygan Counties in Wisconsin to compare study and control routes. Data from roads adjacent to Road Weather Information System (RWIS) stations were collected in Iowa and Wisconsin to assess the impact of weather conditions and winter maintenance. Novel performance metrics—Travel Disruption (TD) and Friction Deficit (FD)—were introduced to quantify operational and safety impacts. Results showed that friction between study and control routes were statistically similar. Based on a limited data, study routes had similar TD and time to bare/wet than control routes. Application rates at control routes were 200-300 pounds per lane-mile, while study routes application rates were 35-50 gallons per lane-mile, a difference in salt usage of between 40-72% would be expected, accomplishing similar roadway conditions as measured by friction and other performance measures. RWIS-based analysis further demonstrated the usefulness of the metrics of TD and FD as objective and practical measures for evaluating winter storm and treatment effects.

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Final Report

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List of Abbreviations

DLA	Direct liquid application
RWIS	Road Weather Information System
TD	Travel Disruption
FD	Friction Deficit
LOS	Level of Service
ATR	Automatic traffic recorders
NCRT	Normal Condition to Regain Time
IRIS	Intelligent Roadway Information System
RTMC	Minnesota Department of Transportation Regional Transportation Management Center
NOAA	National Oceanic and Atmospheric Administration
SN	Skid number
FN	Friction number
MARWIS	Mobile Advanced Road Weather Information Sensor
RSI	Road Condition Index
NB	Negative Binomial
DOT	Department of Transportation
NPMRDS	National Performance Management Research Data Set
NaCl	Sodium chloride
MgCl2	Magnesium chloride
GPS	Global Positioning System
AVL	Automatic Vehicle Location
CCTV	Close-circuit television
AADT	Annual Average Daily Traffic
MDSS	Maintenance Decision Support System
WisDOT	Wisconsin Department of Transportation

Executive Summary

Limited information is available of performance measures exclusively comparing salt brine direct liquid application (DLA) to conventional solid salt application. Previous field-based studies inclusively compared the performance of different salt brine applications (DLA, prewet, shake and bake, and blends) with granular salt using field data collected during storms. Salt brine applications were found to reduce the amount of salt used, reduce time to bare/wet, and result in higher pavement friction. Friction results from a previous study were based on a split route design (segment divided into study and control route), treatments were not implemented within the same time period (two different agencies operated each route), and salt brine DLA was not specifically evaluated. Therefore, real-world evidence of operational and safety performance of salt brine DLA versus granular salt is missing in the literature.

This study sought to fill that gap by synthesizing existing literature, conducting a survey of practice, developing a field data collection protocol, and conducting field testing to evaluate operational and safety performance across multiple performance metrics. Findings of existing literature indicate that winter storms have an impact on roadway operations and safety, and quantifying the effectiveness of winter maintenance treatments is very challenging. Performance measures that have been traditionally used focus on materials used, cost, time to bare/wet, storm severity, and crash rates. Alternatively, roadway surface friction has also been considered as a feasible measure to evaluate performance. Operational measures such as travel speed also seem to be a feasible alternative to consistently monitor performance and quantify the effectiveness of treatments during winter storms. The survey of practice revealed that DLA with salt brine is the most common anti-icing method, although agencies often rely on subjective or resource-based performance measures such as material usage or time to bare/wet pavement. Few agencies collect friction or travel speed data for performance evaluation purposes.

A field-based data collection protocol for study and control routes was developed. The research team reached out to agencies to inquire about the possibility to accommodate the experiment and data collection requirements. Due to the lack of friction equipment, routing, truck requirements, and staff time, most agencies were unable to accommodate the data collection protocol. Jefferson and Sheboygan counties in Wisconsin were able to rearrange routing and maintenance operations to collect field data during storms at parallel study and control routes during the 2024-2025 winter season. Additionally, data from roadways adjacent to Road Weather Information System (RWIS) stations in Iowa and Wisconsin with prewet salt treatments were obtained to evaluate roadway friction and vehicular speed as a function of storm conditions. Introduced in this study, the performance metrics Travel Disruption (TD) and Friction Deficit (FD) provide operational and safety surrogate measures of roadway performance by quantifying the changes in speed and friction over time in relation to normal baseline conditions.

Results of the field data analysis indicate that friction at study and control routes were statistically similar. Based on limited data and number of storms, study routes had similar TD and time to bare/wet than control routes. Since control route applications were 200-300 pounds per lane-mile, while study route applications ranged between 35 to 50 gallons per lane-mile, a difference in salt usage of between 40% and 72% would be expected, accomplishing similar roadway conditions as measured by friction. RWIS-based analysis further demonstrated the usefulness of the metrics TD and FD as objective and practical measures for evaluating winter storm and treatment effects. The measures significantly

contributed to assess the impact of weather conditions and winter maintenance treatments. Continuous friction measurements from RWIS stations and AVL data also provided valuable information about trends in friction, impact of storm, impact of treatment, and thresholds of operation during a storm.

Chapter 1: Introduction

1.1 Background

Research on salt brine for winter maintenance operations has been conducted mainly in laboratory settings and some field tests. Laboratory studies have focused on evaluating ice melting capacity and ice melting rate—salt brine performance has been compared to granular salt, other liquid chemical materials, and blends. Toxicity and chloride concentrations have also been studied in laboratory environments to evaluate the effect on concentration of chlorides in water, microorganisms, flora, fauna, and roadway infrastructure materials. In terms of field-based research, previous studies conducted by the research team compared the performance of different salt brine applications—direct liquid application (DLA), prewet, shake and bake, and blends—with granular salt using field data collected from 249 storms over three winter seasons across 10 counties in Wisconsin (Claros et al. 2019, Claros et al. 2021a, Claros et al. 2021b, Claros et al. 2023a). When compared with granular salt, salt brine applications were found to:

- Reduce the amount of salt used by 23.8%,
- Reduce time to bare/wet by 15.0%, and
- Result in 8.1% higher pavement friction.

Friction results from a previous study were based on a split route design (segment divided into study and control route), treatments were not implemented within the same time period (two different agencies operated each route), and salt brine DLA was not specifically evaluated. Therefore, real-world evidence of operational and safety performance of salt brine DLA versus granular salt is missing in the literature. Naturally, several stakeholders including the traveling public, law enforcement officers, and transportation agencies across the country have questions about the operational and safety performance of salt brine DLA.

1.2 Objectives

The objectives of the project were to:

- Collect and synthesize information about the differences between DLA of salt brine and granular salt in performance and safety metrics,
- Develop a field data collection protocol, and
- Conduct field testing to compare the performance of DLA of salt brine with granular salt.

1.3 Organization of the Report

Following the Introduction, Chapter 2 presents the literature review. Chapter 3 presents the survey of practice from different agencies in the United States and abroad. Chapters 4 describes the field testing protocol and considerations for field data collection. Chapter 5 provides details of the procedures and data collected from study/control routes and Road Weather Information System (RWIS) stations. Chapter 6 presents the analysis of the comparison between study routes treated with salt brine DLA and control routes treated with granular salt, and time series analysis of RWIS stations' environmental, road friction, and vehicular speed performance metrics. Finally, Chapter 7 provides the conclusions of the comparison between field performance of salt brine DLA and granular salt.

Chapter 2: Literature Review

The literature review focused on performance measures used in winter maintenance. Performance measures include safety, accessibility, mobility, environment, and operational efficiency metrics. Definitions and classification of performance measures in winter maintenance include input-, output-, and outcome-based metrics.

Input measures are directly associated with resources spent, output measures quantify accomplishments and coverage such as the amount of material used over miles treated, and outcome measures reflect how well operations meet organizational goals and customer expectations (ICF 2019, Qiu and Nixon 2009). Most importantly, application of performance measures requires quantifiable data, sample size considerations, and frequency of measurements. Extensive literature reviews on winter maintenance performance measures have been conducted by Strong et al. (2009), Xu et al. (2017), Fu and Kwon (2018), and ICF (2019). The following sections provide some references of performance measures in winter maintenance and the observed effects of winter weather on traveling speed, recovery time, delay, volume, capacity, friction, and crashes.

2.1 Speed and Recovery Time

Snow events and poor visibility were found to be associated with reductions in speed and increase of variation in speed. Brown and Baass (1997) found a 10% to 30% reduction in free flow speed. Liang (1998) found variations in speed three times larger than normal during a snow event. Studies evaluating travel speed suggest that decrease in speed and increase in speed variation during snowstorms were influenced by road classification and vehicle type (Padget 2001, Liang 1998). To illustrate this trend, Hanbali (1994) found snowy/icy conditions were associated with an average 18% to 42% speed reduction on two-lane highways and 13% to 22% reduction on freeways. Qui and Nixon (2009) reported that average speed may reduce as much as 24 mph based on the storm severity and road type. Other studies were also able to quantify the effect of winter operations on speed using different methodological and modeling approaches (Barajas et al. 2017, Cao 2014, Chen and Shi 2019, Donaher 2014, Greenfield et al. 2012, Lyon et al. 2014)

Travel speed can be used as a performance measure to assess the impact of winter storms and effectiveness on winter treatments. Wallman (2001) collected continuous measurements of traffic and weather on five roadways in Sweden. Data included precipitation, intensity, risk of slipperiness, air temperature, road surface temperature, wind force and wind direction. Data was aggregated in one-hour intervals. The analysis consisted of comparing average speed and flow under different roadway surface conditions with bare road conditions. Results of the analysis showed a significant, systematic, and plausible difference in vehicle speed between different roadway surface conditions and bare road conditions (Wallman 2001).

Based on data gathered from automatic traffic recorders (ATR) and winter storm reports, Lee and Ran (2004) estimated the average vehicle speed reduction and time needed to regain normal speeds during storm events in Wisconsin. Data from five ATRs were collected in one-hour intervals for 19 storms. Figure 2.1 provides a diagram of a storm event and the effect on speed from normal conditions, speed-recovery duration, maximum speed reduction, start/end of storm, pavement bare/wet and vehicle speed recovery. From a correlation analysis, total snow amounts, temperature, and average snowfall per hour did not show a statistically significant correlation with speed-recovery duration. Through regression modeling, the relationship of the response variable speed-recovery time and predictor variables snow event duration and maximum speed reduction was evaluated. Results indicated that snow event duration and maximum speed reduction had a significant effect on the speed-recovery time.

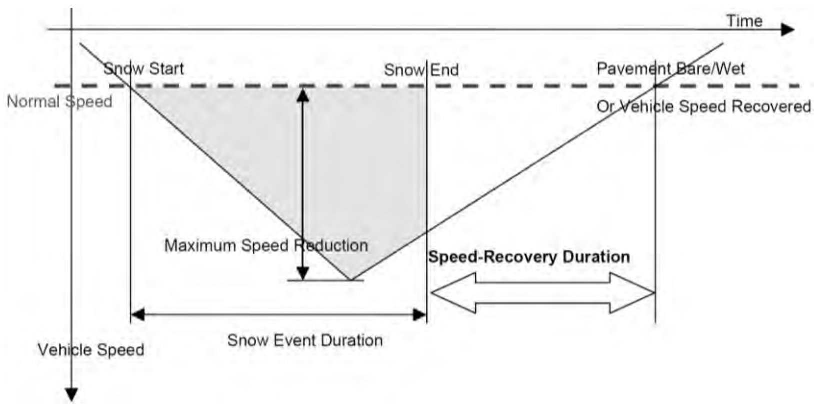

Figure 2.1 Diagram of speed reduction and recovery duration (Lee and Ran 2004).

The study conducted by Lee and Ran (2004) was an initial attempt with limited data to develop a performance measure based on speed and recovery time compared to normal conditions. Lee et al. (2008) expanded and refined speed-based performance measures using 954 winter maintenance records in 24 counties in Wisconsin. Variables evaluated consisted of storm duration, maintenance operation hours, maximum speed reduction, and start/end of storms. Speed data was collected using ATRs. The average speed under normal conditions was estimated with hourly speed data from three dates before the beginning of the storm and three dates after the end of the storm. Storm dates used for average speed estimation were within three weeks before and after the storm. Figure 2.2 provides an updated diagram of speed reduction and recovery duration with variables of interest.

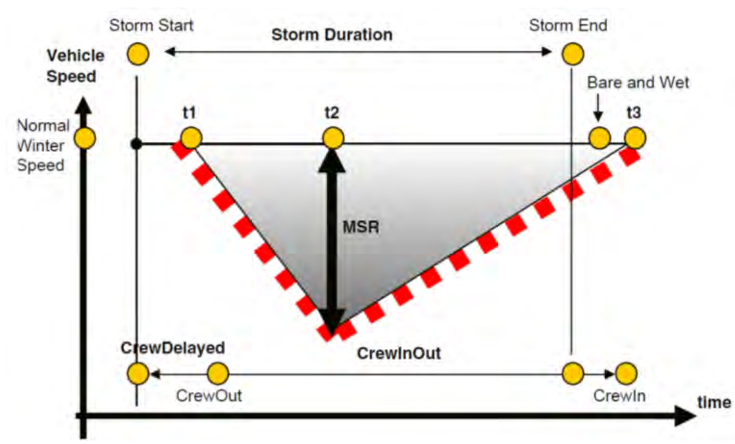

Figure 2.2 Diagram of speed reduction and recovery duration variables of interest (Lee et al. 2008).

The objective of the study conducted by Lee et al. (2008) was to find potential effects of winter storm related variables on the speed recovery duration and assess the potential of implementing speed-based performance measures in winter maintenance. A regression tree algorithm that combined traditional statistical approaches with machine learning was implemented. The maximum speed reduction as a percentage and time can be used as an index of winter severity and speed recovery duration as illustrated in Figure 2.3. Modeling results indicate that vehicle speed during winter storms was closely associated with pavement condition, and speed recovery duration was associated with maximum speed reduction, time to maximum speed reduction after the beginning of the storm, time lag to deploy maintenance crew after snowstorm starts, and snow precipitation. The results of the study confirmed that speed reduction is a good performance measure to evaluate winter maintenance operations (Lee et al. 2008).

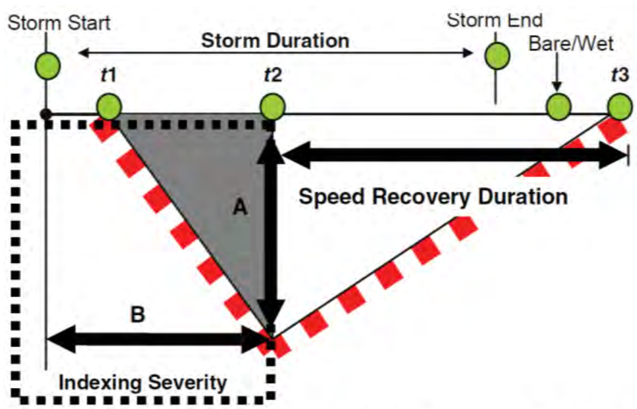

Figure 2.3 Speed recovery duration (Lee et al. 2008).

Thill and Sun (2009) collected data from two segments in Buffalo, New York and evaluated speed recovery through linear regression. The dependent variable was speed reduction as a percentage in reference to the baseline speed under normal conditions. Two speed recovery models were developed: during the storm and after the end of the storm. Predictor variables in the model included precipitation, accumulation, storm duration, storm intensity, past intensity, volume, and maximum/average/medium speed reduction. Two roadway segments with the same roadway classification were evaluated. Each roadway segment was maintained by a different agency with different response standards, so the performance of the two segments were compared. There was a very small difference (not statistically significant) of approximately 5.7% in loss of average speed between the two segments.

Bandara (2015) evaluated average travel speed and regain of speed time during winter maintenance operations of 22 storms on I-96 and US-23 in Michigan during the 2012-2013 winter season. Baseline average speed was estimated with speed data in 10-minute intervals over a three-year period. Average traveling speed during a storm was computed also in 10-minute intervals and compared to the baseline average speed. Regain of speed time was defined as the time between the end of the storm and the time when the average speed is within five mph of the baseline average speed for a period of at least one hour. Bandara (2015) proposed the performance measure “area”, which uses the average speed deviation from a baseline average to compute an area of variation that captures speed reduction and recovery time. However, units and interpretation of the "area" were not formally provided. Based on linear regression, the amount of snow was associated with speed and recovery time measures. Kwon and Park (2018) proposed the performance measure Normal Condition Regain Time (NCRT) which consists of estimating speed during the recovery process when reaching free flow conditions. A large amount of traffic, weather, and incident data was gathered from external databases including Intelligent Roadway Information System (IRIS) server from Minnesota Department of Transportation Regional Transportation Management Center (RTMC) and weather data from the National Oceanic and Atmospheric Administration (NOAA). A system was developed to integrate datasets and produce results automatically through a data management module with a user interface and server which processed the roadway network configuration, traffic, and weather data. The system was applied to a sample of storm events and provided estimates of NCRT. However, the causal relationship of the performance measure was not evaluated in relation to specific winter maintenance strategies (Kwon et al. 2012, Kwon and Park 2018).

2.2 Traffic Volume and Capacity

Weather may impact traveling speed, traffic volumes, or capacity. During rain fall, highway traffic volume decreases up to 2% depending on the precipitation rate. Traffic variations are also significant according to the time of the day (Keay 2005, Doherty et al. 1993, Codling 1974). During snow fall, Hanbali (1994) found that traffic volume decreases substantially by 7% to 56%. Similarly, Knapp (2000) obtained traffic volume reductions between 10% and 50%. In terms of likelihood to observe different traffic volumes during snowstorms conditions, it is common to observe very low traffic volumes than conditions with rain or no precipitation (ElDessouki, 2004). Figure 2.4 shows traffic flow conditions evaluated by Kwon and Fu (2012) in which capacity significantly reduces under snow conditions compared to clear conditions.

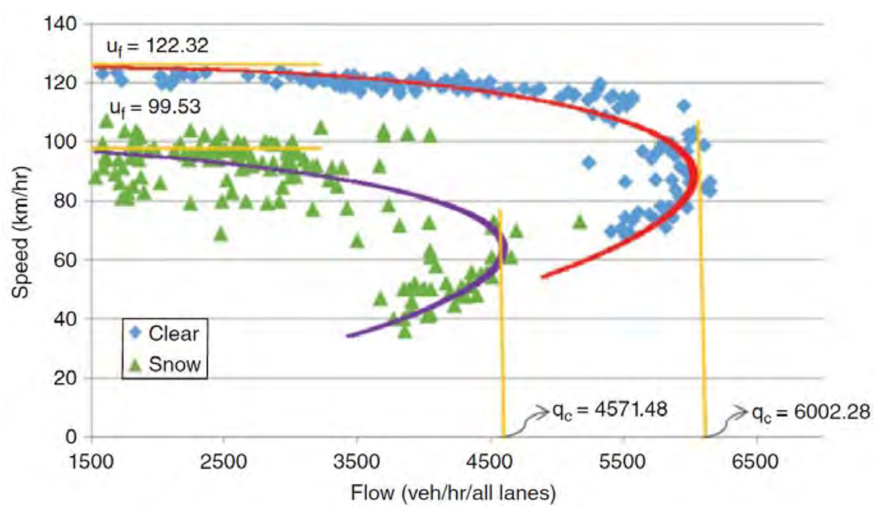

Figure 2.4 Effect of road weather conditions on free flow speed and capacity (Kwon and Fu 2012).

2.3 Traffic Delay

Traffic delay is the additional travel time experienced by a driver compared to normal conditions. Holik et al. (2015) evaluated the impacts of two types of winter maintenance equipment on vehicle delay. A plow capable of plowing two lanes in one pass was compared to a standard winter maintenance truck that covers one lane per pass. Speed data was collected using Bluetooth technology by placing one node at the location of entry and another node at the exit location of a segment with a known distance along the road between the nodes. The space mean speed of vehicles was calculated using data collected. To evaluate the impact of winter maintenance, equipment type, speed estimates, weather, and winter maintenance data were integrated. The performance measure consisted of the cumulative delay per mile. Results of the study indicated that the plow equipment that covered two lanes created a larger delay than the standard truck that covered only one lane. When heavy snowfall was considered, delay of both truck configurations was similar which indicated that the truck that covered two lanes was more effective with heavy snow conditions since the number of passes were significantly lower when compared with the truck just covering one lane.

Since field data may be difficult to obtain, simulation of winter storm events and impact on vehicle operations has been explored. Shahdah and Fu (2010) developed a microsimulation model to evaluate the mobility benefits of road winter maintenance. Traffic patterns were evaluated under adverse weather and roadway surface conditions. A segment in the Greater Toronto Area, Ontario was used to collect field data for calibration of the simulation model. Travel time and delay were estimated to evaluate performance. Results of modeling several scenarios indicated that strategies aimed at reaching bare/wet conditions during heavy snowfall had the potential of reducing total traffic delay by five to 36%.

2.4 Pavement Surface Friction

Friction has long been considered for evaluation of performance of winter maintenance. Al-Qadi et al. (2002) assessed the feasibility of implementing friction measurements to improve winter operations, specifically when deceleration contact devices were used. Recommendations were made to automate the process and ensure that contact device traction applied is beyond the point of slip. Similarly, Nixon (1998) examined the possibility of using fiction as an operational tool for decision making in winter maintenance, and Zein (2009) assessed the current use of friction in winter maintenance and how to improve quality standards. Recommendations were made for the considerations to integrate friction measuring devices and procedures into conventional winter maintenance operations. Fundamental questions were raised regarding the impact of friction on volume and speed.

Friction measurements can be described in terms of friction coefficient (μ), coefficient of static friction (μ_s), coefficient of kinetic friction (μ_k), coefficient of sliding friction (μ_{sf}), skid number (SN), friction number (FN), Halliday friction number, British Pendulum Number, International Friction Index, to mention some. The friction coefficient is the ratio of horizontal friction force to vertical load (usually less than one). The skid number is the friction coefficient multiplied by 100. Also, the Halliday friction number uses a scale of 0 to 100 (Fay et al. 2010). There are several devices to measure friction on roads including contact and optical devices. The operating principle for contact devices includes locked wheel, fixed slip, variable slip, and angled slip. Friction measurements can also be obtained with instrumentation to measure vehicle stopping distance or deceleration. Comfort et al. (2006) developed friction curves as a function of percentage of slip for different roadway conditions. Slip was defined as 0% for a rolling tire and 100% for a locked wheel. Figure 2.5 illustrates the variation of friction measurements to slip ratio under different roadway conditions (Nixon 1998).

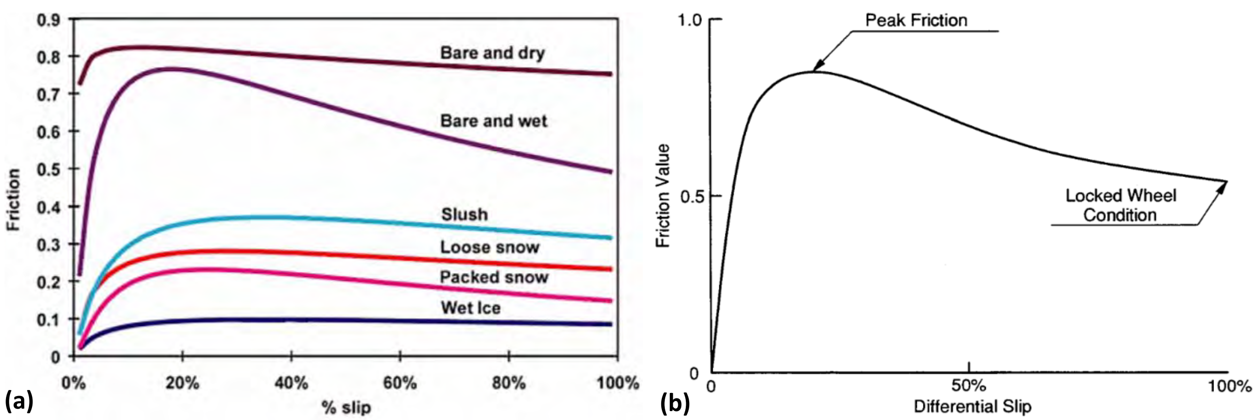

Figure 2.5 (a) Friction versus percentage of slip (Comfort et al. 2006) and (b) variation of differential slip (Nixon 1998).

Optical friction devices, such as the Mobile Advanced Road Weather Information Sensor (MARWIS), collect measurements of road surface dew point temperature, relative air humidity, water film height, ice percentage, and friction. The non-contact device captures optical measurements of the pavement surface condition and correlates these measurements to observed friction values under similar conditions to obtain friction estimates (grip) (Lufft 2019).

Bandara (2014) evaluated friction measurements behind a plow truck using a continuous measuring device. Friction measurements were evaluated with simultaneous visual inspection. Five categories of roadway condition were specified as illustrated in Figure 2.6. Data was collected from three storms during the 2013-2014 winter season in Livingston County, Michigan. Friction measurements were collected for 500 ft in 1,000 ft intervals with corresponding visual categorization of the roadway condition. The friction coefficient was associated with the roadway condition categorized from visual inspection.

Surface Condition	Description	Picture
Bare	Bare Pavement	
Centerline Bare (CL Bare)	Entire lane is cleared of snow, ice and slush.	
Wheel Track Bare (WT Bare)	Only wheel tracks are bare, snow/ice/slush in the other areas	
Loose Snow/Slush (Loose Snow)	Loose snow/slush covered	
Snow Covered (Snow)	Entire roadway is covered with packed snow and ice	

Figure 2.6 Winter pavement condition scale (Bandara 2014).

Standards are available for friction levels based on roadway condition and friction value. For instance, in Table 2.1, the Finish standards are provided by roadway condition and corresponding friction value ranges. Not slippery condition should be bare wet or bare dry conditions with friction values of 0.30-0.44 and 0.45-1.00, respectively.

Table 2.1 Friction values for different driving conditions in Finland (Zein 2009, Höyssä et al. 2001).

Description	Driving condition	Friction value
Bad driving conditions, wet ice	Very slippery	0.00-0.14
Icy	Slippery	0.15-0.19
Tightly packed snow	Satisfactory winter condition	0.20-0.24
Rough, packed ice and snow	Good winter conditions	0.25-0.29
Bare and wet	Not slippery	0.30-0.44
Bare and dry	Not slippery	0.45-1.00

Standards from Japan provided in Table 2.2, also provide different ranges of the friction coefficients associated with roadway surface classification consisting of ice film, crust, powder snow, granular snow, slash, wet, dry, and some other combinations. Wet and dry conditions were categorized as conditions with a friction coefficient greater than 0.45.

Table 2.2 Friction values for different roadway classifications used in Japan (Zein 2009, Al-Qadi et al. 2002).

Condition	Classification of road surface	Friction coefficient
1	Very slippery ice film	~ 0.15
	Very slippery ice crust	
	Very slippery compacted snow	~ 0.20
2	Ice crust	0.15 ~ 0.20
	Powder snow and ice crust	
	Ice film	0.15 ~ 0.30
3	Granular snow on ice crust	0.20 ~ 0.30
	Compacted snow	
4	Powder snow	0.25 ~ 0.35
	Granular snow on ice crust	
	Slash	
5	Wet	0.45 ~
	Dry	

2.5 Crashes

Winter maintenance safety evaluations are usually associated with crash rates which account for crash counts and traffic. Exiting literature of crashes in relation to adverse weather conditions suggest that weather is associated with an increase in the number of minor injury and property damage only crashes, and only a minor influence on severe injury or fatal crashes (Andrey 2003). Also, there are temporal variations such as 5.2% increase in crash rate observed during the night compared to 1.9% increase during the day with rain precipitation. The effect of inclement weather is more likely to reduce mobility by deterring traffic or reducing speeds than to increase crash occurrence (Andrey 2003, Qiu and Nixon 2009).

Eisenberg (2005) and Suggett (1999) found that the risk of fatalities was significantly higher on the first snowy day of the season compared to other days during the same season. Single vehicle crashes, locations with traffic control, and roadway segments with posted speed limits of 60 kph (37.3 mph) are disproportionally associated with snow events (Andrey 2003, Qiu and Nixon 2009). Lane (1995) found that driving maneuvers involving passing or lane change were especially hazardous during winter conditions and risk increased based on slush and snow build up between the right and left lanes and on the shoulders. An important factor in crashes observed during these weather conditions was excessive vehicle speed. Similarly, crash risk is particularly high during freezing rain and sleet events, and crash risk is low for drizzle or dry snow (Suggett 1999). Crash risk remains consistent even after precipitation ends which may be associated with accumulation of precipitation and remaining slippery roadway conditions. Qiu and Nixon (2009) reported that crash rates increased by 84% during winter storms compared to normal conditions.

Abohassan et al. (2021) collected information about weather, road surface conditions, traffic volumes, crash records, and the status of winter maintenance operations to evaluate the effects on pavement friction and traffic safety. Through Structural Equation Modeling and Path Analysis, precipitation, low temperatures, and black ice were found to have a negative effect. Anti-icing and plowing operations provided a positive effect on friction and safety. In a case study, anti-icing reduced

14% of crashes, plowing operations reduced crashes by 33%, and both anti-icing and plowing operations combined reduced 42% of crashes per storm.

Usman et al. (2010) quantified the safety benefits of winter maintenance through crash frequency modeling. Different data sources were used including weather, road condition observations, traffic counts, and crashes. The modeling approach consisted of evaluating a road surface condition index (RSI) as a surrogate measure of friction. Table 2.3 provides a summary of the RSI values according to road surface conditions.

Table 2.3 RSI based on road surface conditions (Usman et al. 2010).

Road surface condition	RSI range
Bare and dry	0.90-1.00
Bare and wet	0.80-0.89
Partly snow covered	0.50-0.79
Snow covered	0.25-0.49
Snow packed	0.20-0.24
Slushy	0.16-0.19
Icy	0.10-0.15

Events were defined based on weather conditions and road surface conditions. Each event was defined at the time when it started to snow/freezing rain, when snow/freezing rain stopped and a specific road surface condition was achieved, precipitation greater than zero, air temperature less than 5 °C (41 °F), and road surface conditions index value was not equal to bare dry conditions. Modeling approaches consisted of the Negative Binomial (NB) model, the generalized NB model, and the zero inflated NB model. Results of the study indicated that the road surface condition index had a statistically significant effect on crashes. Figure 2.7 illustrates the results with mean number of crashes, roadway surface condition, and traffic level.

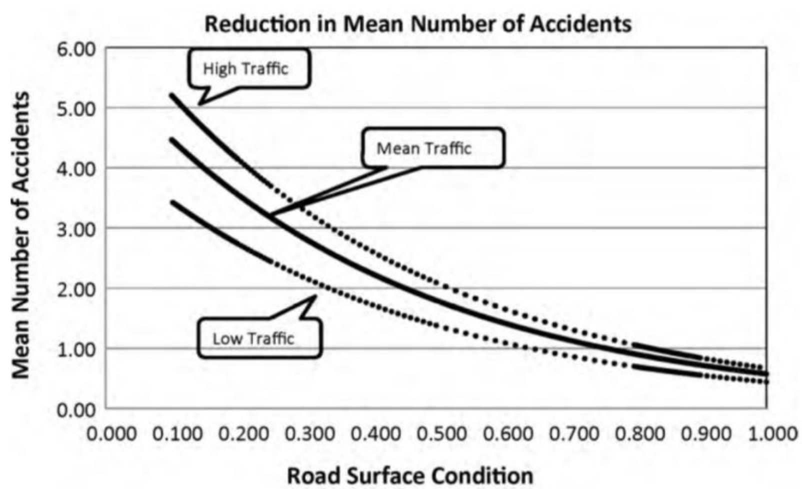

Figure 2.7 Crash frequency as a function of RSI (Usman et al. 2010).

Usman et al. (2012) further evaluated winter maintenance effects on safety at a disaggregate level. Crash frequency models were developed with data at the hour level on 31 routes in Ontario, Canada during six winter seasons between 2000-2006. The methodological approaches consisted of a multilevel Poisson Log-Normal model and a single level generalized NB model. The authors claimed that the findings of the study were the first to empirically show the relationship between safety and roadway surface conditions at the hourly level during winter storms. Statistically significant predictor variables in the models include the roadway surface index (RSI), visibility, precipitation intensity, air temperature, wind speed, storm hour, month of the winter season, and measure of exposure. Safety benefits were quantified for a case study in which the safety benefit of winter road maintenance was the difference of expected crashes with and without winter road maintenance over the storm period. The treatment consisted of plowing and salting. The case study is illustrated in Figure 2.8 which provides different time frames when the treatment is implemented and the effect on safety.

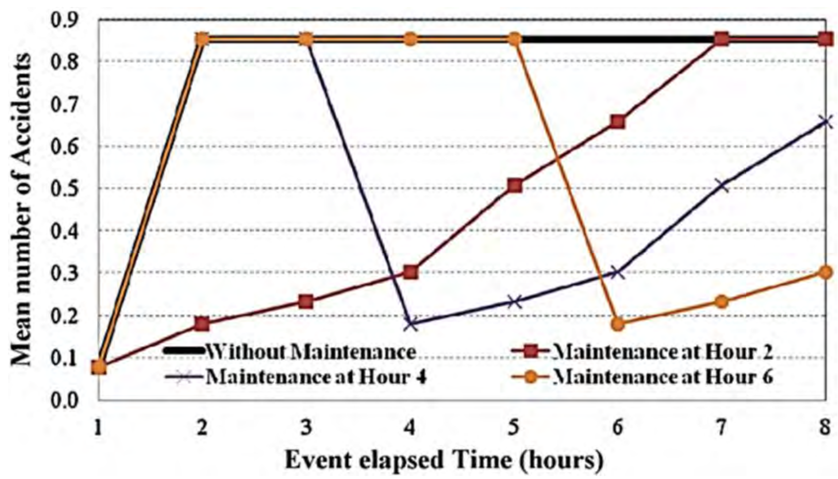

Figure 2.8 Mean number of crashes as a function of different winter maintenance timelines (Usman et al. 2012).

Based on a synthesis of existing literature, Strong et al. (2010) developed a conceptual framework of the effect that storm events have on mobility and safety. In Figure 2.9, Strong et al. (2010) indicated that weather severity has a direct impact on traffic mobility and safety, specifically on travel time and speed impacting crash rate or fatality rate.

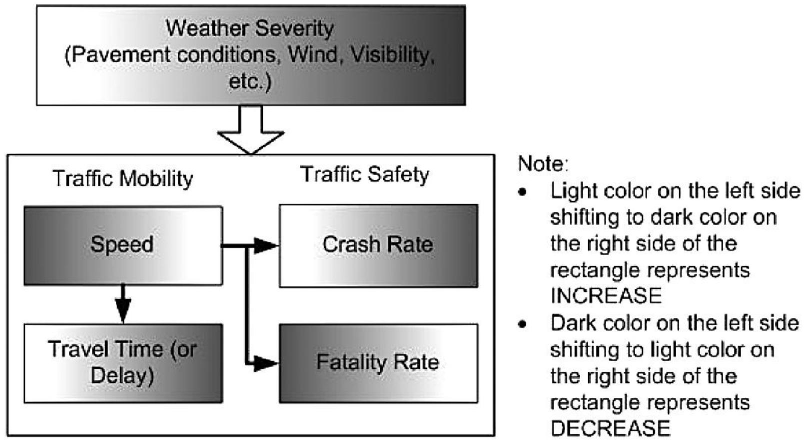

Figure 2.9 Conceptual framework of storm events (Strong et al. 2010).

2.6 Weather and Roadway Conditions

Several factors influence decision-making for the implementation of treatments in winter maintenance. Measures such as storm precipitation, pavement temperature, and roadway surface condition provide valuable information to determine the type of chemical material, rate, and frequency of application.

Existence guidance has different precipitation definitions and ranges to characterize various weather conditions. Precipitation parameters are presented in terms of intensity and type including light/medium/heavy snow, ice, frost, black ice, slush, sleet, and freezing rain. Pavement temperature is evaluated based on temperature range and trend. Temperature ranges are in reference to freezing temperature of water which is 32°F. For instance, Shi et al. (2019) provided guidance for application rates of liquid applications for pavement temperature ranges above 32°F, 25-32°F, 20-25°F, 15-20°F, 0-15°F, and below 0°F. Pavement temperature trend is evaluated as remaining within a temperature range, steady, rising, or falling. Pavement roadway surface conditions usually refer to dry, wet, slush, ice, and snow cover.

2.7 Surveys of Practice

Agencies have different administrative procedures and goals, so surveys of practice contribute to understand commonly used performance measures and resources required. Kipp and Sanborn (2013) conducted a survey of practice with 21 states and the main performance measures used were the following:

- Time to achieve bare pavement conditions after storm events ended
- Material used
- Storm severity classification
- Crash rates

Similarly, Dao et al. (2019) conducted a survey with 31 state departments of transportation (DOTs) on winter maintenance performance measures. The results of the survey indicated that agencies were highly dependent on weather information for planning rather than tactical purposes. The most common performance measures used for decision making were weather variables (snowfall, road temperature, and freezing rain), labor/equipment hours, and amount of material used. Xu et al. (2017) also conducted a survey of practice with 75 transportation agencies including state DOTs, local agencies (cities, counties), Canadian ministries of transportation, European agencies, and private firms. Through a ranking process, agencies were asked to evaluate different goals with a rating of 5 indicating "most important," and 1 indicating "least important" as illustrated in Figure 2.10. Most agencies ranked safety as the most important metric to achieve winter maintenance goals, followed by mobility and economy. Metrics such as the environment, infrastructure and livability were ranked as the least important.

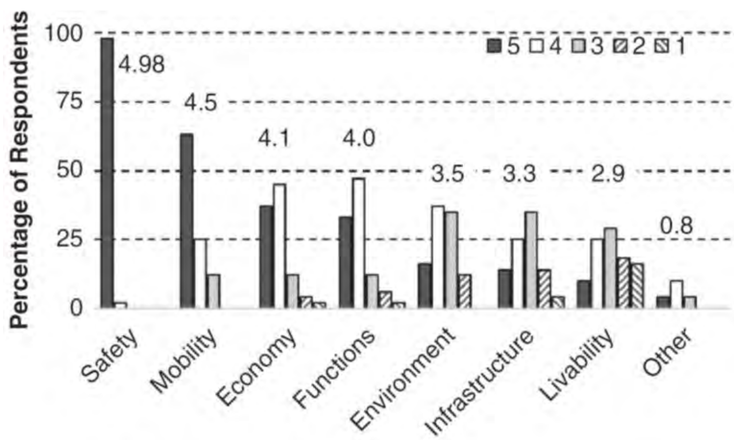

Figure 2.10 Rating distribution of performance goals (Xu et al. 2017).

Also, Figure 2.11 provides the distribution of performance measures considered by the different agencies surveyed (Xu et al. 2017). The most common metric was the time taken to achieve established LOS after a storm. The least common performance metric considered was friction.

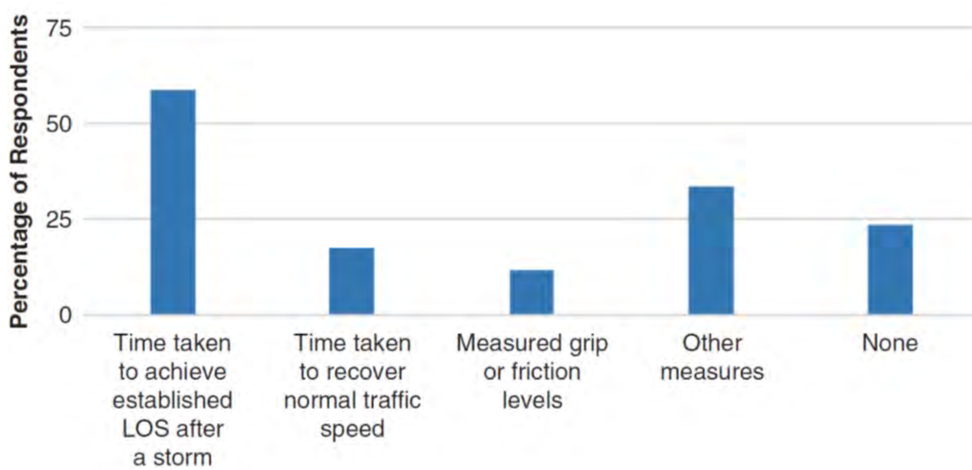

Figure 2.11 Distribution of performance measures considered by agencies (Xu et al. 2017).

Based on the responses from agencies, Xu et al. (2017) developed a typology matrix to classify performance measures as a function of cost as illustrated in Figure 2.12(a). For instance, material usage through automatic vehicle detection (AVL) technology and friction were the most expensive performance measures. Xu et al. (2017) also developed a qualitative comparison of timeliness, reliability, and effectiveness of performance measures as illustrated in Figure 2.12(b). Friction, time to speed, and system outcomes were qualitatively categorized as highly reliable and timely.

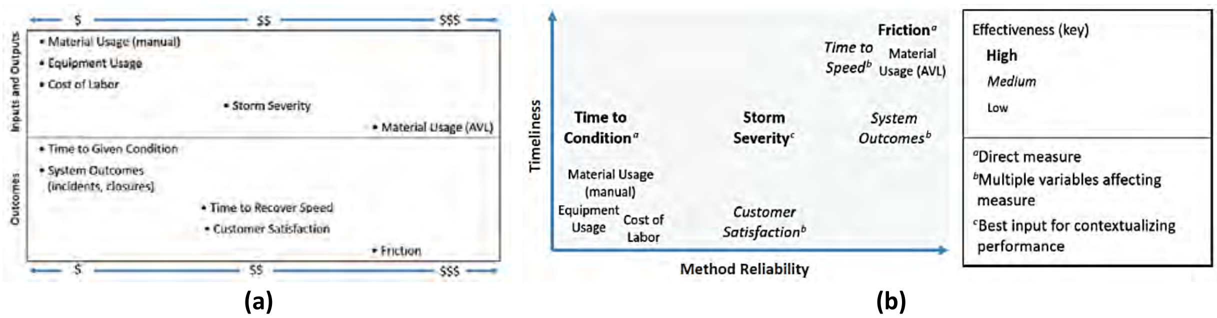

Figure 2.12 Performance measures (a) typology matrix and (b) qualitative comparison of timeliness, reliability, and effectiveness (Xu et al. 2017).

In NCHRP 889: Performance Measures in Snow and Ice Control Operations, several measures and indicators of performance were identified and were classified into the following categories (ICF et al. 2019):

- Storm characteristics/severity
- Material management
- Labor resource allocations
- Level of maintenance response
- Maintenance response outcomes
- Level of operational responses
- Traveler experience, mobility, and safety
- Cost, budget, and funding
- Transportation resilience
- Economic activity

Based on a categorization taxonomy and evaluation criteria, NCHRP 889 report identified core measures according to input-output-outcome-impact categories that fell under each category. As illustrated in Figure 2.13, a core set of measures were identified for safety, mobility, and sustainability. The term sustainability in the context of the research is defined from an agency's perspective of sustainable operations defined by their environmental stewardship, efficiency of response, and public satisfaction (ICF et al. 2019).

Figure 2.13 Core set of performance measures (ICF et al. 2019).

Based on the core set of performance measures, Figure 2.14 illustrates the application of performance measures as a function of the storm timeline.

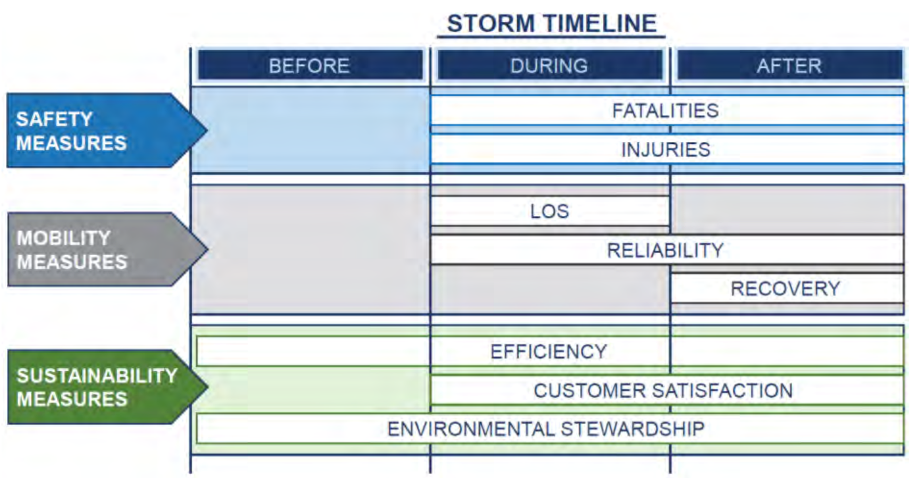

Figure 2.14 Applicability of performance measures with respect to the timeline of a storm. (ICF et al. 2019).

2.8 Chapter Summary

Winter storms have an impact on roadway operations and safety. Winter maintenance consists of treatment strategies that attempt to mitigate the effects of winter storms on the roadway surface to provide transitable and safe roadways. Quantifying the effectiveness of winter maintenance treatments is very challenging. There are several performance measures that have been traditionally used, and with new technologies and data sources becoming available, additional performance measures have been considered.

Performance measures that have been used traditionally focus on materials used, cost, time to accomplish specific roadway pavement surface conditions, storm severity, and crash rates. In terms of operational performance, traditional metrics do not directly capture the effect of treatments on operational conditions. Measure such as time to bare/wet is a subjective measure and depends on a person's opinion or agency standard. Safety measures are usually considered in prolonged periods of analysis to gather representative data. However, storm durations are not long enough, conditions are variable, and roadway geometry is not homogenous. It is challenging to gather a representative sample to conduct a rigorous analysis of crashes. Also, the measure of exposure such as traffic volume is significantly reduced during storms.

Roadway surface friction measurement has been considered a feasible performance measure. There are varied equipment and instrumentation types to collect friction data. Although friction data collection is very complex and may turn out to be expensive, there are guidelines for friction data collection. During winter storms, roadway conditions may be impacted or change over a short period of time. Also, roadway surface is not homogeneous across and along the roadway. Thus, frequency, sequence of events, roadway geometry, treatment, and location along and across the roadway surface has a significant influence on the friction data collected.

Travel speed seems to be a more feasible alternative to consistently monitor performance and the effectiveness of treatments during winter storms since there are automated processes for data collection and historical records. Travel speed has been evaluated with data from ATRs that estimate travel speed and count number of vehicle passing by a specific location on the roadway. Travel speed estimates provide a quantifiable measure to assess the impact of winter storms and the effect of winter treatments. Travel speed performance measures include maximum reduction in speed from normal conditions, rate of speed reduction and recovery, or time to return normal condition speeds. Although ATRs may not be available for most sections of road, databases such as the National Performance Management Research Data Set (NPMRDS) are available. The NPMRDS is a comprehensive nationwide database derived from probe vehicles containing information on speed and travel time with an extensive coverage of the roadway network in the United States.

Chapter 3: Survey of Practice

A survey of practice was conducted to gather agencies' performance assessment measures to quantify the effectiveness of winter maintenance treatments. Information gathered in Chapter 2: Literature Review was considered for the survey design. Survey questions were constructed and targeted to participants representing winter maintenance practitioners at the state and local level in a manner that contributes to the overall research plan and ensures the survey captures a wide range of experiences. This chapter presents the results of the survey.

3.1 Survey Design

The research team identified several performance measures that have been traditionally used, and with new technologies and data sources becoming available, additional performance measures have been introduced for winter maintenance. Questions were formulated based on the information gathered from the literature review to identify predominant agency practices, experience, policies, trends, performance measures and use, and data availability for the purpose of this study.

The survey was developed and supported in the online Qualtrics software, Version XM of Qualtrics. Copyright © 2023 Qualtrics. Qualtrics and all other Qualtrics product or service names are registered trademarks or trademarks of Qualtrics, Provo, UT, USA. https://www.qualtrics.com.

3.2 Survey Introduction

The first section of the survey included a brief introduction to the research project information and objectives. Figure 3.1 provides the survey introduction presented.

CLEAR ROADS

Evaluation of Direct Liquid Application of Salt Brine vs Granular Salt as Measured through Various Performance and Safety Metrics

Previous research on salt brine applications has shown reduced salt usage, shorter times to bare/wet, and higher pavement surface friction. Nonetheless, there are still concerns regarding operational and safety performance of roadways treated with salt brine. Commonly used performance measures in winter maintenance provide valuable information; however, some metrics are entirely subjective, rely on historical records, depend on agencies' practices, or only capture specific information. Therefore, this survey of practice intends to gather information about the experience of agencies with salt brine applications, performance measures used, and interest to contribute data to this research effort.

The survey should take less than 10 minutes to complete.

Project information: https://clearroads.org/project/22-04/

Note: This survey has been sent out to contacts from different organizations which may have some members in common. Thus, if you have completed this survey already, please, disregard this survey.

Figure 3.1 Survey introduction.

3.3 Survey Questions and Responses

The survey was divided into four sections: agencies' 1) winter maintenance practices, 2) performance measures, 3) data availability, and 4) contact information. A total of 28 responses were received state agencies, one international (Denmark), and one response was an undetermined location in the United States. Figure 3.2 illustrates the distribution of the 28 responses by state in the United States. Based on the responses to the survey, personal follow-up telephone calls were employed to coordinate field data collection and to clarify agencies' experiences and recommended practices.

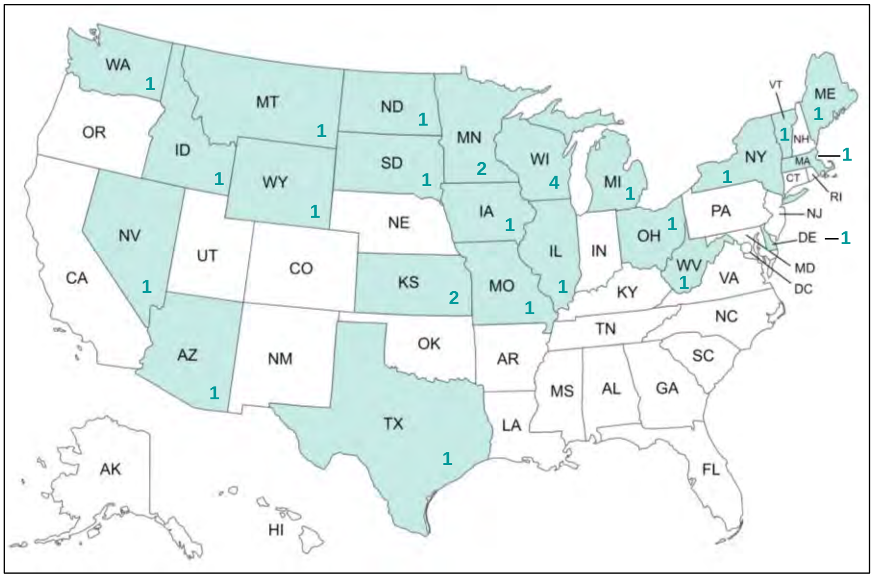

Figure 3.2 Geographical distribution of responses by state.

3.3.1 Agency Winter Maintenance Practices

Questions in this section of the survey intended to gather information about treatments implemented by agencies for anti-icing, deicing, and agencies' experience. For reference, the definitions provided in the survey are presented in Figure 3.3.

SECTION 1

Agency Winter Maintenance Practices and Experience

Anti-icing
Anti-icing consists of proactively applying chemical material to the roadway surface in anticipation of an imminent storm within 72 hours before the start of storm conditions to prevent or delay snow and ice bonding with the surface of the roadway.

Deicing
Deicing consists of actively breaking the bond between snow/ice and pavement surface through application of chemical material usually after mechanical removal (plowing).

Direct Liquid
Direct liquid is the application of chemical material in liquid form through spraying systems.

Prewet Material
Prewetting is the activity of adding liquid chemical solutions to solid chemical materials before the mixture is spread out on the surface of the pavement.

Shake and Bake
Simultaneous application of solid salt and spraying of liquid directly on the pavement.

Figure 3.3 Winter maintenance treatments definitions in the survey.

QUESTION 1

The question covered anti-icing treatments implemented by agencies, and among the alternatives provided, direct liquid application with salt brine was the most common anti-icing treatment. Some agencies implement direct liquid application with other chemical materials (i.e., Calcium Chloride), prewet salt, solid salt, or Shake and Bake with salt brine. There were no responses indicating the implementation of Shake and Bake with other liquid chemical materials (i.e., Calcium Chloride). Table 3.1 provides a summary of Question 1, alternatives, and response count. Other anti-icing treatments provided by respondents were:

- 85% NaCl brine + 15% of $MgCl_2$ (28% concentration) brine.
- Salt and sand mix and prewet with both brine and $MgCl_2$.
- Salt brine mixed with Geo Melt (beat juice).
- No longer perform anti-icing, but start treatments as soon as possible before storm.

Table 3.1 Results summary of Question 1 related to anti-icing treatments.

1. What anti-icing treatments are implemented by your agency in winter maintenance?	Count
Direct liquid (salt brine)	29
Prewet material (solid salt + salt brine)	8
Direct liquid (Magnesium Chloride, Calcium Chloride, or other)	7
Solid material (dry solid salt)	5
Prewet material (solid salt + Magnesium Chloride, Calcium Chloride, or other)	4
Other	4
Shake and Bake (solid salt + salt brine)	3
Shake and Bake (solid salt + Magnesium Chloride, Calcium Chloride, or other)	0

QUESTION 2

In this question, the types of deicing treatments used by agencies were covered. From the alternatives provided, direct liquid application with salt brine was the most common deicing treatment. Deicing with prewet material including salt brine or other liquid chemical materials were also representative among responses. Of all respondents, 14 indicated that direct liquid application with Magnesium Chloride, Calcium Chloride, or other chemical material was implemented at their agencies. Shake and Bake with salt brine was common with 11 respondents and it was less common with other liquid chemical materials, with only six respondents. Table 3.2 provides a summary of Question 2, alternatives, and response count. Other deicing treatments provided by respondents were:

- Ice Slicer or Ice Kicker.
- Salt and sand mix, and prewet with both brine and $MgCl_2$.

Table 3.2 Results summary of Question 2 related to deciding treatments.

2. What deicing treatments are implemented by your agency in winter maintenance?	Count
Direct liquid (salt brine)	27
Solid material (dry solid salt)	20
Prewet material (solid salt + salt brine)	20
Prewet material (solid salt + Magnesium Chloride, Calcium Chloride, or other)	16
Direct liquid (Magnesium Chloride, Calcium Chloride, or other)	14
Shake and Bake (solid salt + salt brine)	11
Shake and Bake (solid salt + Magnesium Chloride, Calcium Chloride, or other)	6
Other	2

QUESTIONS 3-5

Based on the responses to Questions 1 and 2, survey participants were asked to indicate how many years of experience their agency had with direct liquid (Question 3), prewet (Question 4), and/or Shake and Bake (Question 5) applications, as provided in Table 3.3. For direct liquid application, 67% of respondents indicated that their agencies had over five years of experience and approximately 20% of respondents had only two to three years of experience. In terms of prewet applications, 96% of responses indicated that agencies had more than five years of experience. Experience with Shake and Bake was more limited with only 12 respondents for this category. Five responses out of the 12 indicated that their agency had over five years of experience and the remaining seven responses indicated five or less years of experience.

Table 3.3 Results summary of Questions 3 to 5 regarding years of experience.

Approximately how many years has your agency implemented … applications?	3. Direct liquid		4. Prewet		5. Shake and Bake	
	%	Count	%	Count	%	Count
1 year	3%	1	0%	0	8%	1
2-3 years	20%	6	0%	0	42%	5
4-5 years	10%	3	4%	1	8%	1
More than 5 years	67%	20	96%	23	42%	5
Sum	**100%**	**30**	**100%**	**24**	**100%**	**12**

3.3.2 Agency Winter Maintenance Performance Measures

Questions in this section of the survey were aimed at gathering information about performance measures used by agencies to assess the effectiveness of winter maintenance treatments.

QUESTION 6

To gather information regarding performance measures, participants were asked to provide the metrics used by their agencies during and after winter storms. Respondents were provided with 18 potential metrics for multiple selection. Thus, from 30 respondents, the most common performance measure used in winter maintenance was the quantity of materials used, which was selected by 18 (60%) respondents. Time to bare-wet pavement and level of service (LOS) were also commonly selected by 16 (53%) and 14 (47%) respondents, respectively. Labor hours, travel speed, and pavement temperature were selected by 40-43% of respondents. Equipment hours, lane-miles plowed, and friction were relatively common with 30-33% of respondents. Crash-related measures, fuel usage, or customer satisfaction were less common (less than 20% response rate). Figure 3.4 illustrates the results to Question 6. Other performance measures provided by participants include:

- Plow speed, pre-wet application, and response time from the time an event begins.
- The percentage of time pavement is below 32°F with no ice or snow present during a storm event.
- Time to normal winter seasonal driving conditions.
- Wind Speed.

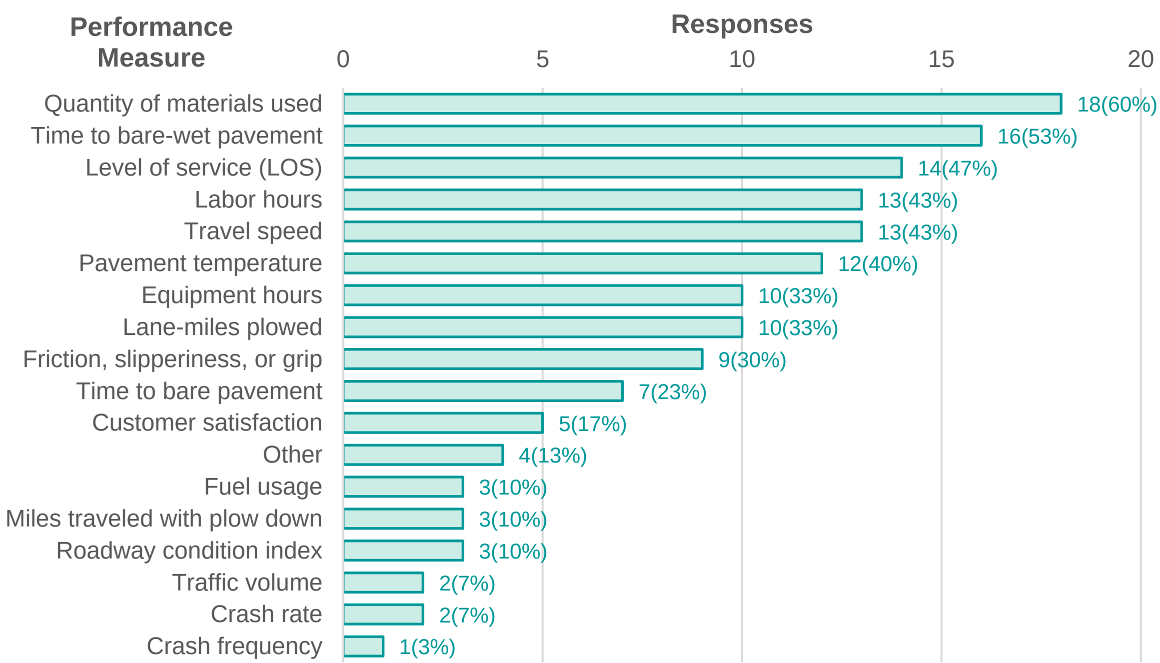

Figure 3.4 Results summary of Question 6 about performance measures.

QUESTION 7

Participants were asked to provide their agency's policy or guide to assess performance measures. Four respondents provided the following:

- Chapter 2: Snow and Ice Level of Service Data Collection Processes Statewide Weather Forecasting. Washington Department of Transportation.
- Winter Maintenance Policy. Rock County Department of Public Works, State of Wisconsin.
- Maintenance Operations and Procedures Manual. State of Montana. Montana Department of Transportation.
- Anti-icing/De-icing Guidelines. Arizona Department of Transportation.

QUESTION 8

Winter maintenance data may be collected through different technologies and methods. Most survey respondents (83%) indicated that visual inspection was the most common method to measure winter maintenance performance. Global Positioning Systems/Automatic Vehicle Location (GPS/AVL) is also another common technology used by 47% of respondents. Video is another method used to monitor performance as reported by 33% of respondents. Non-contact and contact friction devices were reported to be used by 20% and 3% of respondents, respectively. Figure 3.5 illustrates the results of Question 8. Other technologies or methods indicated by respondents were:

- Traffic Speeds.
- Data generated from Road Weather Information Systems (RWIS) stations.

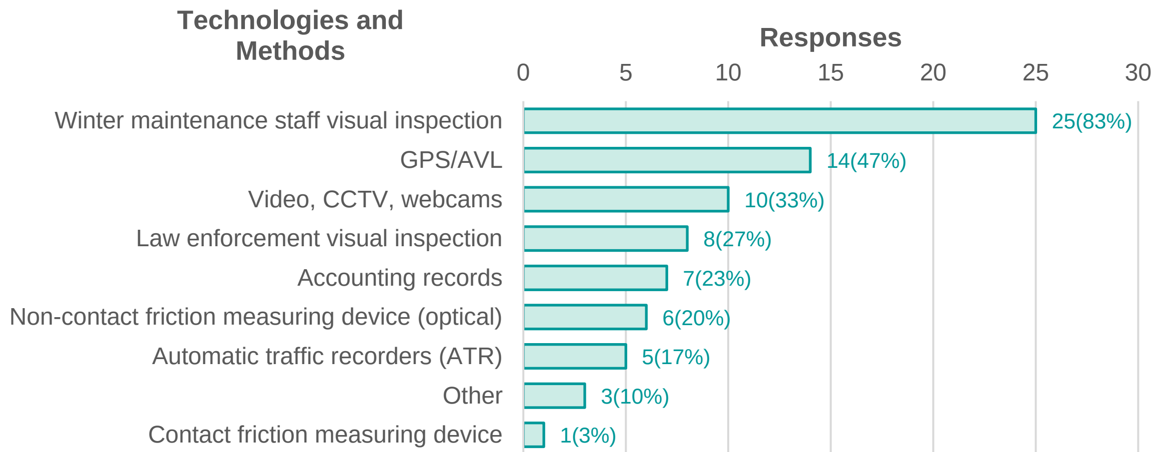

Figure 3.5 Results summary of Question 8 about technologies and methods.

QUESTION 9

Information of interest include performance measures monitored by winter maintenance agencies for decision making. From multiple selections, roadway condition was selected by 70% of respondents. Level of service (LOS), traffic flow, speed, safety, and amount of material used were selected by 50-57% of respondents. Cost, application rate, and effectiveness were performance measures monitored by 40% of respondents. The amount of labor employed and frequency of treatment implementation were less common with 27% and 7% of responses, respectively. Figure 3.6 illustrates the results of Question 9. Other performance measures monitored were not provided by respondents.

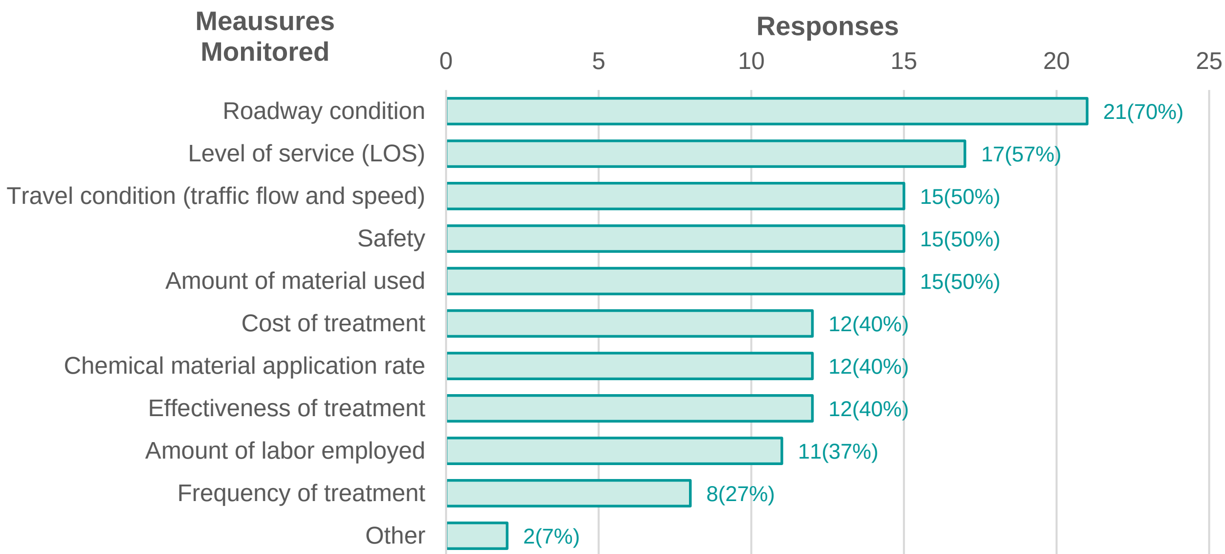

Figure 3.6 Results summary of Question 9 about measures monitored.

QUESTION 10

As part of the project, it is of interest to learn about agencies' studies or experiences. Thus, participants were asked if their agency had conducted a performance comparison of solid and liquid applications. Seven (23%) respondents affirmatively answered this question. Details provided by respondents are the following:

- Varies very much depending on temperature.
- Not exactly as worded. We compare the effectiveness of prewet granular salt to using dry salt. Districts that prewet salt note substantial salt savings compared to one that applies dry salt only.
- The result of the studies conducted concluded that direct liquid provides a quicker return to bare/wet pavement.
- The city has participated in a few Clear Roads studies and one through other agencies.
- We run 4 liquids only routes. showing a 38% savings in salt usage on each route. giving us an average of 8-10% total salt savings for the season.
- During the winter of 2021-2022 we rented a closed track to do a comparison between dry rock salt and a super saturated salt slurry. When arriving at the track in February, the track was completely snow covered- we drove around the track with 11 vehicles compacting the snow to the roadway. Then the plow was allowed to scrape the track and apply material- during this whole process there was friction readings, video and photo images, staff

observations and traffic was continuously moving during application. After the truck applied material, they were not allowed to scrape and or apply any more material for a minimum of 3 hours. On the supersaturated half of the track, application rate was reduced by 31%. The end result was that we used 31% less "salt" on the "slurry" side vs. the dry rock salt side. In terms of bare lane regain, the slurry half regained 33 minutes faster.

- We use less than 60% NaCl and less than 60% snow plow hours.

3.3.3 Data Availability

The data availability section of the survey is intended to gather information about data from agencies for this study. Desired data for the study include routes treated with salt brine, routes treated with solid salt, start/end of storms, performance measures, and GPS/AVL data.

QUESTION 11

To identify agencies for potential data collection, survey respondents were requested to provide information about the data their agencies have available. This section of the survey was only completed by 26 respondents. Data available in terms of route information, GPS/AVL, start/end of storms, chemical materials used per storm/route, and chemical material predominantly used per route were selected by over 65% of respondents in each alternative. However, performance measures for every storm event and route were only available for 15% of respondents. Other information provided indicated that data was not available by route. Figure 3.7 illustrates the results of Question 11.

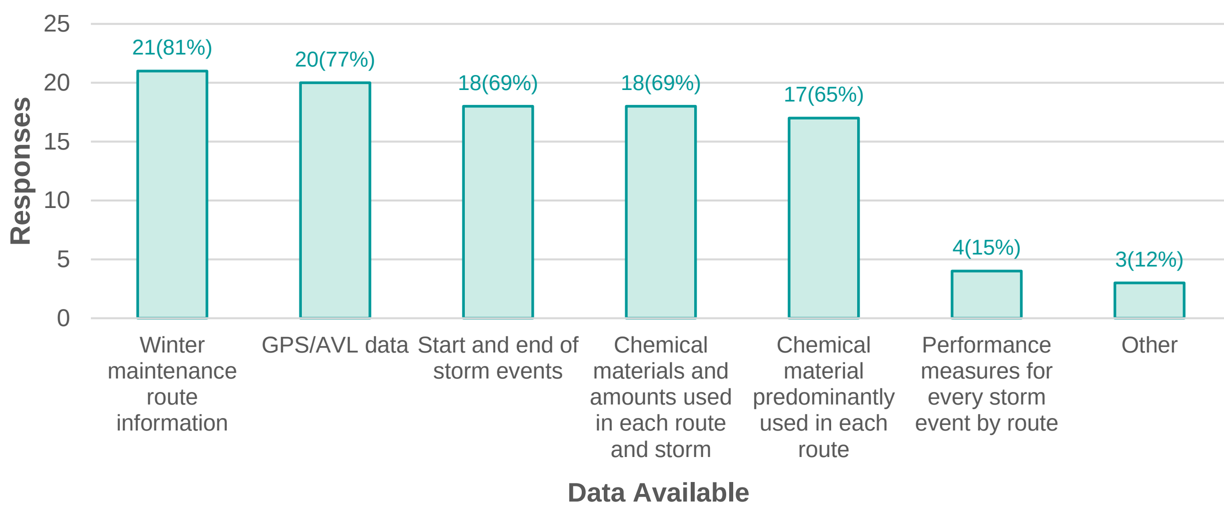

Figure 3.7 Results summary of Question 11 about data availability.

QUESTION 12

Participants were asked to indicate their willingness to share data for this project. This section of the survey was only completed by 26 respondents. Of responses received, 16 respondents indicated “Yes” and 10 “Maybe”. None of the responses were “No”.

3.3.4 Contact Information

Information from survey participants was collected to conduct follow-up calls to clarify responses and coordinate data collection.

QUESTION 13

Contact information of survey participants was requested including name, job title, agency, email, and telephone number. Contact information was available from 26 survey participants. Four respondents did not provide contact information or did not complete this section of the survey.

3.4 Chapter Summary

The survey of practice was conducted to gather agencies' predominant practices, experience, policies, trends, performance measures and use, and data availability. Key findings of the survey showed that:

- Direct liquid application with salt brine was the most common anti-icing treatment.
- Agencies have a diverse set of treatments with direct liquid, prewet salt, and solid salt applications. Shake and Bake was found to be less common.
- Respondents' agencies were overwhelmingly more experienced with prewet application and there was a relatively high number of respondents (67%) that had over five years of experience with direct liquid applications.
- The most common performance measure used in winter maintenance was the quantity of materials used, time to bare-wet pavement, and level of service. Travel speed was also a common performance measure among 43% of respondents.
- Visual inspection remains the most common method to measure winter performance. GPS/AVL is the second most common method to assess performance. Non-contact friction devices were reported to be used by 20% of respondents.
- Roadway condition was the metric most commonly monitored. LOS, traffic flow, speed, safety, and amount of material used were performance measures monitored by 50-57% of respondents.
- Route information, GPS-AVL, start/end of storms, chemical materials used per storm/route, and chemical material predominantly used per route are available from 17-21 (65-81%) respondents.
- Sixteen respondents were willing to provide data and 10 respondents indicated that may be able to provide data.

Based on the key findings of the survey of practice, there were agencies with vast amount of experience in direct liquid application, performance measures, and data collection. The research team identified agencies for potential data collection with study and control routes.

Chapter 4: Field Testing Protocol

The field-testing protocol was intended to lay out the procedure to collect field data to compare the field performance of salt brine with granular salt applications. Information gathered from the literature review and survey of practice; methods, technology, agency practices, and data available were considered for the development of the testing protocol.

The testing protocol consisted of gathering route information, route sampling of study and control locations, and data collection of materials used, storm data, and performance measures. Since agencies have different data available or willingness to accommodate specific data collection requirements, the research team categorized data as required and desired. Required data was essential to conduct the analysis, and desired data was used to supplement the analysis. Table 4.1 provides an overview of required and desired data.

Table 4.1 Required and desired data.

Data Type	Description	Frequency	Required	Desired
Route Information	Start/end of route	One time	X	
	AADT	One time	X	
	Number of lanes	One time	X	
	Functional classification	One time	X	
Treatment	Anti-icing or deicing	Every storm	X	
	Materials used	Every storm	X	
	Amount used	Every storm		X
	Application rate	Every storm		X
	Frequency of application	Every storm		X
	GPS/AVL	Every storm		X
Storm Conditions	Storm start/end	Every storm	X	
	Pavement temperature	60 min interval or range for every storm	X	
	Air temperature	60 min interval or range for every storm		X
	Type of precipitation	60 min interval or range for every storm		X
	Precipitation amount	60 min interval or range for every storm		X
Performance Measure	Time to bare/wet	Every storm	X	
	Travel time and speed	15-60 min interval for every storm and normal condition		X
	Traffic Volume	15-60 min interval for every storm and normal condition		X
	Friction	15-60 min interval for every storm and normal condition		X
	Road conditions rating	15-60 min interval for every storm and normal condition		X
	Crashes	Every storm and normal conditions		X

4.1 Route Information

Winter maintenance routing information was requested from agencies. Specific information of routes includes start and end of routes, geometry, functional classification, and annual average daily traffic (AADT). For reference, treatments commonly implemented or chemical materials predominantly used in each route were required to identify routes with salt brine and granular salt.

4.2 Route Sampling

Based on route information and review of existing route attributes, routes selection considered location, configuration, and chemical material used. Study routes are treated with salt brine and control routes are treated with solid salt. In the selection of routes, homogeneity, accessibility, and availability of data collection stations or National Performance Management Research Data Set (NPMRDS) data were considered. Homogeneity refers to sections of road that have consistent functional classification, operations, and geometry. Although not required, it was desired that segments have traffic and speed data collection stations at any point on the route. Similarly, it was desirable to have Maintenance Decision Support System (MDSS), AVL/GPS, friction, and crash data if available. Desired route characteristics consisted of segments:

- Ranging from three to 25 miles long with one to three lanes by direction,
- With varied functional classifications, geometry, traffic conditions, and speed limits, and
- From different geographical regions.

Pairs of study and control routes should be in the same vicinity, same county, or region and have similar roadway geometric, traffic, and weather characteristics. However, paired routes may not be available, and similarity of route attributes were considered to evaluate potential comparison routes. Three segment selection criteria were considered for study and control routes:

- **Parallel Routes.** For ideal conditions, multilane divided roadway segments may be used as study and control segments. One direction of travel may be treated with liquid application and the opposite direction with a baseline application. Selection of routes in parallel ensure consistent and accurate data collection under similar geometric, traffic, and environmental conditions for an ideal control experiment.
- **Split Routes.** The split route approach consists of dividing a route into two segments. One segment of the route may be treated with a baseline application and the other segment with liquid applications. This split approach provides proximity between study and control routes with similar conditions. Data must be collected at least 0.5 to 1 mile away from the junction of the study and control routes to prevent spillover of material from one section to the other which may provide inaccurate data for analysis.
- **Independent Routes.** Study and control routes in the same area, county, or region may not be available. Thus, routes may be selected based on similarity of geometric, operational, and weather characteristics.

4.3 Data Collection

The research team provided access to online forms (through Qualtrics) to collect material, storm conditions, and performance measure data.

4.3.1 Materials Used

For study and control routes, information about the treatments for each storm was required. Of primary interest was to know the amount of salt brine, granular salt, or other materials used in each storm. Additional information included the application rate and frequency of application of materials which was supplemented with GPS/AVL data to determine the time the plow truck and/or chemical material was applied.

4.3.2 Storm Conditions

Storm conditions refer to the characteristics of each storm in terms of the beginning and end of the storm, type of precipitation (wet snow, dry snow, freezing rain, sleet, lake effect), amount of snowfall or precipitation, pavement and air temperature, humidity, and wind speed and direction. Storm data conditions were required for study and control routes for hourly intervals (if available) or range of measures observed during the storm. For instance, the lowest and highest pavement temperature during a storm. Access to data from agencies enabled the research team to identify storms, evaluate storm events, and collect data for the project.

4.3.3 Performance Measures

Identified from the literature review and survey of practice, performance measures of interest for the evaluation of salt brine applications compared to granular salt in order of priority are:

- Time to bare/wet
- Travel time and speed
- Traffic Volume
- Friction
- Road conditions rating
- Crashes

4.3.3.1 Time to Bare/Wet

Effectiveness of winter treatments can be measured with the time from the beginning of the storm until reaching bare/wet conditions. Time to achieving bare/wet provides quantifiable performance of treatments.

4.3.3.2 Travel Time and Speed

For routes under study, travel times in five- or 15-minute intervals were considered for analysis. Ideally, agencies have sensors that collect these data in the routes of interest. Otherwise, the research team had access to the NPMRDS dataset to collect travel data and speed from an extensive coverage of the roadway network in the United States. Travel time and speed integrated with storm information and time to bare/wet is intended to be used to estimate travel disruption (TD) which is a performance measure proposed by the research team (Claros et al. 2024). The TD measures the impact of winter storms on travel speed by calculating the area generated by the difference in speeds between normal and storm conditions. The performance measure represents the additional travelled distance that could have been covered during the same time and travel speed under normal conditions. The TD metric provides a more integrated understanding of the storm's effect on performance, by considering different storm elements, such as intensity, duration, and intermittence. Ultimately, the TD can be used to estimate the average travel time lost during a storm, based on the speed values for normal conditions. More details about the TD metric are provided Chapter 6: Data Analysis.

4.3.3.3 Friction

Friction may not be readily available at all agencies since it requires specialized equipment and procedures. The research team has experience working with friction data, so the research team was able to work closely with agencies that had friction data collection devices and were willing to collect data. The route set up for friction data collection consisted of having salt brine treatment on one section or direction, and granular salt on the other section or direction of the roadway. Some considerations for friction data collection include included that sections of road should not exceed five miles, friction data collection at study and control should be conducted by the same unit and continuously throughout the two routes. To facilitate the process and planning, friction data should be collected based on anticipated weather conditions that will contribute to the diversity and quality of the data collected. Thus, friction data should be collected during the following times:

- **Before the Storm.** One to two hours before the anticipated start of precipitation. If inti-icing is implemented, data collection should be conducted right before application of the anti-icing chemical material.
- **During Storm.** The frequency of data collection depends on the time interval when plowing and application of material is implemented. Thus, at least two data collection runs should be conducted between treatment cycles. Each reading should be at least 10 minutes after and before treatment application. Thus, data collection should be conducted in intervals of 10-30 minutes.
- **After Storm.** If the storm event duration is short (less than five to six hours), friction data will be collected for intervals of 10-30 minutes after the end of the storm or when the last treatment is applied.

Figure 4.1 illustrates an example where the frequency of application of chemical material is 50 minutes, and the friction data collection is conducted in intervals of 20-30 minutes. In terms of roadway condition rating, friction measuring devices have proprietary processes that integrate different sensor data to estimate the condition of the roadway and provide a rating as function of friction which can be part of the road performance analysis.

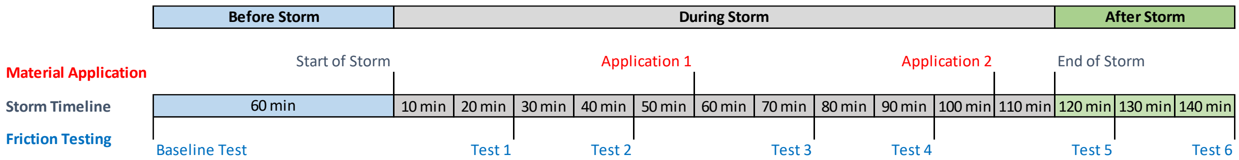

Figure 4.1 Storm, material application, and friction data collection timeline example.

4.3.3.4 Crashes

Crash data is limited in reduced periods of time such as winter storms. Also, depending on the state, crashes during winter storms may not be attended to by law enforcement and crashes may be self-reported or not reported at all. First, data was requested from agencies willing to provide crash data and the research team explored ways to analyze crashes in terms of winter maintenance treatment with salt brine and granular salt. Winter storm crashes were evaluated under storm and normal conditions. Crash analysis tried to identify contributing conditions in which traffic is most vulnerable to crashes. Safety surrogates have gained popularity for their capacity to estimate risk of crashes in the absence of sufficient crash data. Speed measurements were explored to categorize the effect of winter conditions and subsequent liquid applications on traffic speed. Thresholds of weather conditions and speed values were explored to determine crash risk. Traveling speed or pavement friction may also be used as safety surrogates to estimate the degree of risk during storm conditions compared to normal conditions. At the same time, GPS/AVL data were collected to record timestamps when trucks plow and apply chemical materials at segments, so safety measures could be evaluated in a time series format related to the effect of the treatment. The safety analysis depended on crash data availability.

4.4 Outreach

Based on the survey results, the research team reached out to agencies willing to provide data to request additional information. The research team also reached out to agencies with known experience and application of salt brine with collaboration of Clear Roads project panel. In total, 27 agencies were contacted. Virtual meetings were arranged to go over the data collection requirements with agencies that responded and could potentially collect data. However, due to the data requirements, lack of friction equipment, routing, equipment, and staff time, most agencies were unable to accommodate our data collection protocol and the study/control route set up. With the support of the Wisconsin Department of Transportation (WisDOT), there were initially three counties in Wisconsin (Jefferson, Sheboygan, and Rock) with friction devices, willing to conduct the field tests during storms. Unfortunately, Rock County was not able to collect field data, and only Jefferson and Sheboygan counties were able to collect field data during storms at parallel study and control routes the 2024-2025 winter season. Alternatively, RWIS data containing friction data were pursued, and Wisconsin and Iowa Departments of Transportation were able to collect historical data for analysis.

4.5 Chapter Summary

Chapter 4 outlines the protocol developed to compare the field performance of salt brine DLA and granular salt for winter road treatments. Based on the literature and agency practices, the protocol involved collecting route information, selecting comparable study and control routes, identifying materials used, storm conditions, and performance metrics. Routes were chosen based on geometry, traffic, weather conditions, and data availability. Data collection focused on treatments, storm details and performance measures. Agencies were provided online tools to submit data, and friction data was collected under specific timing protocols. Despite an extensive outreach effort, only Jefferson and Sheboygan counties in Wisconsin were able to accommodate the protocol and data requirements to conduct testing during the 2024–2025 winter season. To supplement the analysis in this project, historical RWIS data containing friction was also collected from Wisconsin and Iowa.

Chapter 5: Field Data Collection

The field data collection consisted of historical records and gathering route field information of the amount of materials used, storm data, and performance measures at study and control routes. Data was collected from study and control routes in Jefferson and Sheboygan counties in Wisconsin. Historical storm, RWIS, and AVL data were also obtained from Wisconsin and Iowa. Details of the data collected are provided in the following sections.

5.1 Study and Control Routes

Based on route information and review of existing route attributes and coordination with agencies, parallel routes were established in Jefferson and Sheboygan counties in Wisconsin. The research team verified that the routes had mobility performance measures data available in the National Performance Management Research Data Set (NPMRDS).

Multilane divided roadway segments were used as study and control segments. One direction of travel was treated with salt brine direct liquid application and the opposite direction with solid salt. Selection of routes in parallel ensured consistent and accurate data collection under similar geometric, traffic, and environmental conditions for an ideal controlled experiment. The following data was submitted by counties for every storm:

- Storm start date
- Storm end date
- Storm start time (hour:minutes)
- Storm end time (hour:minutes)
- Type of precipitation
- Storm snow accumulation (inches)
- Roadway surface conditions
- Pavement temperature (°F)
- 23% Sodium Chloride (NaCl) brine (salt brine) in gallons (gal)
- Salt brine application rate (gal/ln-mi)
- Solid salt (dry) in tons (tn)
- Solid salt (pre-wetted) in tons (tn)
- Pre-wet agent (salt brine) (gal/tn)
- Solid salt application rate (lb/ln-mi)
- Application frequency (min)
- Time bare/wet accomplished (hour:minutes)
- Comments
- File upload

5.1.1 Jefferson County

The route in Jefferson County was located on STH 26 between Rock County Line Rd and Old 26 bridge (approximately 3.3 miles). One truck with the capacity to carry 800 gallons of brine and 14-16 tons of solid salt was used. The truck was equipped with a Mobile Advanced Road Weather Information Sensor (MARWIS) friction device and data was automatically uploaded to ViewMondo via cellular connection. Using the NPMRDS dataset, vehicle speed was also collected, and AVL data were collected to record the time the treatments were implemented in storms events. Field data were collected for five storms.

Figure 5.1 Jefferson County study and control route.

5.1.2 Sheboygan County

The route in Sheboygan County was located on STH 23 between County Road P and County Road O (approximately 3.0 miles). One direction of travel was treated with salt brine DLA and the other direction with solid salt. A patrol vehicle was equipped with a MARWIS friction device and data was automatically uploaded to ViewMondo via cellular connection. Friction data was collected for six storms and the county only submitted storm data for one storm. NPMRDS data and AVL were not available for the periods of analysis in Sheboygan.

Figure 5.2 Sheboygan County study and control route.

5.2 Roadway Weather Information Systems (RWIS) Stations

Continuous weather data and pavement friction data were collected from RWIS stations in Iowa and Wisconsin. Using the NPMRDS dataset, vehicular speed was also collected at roadways adjacent to the RWIS stations. Additionally, AVL data were collected to record the time the treatments were implemented during storms events. Intervals of data recorded by RWIS station were six minutes in Iowa and ten minutes in Wisconsin. RWIS stations provided continuous data at a fixed point of the road to assess the performance of roadway conditions and treatments during winter storms. Materials used in winter maintenance during the storms consisted of salt bring DLA for anti-icing and prewet salt for deicing. Anti-icing was only implemented in Iowa. Complete data (storm, weather, friction, AVL, and vehicle speed) was available for a total of eight storms, four storms at each RWIS station. Data collected include the following information:

5.2.1 RWIS Information

5.2.1.1 Storm Data

Storm id

Winter supplement id

Precipitation start time
Precipitation end time
Precipitation type
Air temperature
Pavement temperature
Wind direction
Wind velocity
Visibility type

5.2.1.2 Weather Data

Station id
Latitude
Longitude
UTC time
Precipitation last start
Precipitation last end
Precipitation type
Precipitation intensity
Precipitation rate
Accumulation ten minutes
Accumulation one hour
Accumulation three hours
Accumulation six Hours
Accumulation twelve hours
Accumulation twenty four hours
Temperature
Dew point
Pressure sea level
Wet bulb temperature
Relative humidity
Visibility
Wind direction
Wind gust
Wind speed

5.2.1.3 Friction Data

Station id
Sensor id
Sensor name
Latitude
Longitude
UTC time
Surface condition
Friction
Road temperature
Bridge temperature
Freeze temperature
Chemical percentage
Chemical factor
Water level
Ice percent
Conductivity
Salinity
Sensor error

5.2.1.4 AVL Data

A number
Start time
End time
County id
Route id
Route name
Start post
End post
Solid
Solid quantity
Liquid
Liquid quantity
Prewet
Prewet quantity

5.2.2 Iowa RWIS

Historical RWIS data from three stations in Iowa (2019-2023) and four stations in Wisconsin (2024-2025) were collected. After data processing and review, only one station in each state were found to have data required for analysis. In Iowa, only one RWIS station had friction measurements and only the winter of 2019-2020 had numerical friction values. After 2020, friction was recorded with categorical measures of low, medium, and high. In Wisconsin, only two stations had stable friction measurements. Only one of these two stations had speed data available for analysis, which resulted in only one station with complete data.

The station in Iowa was RWIS IA005, located northbound of I-35 at NE 36th St in Ankeny, IA. Figure 5.3 provides aerial and street view imaging of the Iowa RWIS station. The RWIS station was located in the transition between the overpass bridge to the roadway on NB I-35. The device collected two separate friction measurements, one for the bridge and another for the roadway. The roadway was divided with two lanes in the NB direction, 22 feet left/right shoulders on the bridge transitioning to 12 ft left/right shoulders on the roadway. There was complete data for four storms.

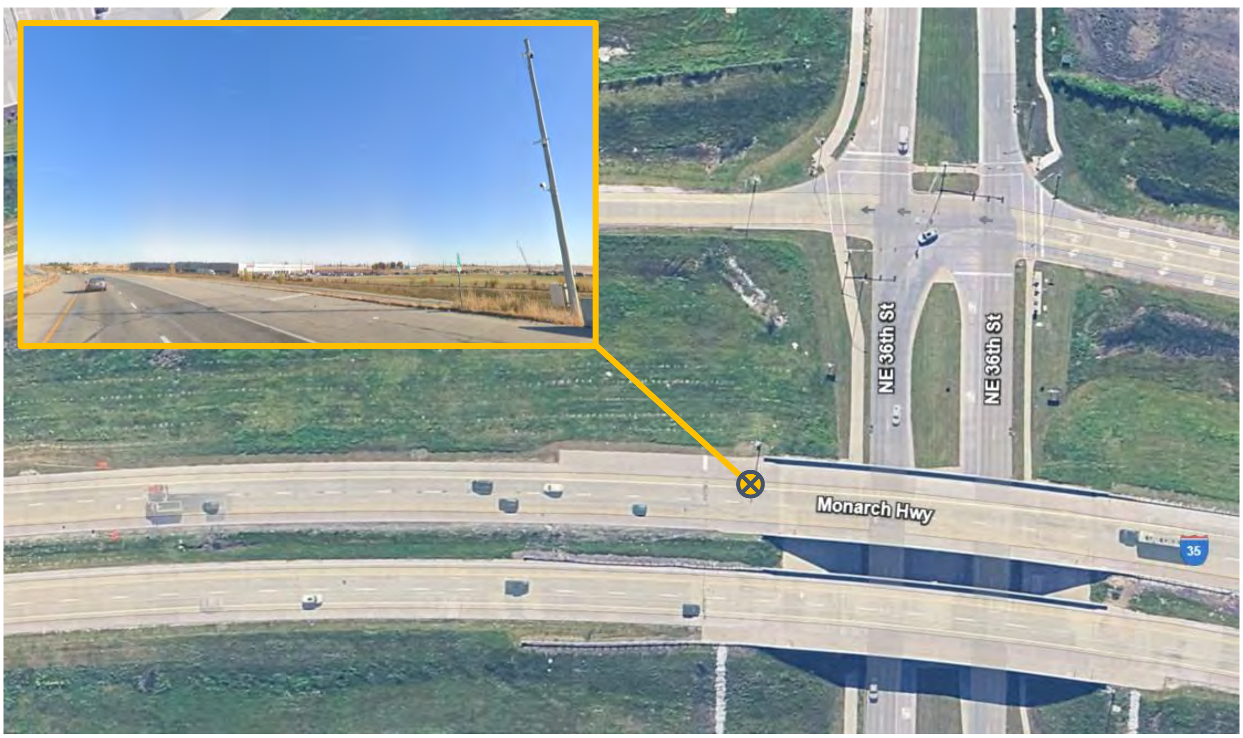

Figure 5.3 Iowa RWIS IA005 station location and street view (I-35 at NE 36th St in Ankeny, IA).

5.2.3 Wisconsin RWIS

The station in Wisconsin was RWIS MSAW3, located westbound of US-10/WI-441 at I-41/US-41 in Neenah, WI. Figure 5.4 provides aerial and street view imaging of the Wisconsin RWIS station. The RWIS station was also located in the transition between the overpass bridge to the roadway on WB US-10/WI-441. The device also collected two separate friction measurements, one for the bridge and another for the roadway. The roadway was divided with two lanes in the WB direction, 9 ft right shoulder and 6 ft left shoulder on the bridge transitioning to 12 ft right shoulder and 4 ft left shoulder on the roadway. There was complete data for four storms.

Figure 5.4 Wisconsin RWIS MSAW3 station location and street view (US-10/WI-441 at I-41/US-41 in Neenah, WI).

5.3 Chapter Summary

Data was collected from study/control routes in Wisconsin and historical records in Iowa and Wisconsin. Data included storm, weather, friction, truck AVL, NPMRDS speed data. There were two pairs of study and control routes in Jefferson and Sheboygan counties in Wisconsin. There was data for five storms in Jefferson County and six storms in Sheboygan County. Historical records included data between 2019-2023 at three RWIS stations in Iowa and between 2024-2025 at four RWIS stations in Wisconsin. Only one RWIS station in Iowa and one RWIS station in Wisconsin had complete data available. Data were available for a total of eight storms, four storms at each RWIS station.

Chapter 6: Data Analysis

The research team collected and evaluated data at parallel study routes with direct liquid application of salt brine and control routes with dry granular salt treatments in Jefferson and Sheboygan counties in Wisconsin, during the 2024-2025 winter season. The research team also collected data from roadways adjacent to Roadway Weather Information Systems (RWIS) stations in Iowa and Wisconsin with prewet salt treatments to evaluate roadway friction and vehicular speed as a function of storm conditions in a time series format. In this study, pavement friction refers to estimates obtained from optical devices that are also referred to as grip values. This chapter presents the analysis conducted for study and control routes, and the analysis of RWIS stations' historical data.

6.1 Study and Control Routes

Performance measures evaluated to compare study and control routes included pavement friction, vehicular speed, and time to bare/wet. The evaluation of crashes was not possible due to the limited number of crashes during the periods of evaluation.

6.1.1 Pavement Friction

Based on agency practices and storm conditions at the routes in Jefferson and Sheboygan counties, the agencies ran tests by applying salt brine in the study routes and solid dry salt in the control routes during the same period and storm conditions. The friction device used in this research was the Mobile Advanced Road Weather Information Sensor (MARWIS) from Lufft (Lufft 2025). The friction device was mounted on the treatment truck in Jefferson County and on a patrol vehicle in Sheboygan County. A pass is defined as friction data collected during the traversal of the device/truck through the study or control route. In Jefferson County, friction data was collected during the storm while in Sheboygan County, the agency collected friction data right before the first treatment and cycled through the routes for an hour or before the next treatment. The objective in Sheboygan County was to collect short interval friction data before and after the initial treatment; however, the storm conditions, route cycle interval, and frequency of treatment limited the number of observations within that time frame.

Table 6.1 provides a summary of the storm conditions and treatment details. Friction data was collected for five storms in Jefferson County and six storms in Sheboygan County. Snow accumulation during the storms ranged between 0.5-5.0 in, pavement temperatures ranged between 15-36 °F, application rates of dry salt on control routes were 200-300 pounds per lane-mile, direct liquid application rates of salt brine on study routes were 35-50 gallons per lane-mile, and the frequency of application ranged between 30-120 minutes.

Table 6.1 Friction storm conditions and treatment details.

County	Date storm start	Snow accumulation [in]	Pavement temperature [°F]	Application rate		Application frequency [min]
				Control route [lbs/ln-mi]	Study route [gal/ln-mi]	
Jefferson	11/21/2024	4.0	30-36	200	45	120
	12/18/2024	0.5	29-31	200	45	60
	12/19/2024	5.0	25-29	200	50	60
	1/10/2025	0.5	20-21	300	50	30
	2/2/2025	1.0	29-33	200	35	90
Sheboygan	2/2/2025	1.0	27-28	200	50	60
	2/8/2025	1.0	24-32	200	50	60
	2/11/2025	1.0	15-20	200	50	60
	2/12/2025	5.0	19-20	200	50	60
	2/13/2025	1.0	15-20	200	50	60
	3/20/2025	4.0	28-29	200	50	60

Notes: in = inches, °F = Fahrenheit degrees, lbs/ln-mi = pound per lane mile, gal/ln-mi = gallons per lane mile, min = minutes.

Additional details of the friction data collected are provided in Table 6.2. During the five storms in Jefferson County, there were a total of 62 passes (4-28 passes per storm) which resulted in 2,350 friction observations on the control route and 2,819 observations on the study route. Similarly, data collected during the six storms in Sheboygan County included 28 passes (2-9 passes per storm) which resulted in 680 friction measurements on the control route and 719 measurements on the study route.

Table 6.2 Control and study friction data.

County	Description	Control route	Study route
Jefferson	Friction observations	2,350	2,819
	Storms	5	
	Passes	62	
	Passes per storm	4-28	
	Data collection unit	MARWIS on treatment truck	
	Data collection period	During the storm	
Sheboygan	Friction observations	680	719
	Storms	6	
	Passes	28	
	Passes per storm	2-9	
	Data collection unit	MARWIS on patrol vehicle	
	Data collection period	One hour, starting right before first treatment	

Note: MARWIS = Mobile Advanced Road Weather Information Sensor, © 2025 Lufft.

Evaluation of friction observations requires careful considerations because in each pass many friction measurements were collected, and several factors could have influenced the variability of these measurements. The location and direction of aim of the device, calibration, data collection vehicle, irregular and inconsistent accumulation of snow and ice, pavement surface variation and irregularities (joints, tire tracks, pavement marking) can provide different friction measurements. Therefore, the mean (average) of friction measurements in a pass was used as representative measure of the friction conditions on a route. The mean is a point estimate that has a corresponding standard deviation that quantifies the variability or spread of observations for the given mean. The mean friction estimates are provided in Figure 6.1 (Jefferson County) and 6.2 (Sheboygan County) at control and study routes for every storm. These results should be interpreted with caution since they only illustrate the mean, and the standard deviation (variability) is not represented in the plot. The following sections will cover the effect of variability of observations with mean estimates, heterogeneity, additional illustrations, and comparison of measurements between control and study routes.

The mean friction values follow similar trends over time. Since the test design was different in each county, Jefferson County routes included Automatic Vehicle Detection (AVL) data of the truck. There were instances in which either the truck did not record friction measurements and AVL data was available, or friction measurements were recorded and there was not AVL data of the vehicle going through the route. The friction device was mounted on the truck in Jefferson County, and it was the only unit treating the route. In the case of Sheboygan County, AVL data was not relevant since the patrol vehicle collected friction measurements right before the treatment, for an hour, and before the next treatment.

The main distinction among mean friction values is the magnitude difference between Jefferson and Sheboygan County routes. Jefferson County mean friction value ranged between 0.4-0.8, whereas Sheboygan County mean friction values ranged between 0.2-0.5. The friction device installation configuration or calibration may have played a role in the lower range of measurements in Sheboygan County. Although the mean friction values from Sheboygan County routes were lower compared to Jefferson County routes, the friction measurements were consistent and deemed reliable in the context of the relative comparison of the control and study routes.

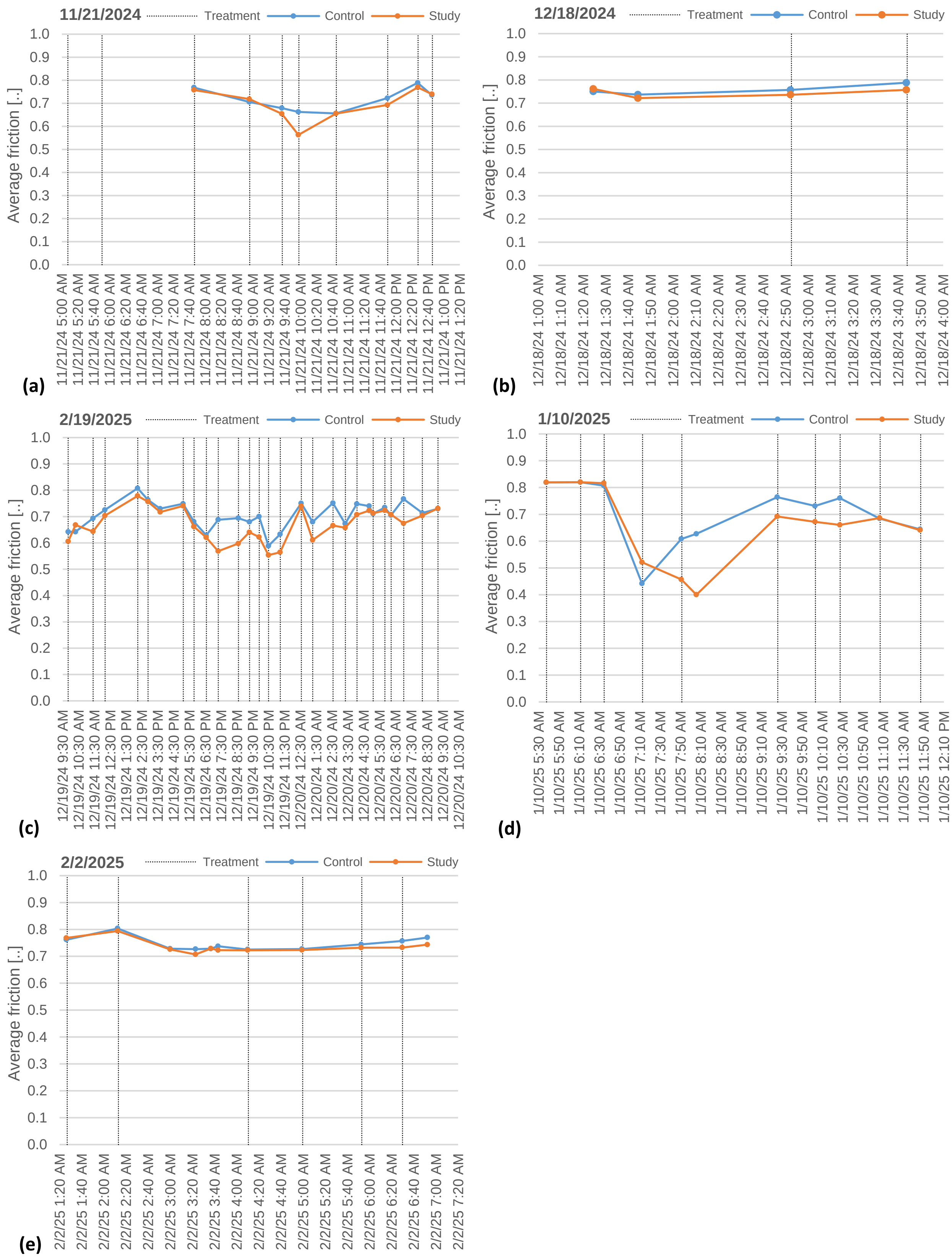

Figure 6.1 Jefferson County mean friction by storm and route.

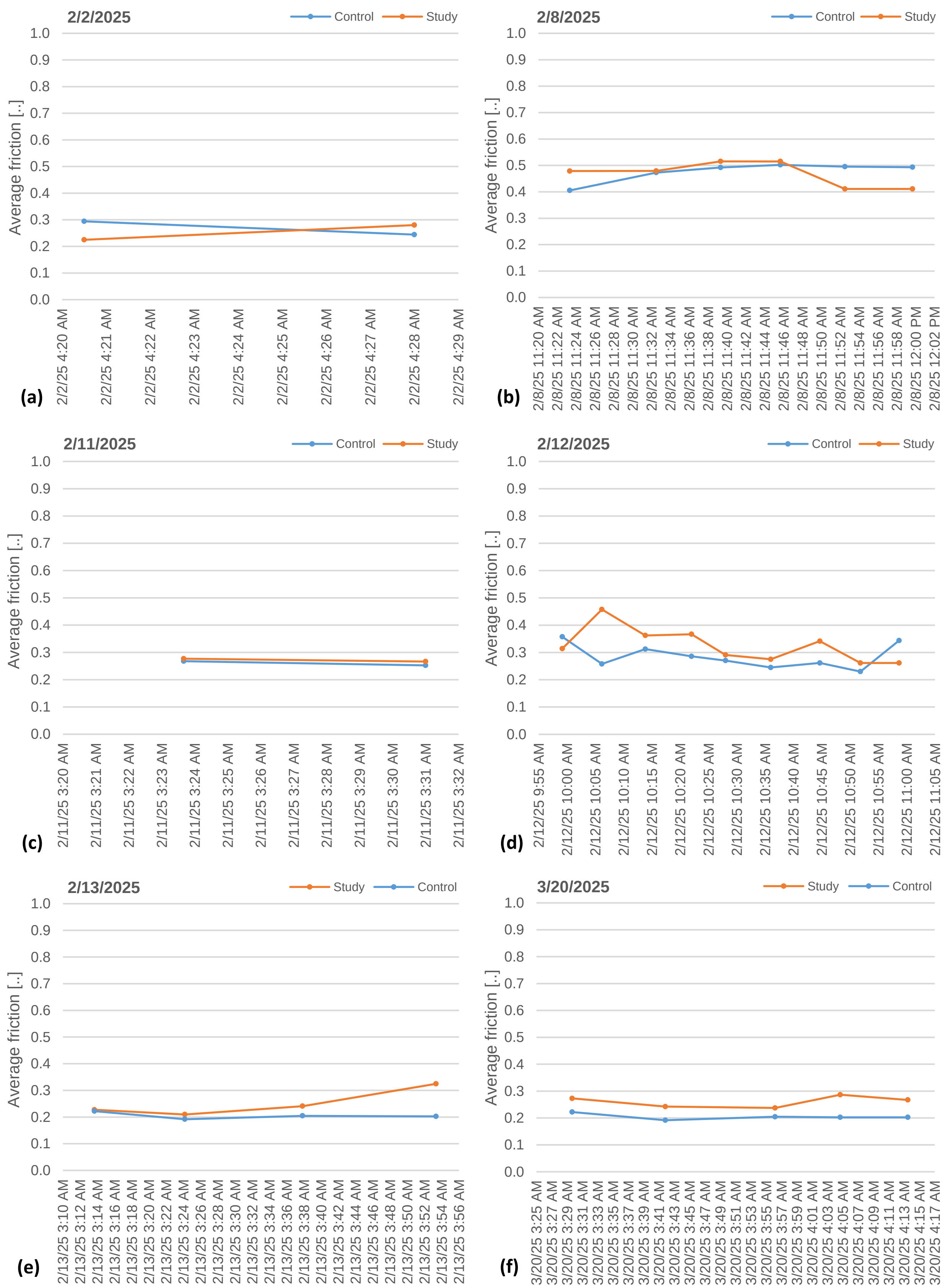

Figure 6.2 Sheboygan County mean friction by storm and route.

Since in each pass there were multiple friction measurements for study and control routes, the data structure was nested (friction measurements, pass, route type). Variability within pass was represented by the standard deviation of the mean friction. Variability exists from one pass to the other within the same route. Thus, the mean of each pass carries a random effect and the route type has a fixed effect. The pass to pass variation while estimating the mean difference of the routes can be accomplished with a mixed effect approach. With this approach, heterogeneity between passes is accounted for, accurate standard errors are obtained, and confidence in statistical inference increases.

Figure 6.3 illustrates the comparison of mean and standard deviation for control and study routes for all friction observations. Each marker represents the mean friction, and the line intervals illustrate plus and minus the standard deviation from the mean in their respective axis. As mentioned previously, Sheboygan County friction values were in a lower range, but were valid for a relative comparison of the pair of study and control routes from that region. By visual inspection of the distribution of mean, standard deviation, and the dashed reference line (1:1), control and study routes are highly correlated and are grouped near the reference line. The reference is the theoretical representation that the friction at study and control routes are the same.

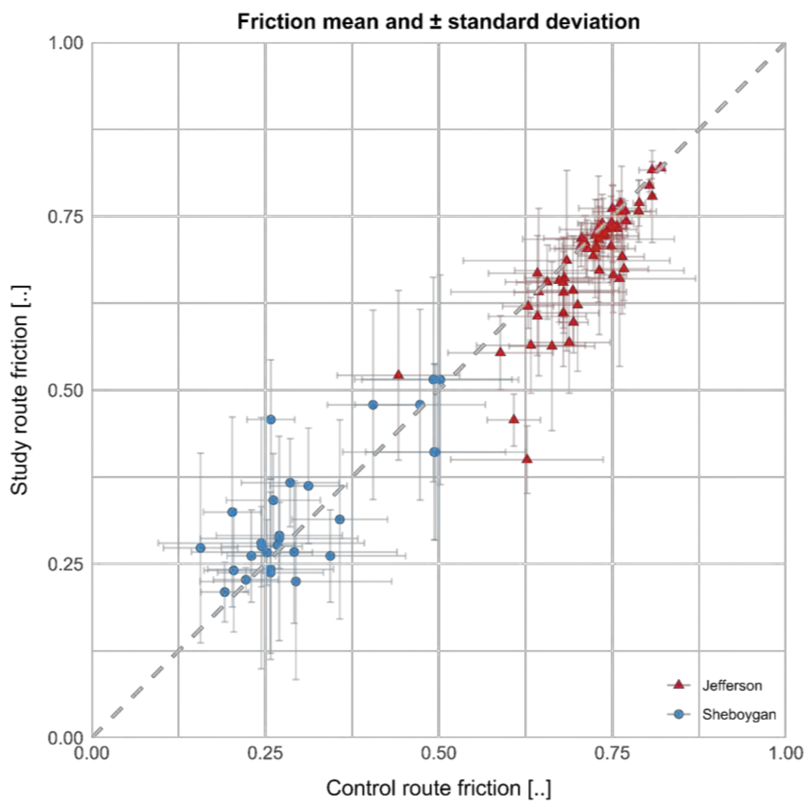

Figure 6.3 Mean and standard deviation of friction measurements.

For more rigorous analysis, through a mixed-effect meta-regression modeling, friction estimates of control and study routes were compared. A meta-regression extends meta-analysis by modeling effect sizes (mean friction) that vary across passes and are a function of moderators such as the route type. The fixed effects are the systemic differences explained by the moderator route type and the random effects considers the residual heterogeneity between passes not explained by the moderator route type. The mixed-effect meta-regression model formulation is provided in Equation 6-1. To evaluate the statistical significance of the comparison between the control and study routes friction measurements, the model coefficient of the moderator route type was evaluated with the Wald test and confidence intervals.

$$y_i = \beta_0 + \beta_1 \times x_i + u_i + \varepsilon_i \qquad (6\text{-}1)$$

Where,

y_i = effect size (mean friction) of the i-th pass,
x_i = moderator (route type, control = 0 or study = 1),
β_0 = intercept (baseline, mean friction of control route),
β_1 = effect of route type (control versus study),
u_i = random effect capturing residual heterogeneity,
ε_i = sampling error derived from sampling variance of y_i (variance of friction divided by the number of measurements in the i-th pass).

Results of the mixed-effects meta-regression modeling are provided in Table 6.3. Evaluation models were developed for each county and with all data. The model for Jefferson County showed an intercept of 0.733 (p-value < 0.001) and a moderator coefficient of route type equal to -0.027 (p-value = 0.026). The results for Jefferson County routes indicate that there is a small statistically significant difference between the control and study route. However, by evaluating confidence intervals, delta threshold (entire confidence interval above +0.05 or below -0.05), magnitude of the effect size, and relative change from the baseline (intercept), the effect is not practically significant. For instance, the control route has a mean baseline of 0.733 (intercept) and the study route has 0.706 (0.733 - 0.027 = 0.706) mean effect friction value, which is merely a 3.7% difference. Although statistically significant, the difference between control and study routes in Jefferson is not practically significant.

In the case of Sheboygan County routes, the model intercept is 0.269 (p-value < 0.001) and moderator is equal to 0.021 (p-value = 0.322), which indicates that friction at study and control routes were statistically similar.

When combining all the data, the model intercept is 0.021 (p-value < 0.001) and moderator is -0.009 (p-value = 0.762), which indicates that friction at control and study routes in Jefferson and Sheboygan were statistically similar.

Table 6.3 Mixed-effects meta-regression modeling.

Model	Variable, coefficient	Estimate	Standard error	Wald test		Confidence interval
				z-value	p-value	
Jefferson	Intercept, β_0	0.733	0.009	86.203	< 0.001	0.716, 0.749
	Route type, β_1	-0.027	0.012	-2.225	0.026	-0.051, -0.003
Sheboygan	Intercept, β_0	0.269	0.014	19.179	< 0.001	0.241, 0.296
	Route type, β_1	0.021	0.021	0.991	0.322	-0.020, 0.062
All	Intercept, β_0	0.598	0.021	29.003	< 0.001	0.557, 0.638
	Route type, β_1	-0.009	0.029	-0.303	0.762	-0.066, 0.049

Note: Route type = Control (0) or Study (1).

The operational implications of these results are relatively straightforward. Friction on both study and control routes were similar. At first, this might appear to be a somewhat negative result, but a review of Table 6.1 indicates that much less amount of salt was used on the study routes than on the control routes. Control route applications were 200-300 pounds per lane mile, while study route applications ranged from 35 to 50 gallons per lane-mile. One gallon of brine contains approximately 2.38 pounds of salt, so the brine applications used between 83 and 119 pounds of salt per lane-mile. That represents a difference in salt usage of between 40% and 72% for the same end surface condition (as measured by friction and other metrics). Those differences in the amount of salt used in treatments are economically and environmentally important.

6.1.2 Vehicular Speed and Travel Disruption

Building on the work initiated by Bandara (2015), the metric Travel Disruption (TD) was introduced by Claros et al. (2024). The TD measures the impact of winter storms on travel speed by calculating the area generated by the difference in speeds between normal and storm conditions. The performance measure represents the additional travelled distance that could have been covered during the same time and travel speed under normal conditions. The TD metric provides a more integrated understanding of the storm's effect on performance, by taking into account different storm elements, such as intensity, duration, and intermittence. Ultimately, the TD can be used to estimate the average traveling time lost during a storm, based on the speed values for normal conditions.

Travel vehicle speed and vehicle travel time probe data were collected from the National Performance Management Research Dataset (NPMRDS) (FHWA 2023). Field data and vehicle probe data were available for study and control routes from Jefferson County in Wisconsin for three storms during the 2024-2025 winter season. The speed analysis was not conducted in Sheboygan County routes because there weren't reliable speed measurements in the NPMRDS during the periods of analysis.

Figure 6.4 provides a diagram illustrating the variables of interest and performance measures at different time frames during a storm event (Claros et al. 2024). Although Figure 6.4 shows linear speed for normal conditions and speed reduction/recovery during storm conditions, linear representations are for illustration purposes only. Speed fluctuates significantly in a time series format according to time of the day, day of the week, season of the year, construction, or other rare events such as accidents or special events. In the case of this study, speed was impacted by winter storm conditions.

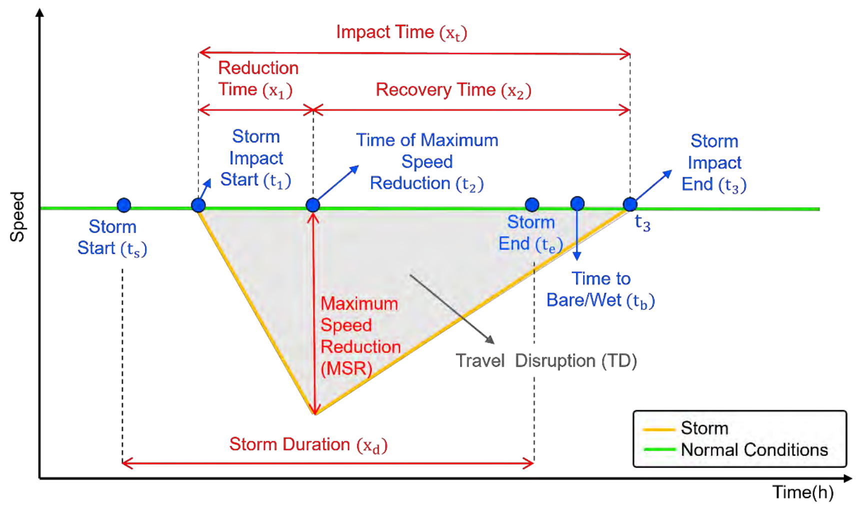

Figure 6.4 Travel disruption concept illustration.

Based on existing literature and the data at hand, the following temporal variables of interest are used for analysis:

- Storm start (t_s)
- Storm end (t_e)
- Time to bare/wet (t_b)
- Storm impact start (t_1)
- Time of maximum speed reduction (t_2)
- Storm impact end (t_3)

The storm start, storm end, and time to bare/wet (t_s, t_e, and t_b) were obtained from field observations reported by the counties. Time to bare/wet (t_b) represents the time necessary to reach pavement bare/wet conditions since the beginning of the storm. The variables t_1, t_2, and t_3 are points in time related with specific travel speed conditions, obtained from the NPMRDS dataset. The start and end of the storm impacts on traveling speeds variables were initially proposed by Lee et al. (2008) and Bandara (2015). Based on the variables presented, performance measures used in this analysis can be defined as:

- Storm duration (x_d)
- Reduction time (x_1)
- Recovery time (x_2)
- Impact time (x_t)
- Maximum speed reduction (MSR)
- Travel Disruption (TD)

The metric storm duration (x_d) is defined as the difference between the storm start and end (t_e and t_s). The storm impact on speeds is captured by the performance measures reduction, recovery, and impact times (x_1, x_2, and x_t). The reduction time (x_1) is the time (t_2 - t_1) to reach the maximum speed reduction (MSR) under storm conditions from the start of the impact of the storm. The speed recovery (x_2) is the time (t_3 - t_2) to reach the end of the impact of the storm from the maximum speed reduction (MSR). The overall impact time (x_t) is equal to the reduction time (x_1) plus the recovery time (x_2). Quantifying the magnitude of the greatest impact point of a storm on vehicular travel speed, the MSR metric may be used. This performance measure is defined as the greatest difference in traffic speed caused by a winter weather event. MSR quantifies the maximum reduction in vehicle speed during a storm compared to the reference speed (Claros et al. 2024). In the present study, the area of TD was calculated following the Trapezoidal rule, as shown in Equation 6-2.

$$\int_a^b f(x)\,dx \approx \frac{\Delta x}{2}\left(f(x_0) + 2f(x_1) + 2f(x_2) + \cdots + 2f(x_{N-1}) + f(x_N)\right) \quad (6\text{-}2)$$

Where in the present context a and b represent t_1 and t_2, respectively; Δx represents the time interval of data in the NPMRDS (10 minutes), x_i represents each of the i time instances with available speed data; N represents the number of time instances available; and $f(x_i)$ represents the speed value for each time instance i.

Travel Disruption (TD) metric can be illustrated through a simplified case study provided in Figure 6.5. For the baseline condition, a vehicle travels under normal dry conditions at a constant speed of 60 mph. However, during a storm, the vehicle's speed reduces to 40 mph and recovers to normal speed conditions during the impact of the storm of four hours. In this example, the region delineated between the normal and storm conditions forms an inverted triangle with an area representing the TD equal to [(60 mph - 40 mph) × 4 hr / 2] = 40 mi. To better understand how the TD represents the miles of travel disrupted by the storm, we can calculate the same value as the difference between the number of miles traveled during that period under normal conditions (60 mph × 4 hr = 240 mi) and the number of miles traveled during the same time under storm conditions (50 mph × 4 hour = 200 mi). Since the speed is variable between 40-60 mph under storm conditions, on average the speed would be 50 mph. Thus, the vehicle could have traveled 40 mi more (240 mi - 200 mi = 40 mi) had it been under normal conditions, as provided by the TD metric. Alternatively, the time lost due to travel disruption can also be calculated as the 40 mi that could have been covered under normal conditions at 60 mph which would be 40 minutes.

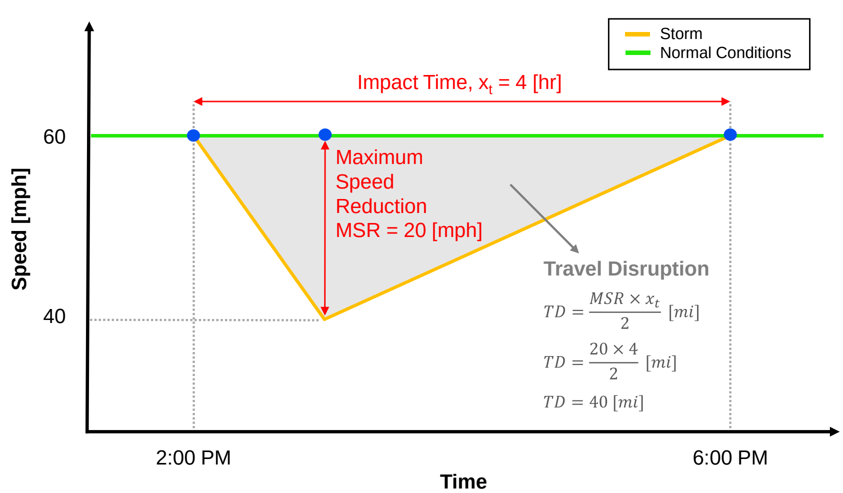

Figure 6.5 Travel disruption case study.

Table 6.4 provides details of the storms and treatments evaluated in Jefferson County routes. Measures of interest were derived from a combination of storm features and vehicle probe data. Table 6.5 presents the start and end time of each storm and other temporal variables of interest. The values of t_1, t_2, t_3 and t_b shown in the table are relative to the start of the storm (t_s). The negative values for the storm impact (t_1) represent situations when the reduction of speeds caused by the storm started before the start of the storm (according to field data). This particular behavior may be attributed to inconsistencies in the reported data from agencies, weather forecast, or drivers proactively anticipating the impending snowfall. Drivers may have preemptively adjusted their speeds, recognizing the potential hazards of the approaching snowstorm and the subsequent deterioration of road conditions. The variables t_2 and t_3 are used together with t_1 to calculate the performance measures.

Table 6.4 Vehicular speed under storm conditions and treatment information.

County	Date storm start	Snow accumulation [in]	Pavement temperature [°F]	Application rate		Application frequency [min]
				Control route [lbs/ln-mi]	Study route [gal/ln-mi]	
Jefferson	11/21/2024	4.0	30-36	200	45	120
	12/19/2024	5.0	25-29	200	50	60
	1/10/2025	0.5	20-21	300	50	30

Notes: in = inches, °F = Fahrenheit degrees, lbs/ln-mi = pound per lane mile, gal/ln-mi = gallons per lane mile, min = minutes.

Table 6.5 Periods of interest based on impact of storm.

Storm start	Storm end	Storm impact start	Storm impact start	Time MSR	Time MSR	Storm impact end	Storm impact end
Date and time	Date and time	Study t_1 [hr]	Control t_1 [hr]	Study t_2 [hr]	Control t_2 [hr]	Study t_3 [hr]	Control t_3 [hr]
11/21/2024 3:00 AM	11/21/2024 12:00 PM	-1.5	-5.0	7.1	6.7	12.5	11.0
12/19/2024 1:00 AM	11/19/2024 15:00 PM	7.0	7.0	21.2	26.9	41.0	35.0
1/10/2024 4:00 AM	1/11/2024 12:00 PM	1.5	1.5	3.7	3.7	7.5	8.8

Figures 6.6 to 6.8 illustrate the performance measures for all three storms evaluated in Jefferson County. The storm presented in Figure 6.6 provides a speed reduction before the impact of the storm, a short recovery followed by a rapid drop in speed due to the impact of the storm. Treatments were implemented throughout and after the storm period, and treatment times were represented by solid red dots. In the case of the storm illustrated in Figure 6.7, a longer storm period was recorded in which speed had an initial drop and recovery followed by a significant drop in speed which fluctuated in lower speed ranges for 10-12 hours with frequent treatments. Speed recovered or reached close to normal conditions before the end of the storm period. In the last storm illustrated in Figure 6.8, the impact on speed occurred after the start of the storm with a consistent and steep drop. The storm recovery at the control route had

a short relapse before fully recovering, whereas the study route had a consistent recovery from the lowest speed to normal conditions. Treatments were implemented during the storm period.

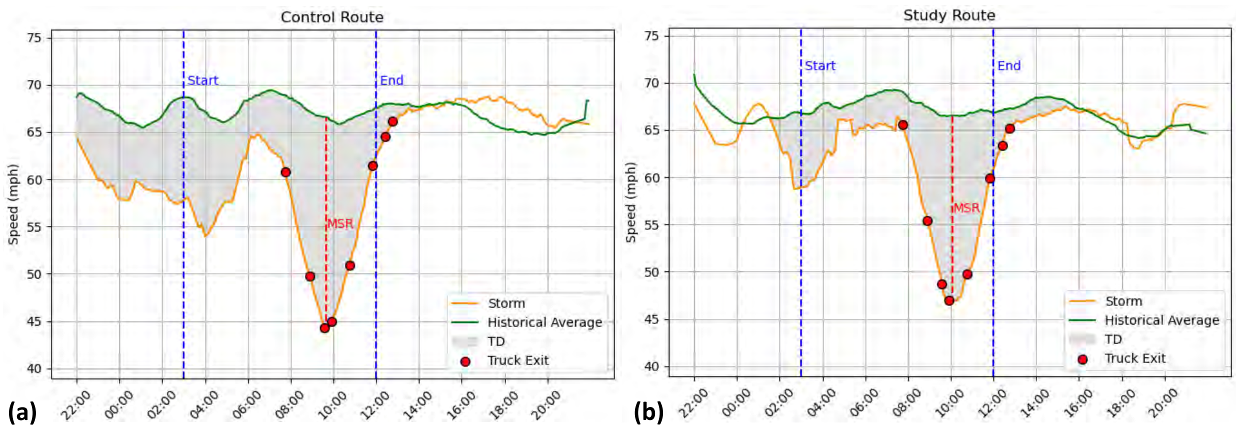

Figure 6.6 Travel disruption for storm on 11/21/2024 at (a) control and (b) study routes.

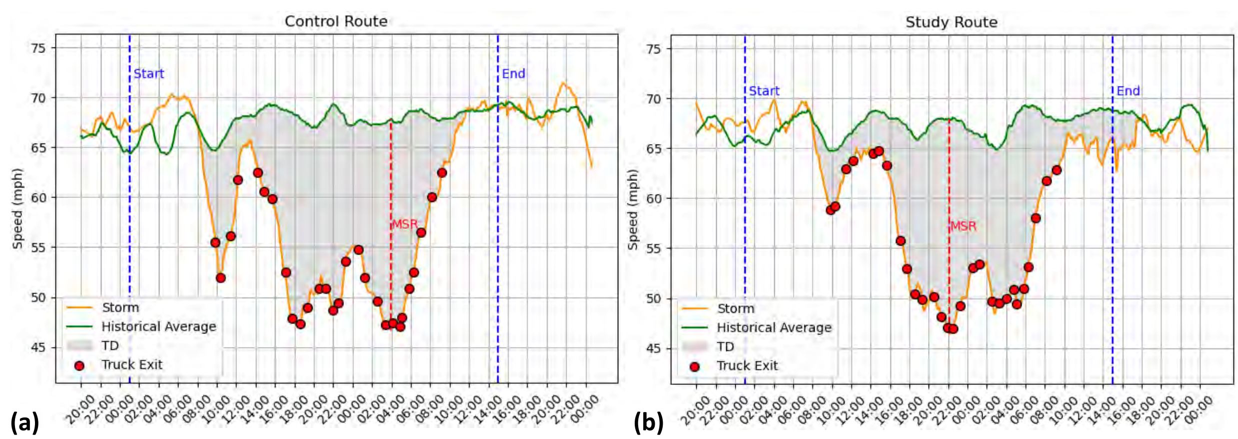

Figure 6.7 Travel disruption for storm on 12/19/2024 at (a) control and (b) study routes.

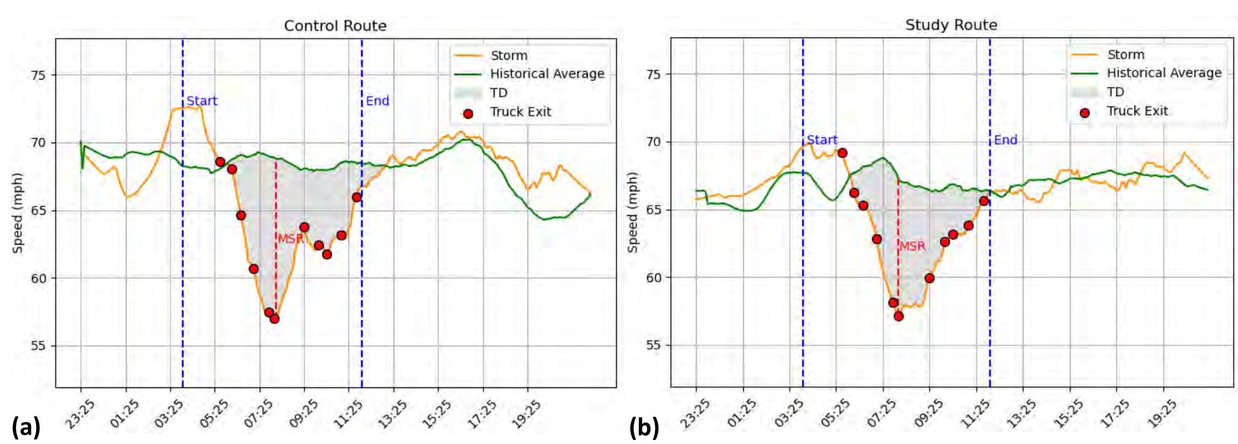

Figure 6.8 Travel disruption for storm on 01/10/2025 at (a) control and (b) study routes.

Results of the speed related performance measures are provided in Table 6.6. The storms dated 11/21/2024 and 1/10/2025 had short storm durations of nine and eight hours, temperatures between 30-

36 °F and 20-21 °F, and snow accumulation of four and 0.5 inches, respectively. In contrast, the storm on 12/19/2025 had a duration of 38 hours overall with temperatures between 25-29 °F and snow accumulation of five inches. Due to the limited sample size of three storms, wide range of magnitude of the estimates, statistical tests to compare the mean of performance measures of the groups of control and study routes are not possible. However, results can be interpreted on a storm by storm basis and the results showed that the Travel Disruption (TD) metric at study routes were similar to the control routes.

Table 6.6 Vehicular speed performance measures.

Storm Start date	Storm duration (hr)	Impact time x_t [hr]		Reduction time x_1 [hr]		Recovery time x_2 [hr]		Max speed reduction MSR [mph]		Travel disruption [mi]	
		Study	Control	Study	Control	Study	Control	Study	Control	Study	Control
11/21/2024	9.0	14.0	16.0	8.6	11.7	5.4	4.3	19.9	22.6	88.9	146.3
12/19/2024	38.0	34.0	28.0	14.2	19.9	19.8	8.1	21.5	21.1	312.5	339.9
1/10/2025	8.0	6.0	7.3	2.2	2.2	3.8	5.0	10.1	11.9	31.6	40.0

6.1.3 Time to Bare/Wet

Reported time to bare/wet were available for five storms in Jefferson County and one storm in Sheboygan County. Time to bare/wet in this study is defined as the period of time between the start of the storm until reaching bare/wet pavement conditions. Based on the information about the start of the storm and reported time bare/wet conditions were accomplished, the period in hours was computed for every storm. Table 6.7 provides the details of the storm period and time to bare/wet comparison between control and study routes. There were limited number of storms to conduct a statistical test to compare the groups of control and study routes. Based on the results from each storm, times to bare/wet for control and study routes were similar. Difference in time to bare/wet between control and study routes for three storms ranged from 30 (0.5 hr) to 50 (0.8 hr) minutes. The remaining three storms had the same time to bare/wet periods.

Table 6.7 Time to bare/wet results.

County	Storm start time	Bare/wet time accomplished		Time to bare/wet [hr]	
		Control route	Study route	Control route	Study route
Jefferson	11/21/24 3:00 AM	11/21/24 10:30 AM	11/21/24 10:00 AM	7.5	7.0
	12/18/24 1:00 AM	12/18/24 7:00 AM	12/18/24 7:00 AM	6.0	6.0
	12/19/24 1:00 AM	12/20/24 11:30 AM	12/20/24 11:30 AM	34.5	34.5
	1/10/25 4:00 AM	1/10/25 8:30 AM	1/10/25 9:00 AM	4.5	5.0
	2/2/25 12:30 AM	2/2/25 7:00 AM	2/2/25 7:00 AM	6.5	6.5
Sheboygan	2/1/25 1:00 AM	2/1/25 6:00 AM	2/1/25 6:50 AM	5.0	5.8

6.2 Roadway Weather Information Systems (RWIS) Stations

The analysis of integrated data from RWIS friction/weather and vehicular speed consisted of quantifying the measures of Friction Deficit (FD) and Travel Disruption (TD), and assessment of the impact of weather conditions and winter maintenance treatments in a time series format. Following the concept of the measure TD previously presented (Figure 6.4, Equation 6-2), the FD can be estimated in a similar way, by quantifying the area under the curve between friction under normal conditions and storm conditions. FD represents the overall friction deficit hours from normal conditions. To supplement the FD metric, the periods of time under different friction thresholds are also provided. Table 6.8 provides a summary of the results. A total of eight storms were evaluated (four in Iowa and four in Wisconsin). Based on the duration of the storm, intensity of snowfall, and temperature, the impact of the storm was quantified by the TD and FD metrics. Although there were a relatively small number of storms, the results showed that TD and FD are highly associated (r = 0.8, correlation). Thus, as expected, when friction decreases due to storm conditions, the vehicles' ability to maintain normal speeds reduces and speeds decrease. Additionally, the cumulative periods of time under a given threshold of friction were evaluated. These measures provided information regarding the conditions in which there may be sudden drops and recovery in friction, extended decrease or recovery, or sustained levels of friction that could serve as measures of risk or safety. The results provide valuable information to quantitatively monitor and assess the mobility and safety performance of roadways and winter treatments.

Table 6.8 Vehicular speed and friction performance evaluation results.

RWIS station	Storm start date	Travel disruption TD [mi]	Friction deficit FD [..×hr]	Period [hr] with friction ≤ f			
				f = 0.8	f = 0.6	f = 0.4	f = 0.2
Iowa	11/11/2019	212.1	5.8	13.2	9.8	7.4	6.0
	1/10/2020	297.7	10.2	24.4	18.7	13.2	6.5
	1/12/2020	158.3	3.5	17.2	7.2	3.7	0.1
	1/17/2020	419.8	7.6	27.4	9.7	9.2	5.2
Wisconsin	12/19/2024	643.3	9.7	31.6	14.2	11.2	6.5
	1/1/2025	97.4	3.0	25.0	3.7	3.3	2.8
	2/12/2025	436.2	11.2	27.2	15.3	14.8	12.0
	3/23/2025	182.9	3.4	30.2	0.0	0.0	0.0

Pavement temperature was not available for the Iowa RWIS station, so air temperature was used. Air and pavement temperature were available for the Wisconsin RWIS station. Figure 6.9 illustrates a storm recorded at the Iowa RWIS station on 1/10/2020 in a time series format. Illustrations of the rest of the storms are provided in Appendix A.

In Figure 6.9, In anticipation of the storm, DLA of salt brine (anti-icing treatment) were implemented at 1/10/2020 8:00 AM and 12:00 PM. Vehicular speed and roadway friction remained steady until 2:00-3:00 PM when there was a sudden drop in speed from 68 mph to 46 mph and friction from 0.81 to 0.15 in the following three to five hours. The impact on speed and friction was clearly a result of snow precipitation between 3:00-9:00 PM, with intensities ranging between 0.01-0.10 in/hr. Air temperature steadily decreased from 27 °F (1/10/2020 12 PM) at the beginning of the storm to 11 °F (1/11/2020 10:00AM) the next day. Air temperature increased to 15-20 °F in the following 12 hours. Wind speeds were between 15-25 mph at the beginning of the storm and decreased to near zero mph towards the end of the storm. At this particular location in Iowa, treatments were implemented in tandem with two trucks covering the treatment of the two travel lanes in the NB direction. The storm impact rapidly deteriorated conditions and was close to the PM peak hour, frequent prewet salt deicing treatments were implemented. Regular prewet treatments were implemented in the following evening/night hours, the frequency of treatments were increased during the early morning of the following day. In this storm, it is not clear whether treatments had an immediate effect on friction, as would be expected. Since trucks would plow accumulated snow and apply prewet salt, an increase in friction should be expected. However, these increases in friction are not easily visualized in a prolonged period of analysis, and significant precipitation of snow may not allow such rapid and brief improvements in friction. Jumps in vehicular speed are not expected because the speed data used in this study comes from probe data that is averaged and smoothed which would not reflect sudden jumps in speed after treatments are implemented.

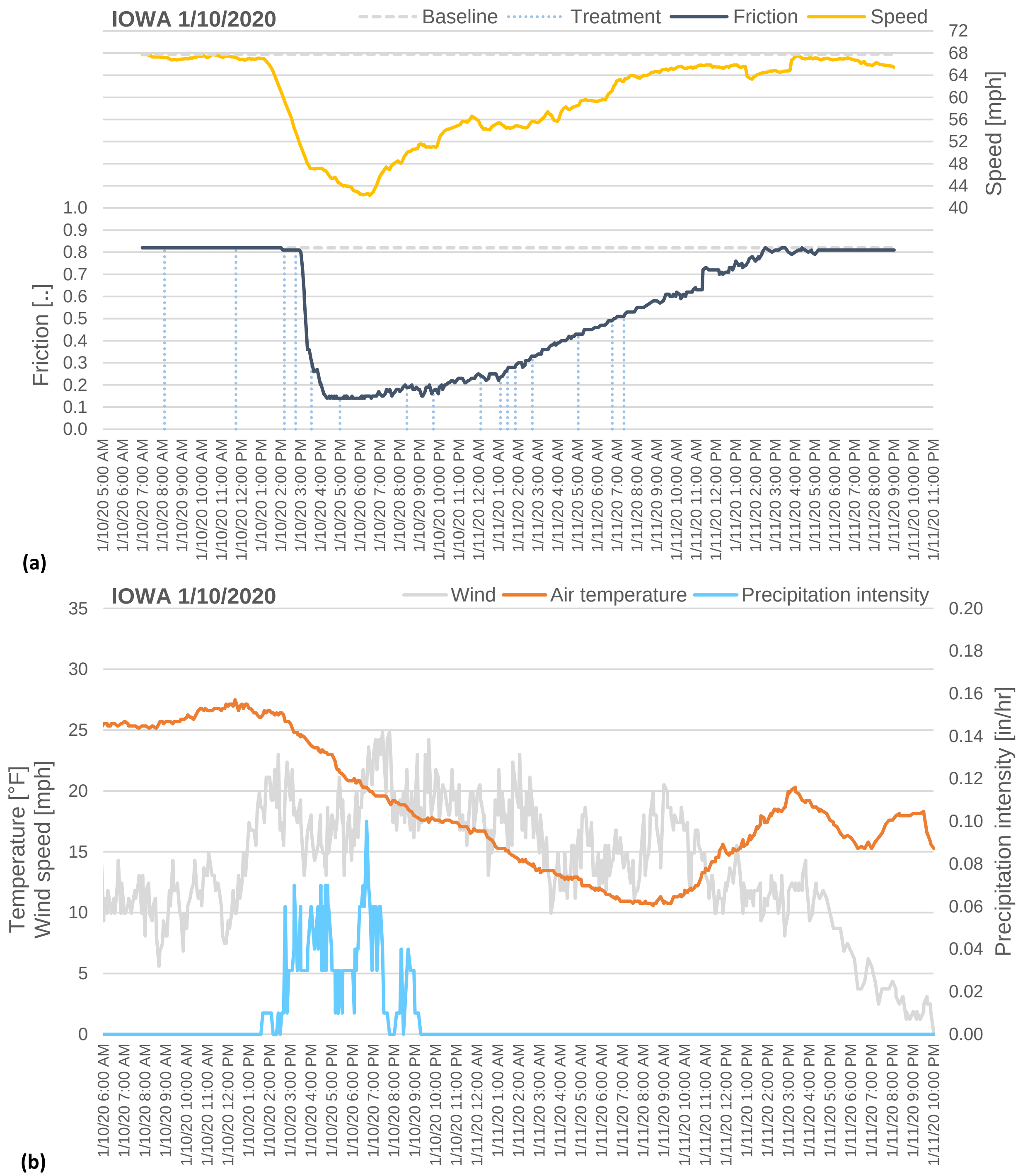

Figure 6.9 Iowa storm 1/10/2020 (a) speed and friction, and (b) weather in time series.

Figure 6.10 provides the friction measurements during a storm in Iowa on 11/10/2019, in which the impact of the treatments can be easily visualized. After the implementation of the treatment, short sudden jumps in friction followed. However, those jumps were between 0.10-0.35 units of friction rather that complete recovery to normal conditions. Although treatments may immediately improve conditions, impacts are short lived and may be more impactful in the following hours after the end of precipitation with steady recovery rather than delayed recovery due to the accumulation and compaction of snow.

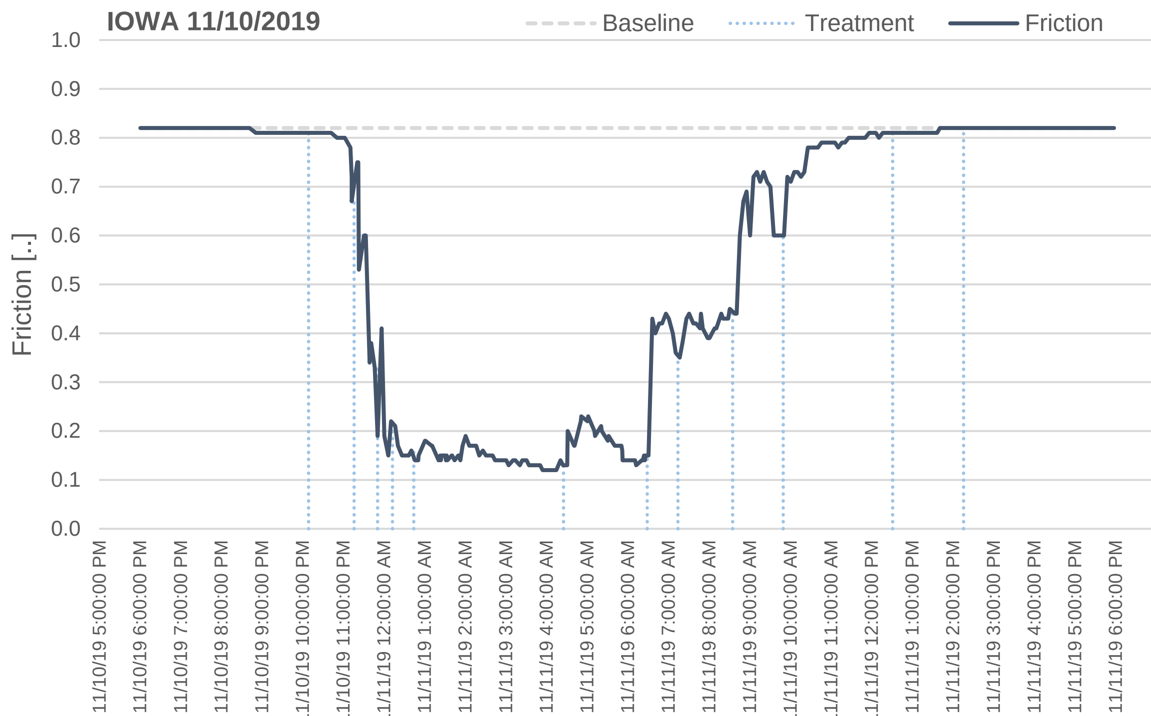

Figure 6.10 Iowa storm 11/10/2019, friction data in time series.

Friction measurements from the RWIS stations are collected with optical devices and different manufacturers and provide friction values in the lower end down to 0.1. Continuous friction data collection and monitoring can contribute to assessing the impact of storms and treatments on roadway mobility and safety performance.

6.3 Summary of Results

Data were collected at parallel study routes with direct liquid application of salt brine and control routes with dry granular salt treatments to compare their performance. The research team also collected data from roadways adjacent to RWIS stations in Iowa and Wisconsin with prewet salt treatments to evaluate roadway friction and vehicular speed as a function of storm conditions.

Friction data was collected for five storms in Jefferson County and six storms in Sheboygan County in Wisconsin. Snow accumulation during the storms was between 0.5-5.0 in, pavement temperatures were between 15-36 °F. Application rates of dry salt on control routes were 200-300 pounds per lane-mile, direct liquid application rates of salt brine on study routes were 35-50 gallons per lane-mile, and the frequency of application ranged between 30-120 minutes. Key findings include the following:

- Friction: Mixed-effects meta-regression modeling showed that friction measurements of control and study routes were statistically similar.
- Vehicle speed: Study routes had similar Travel Disruption (TD) as control routes.
- Times to bare/wet: Control and study routes had similar times to bare/wet. Three storms had identical times to bare/wet for study and control routes. Differences in time to bare/wet between control and study routes for the remaining three storms ranged from 30 (0.5 hr) to 50 (0.8 hr) minutes.

Based on the evaluation of study and control routes with friction data and additional performance metrics such as TD and time to bare/wet, it can be concluded that there is no significant difference in performance between routes treated with direct liquid application of salt brine and routes treated with dry solid salt. Control route applications were 200-300 pounds per lane-mile, while study route applications ranged from 35 to 50 gallons per lane-mile. That represents a difference in salt usage of between 40% and 72% and accomplishing similar roadway conditions as measured by friction and other performance measures. This is the first time that a study conducted the evaluation of salt brine DLA and dry solid salt simultaneously under the same weather conditions and friction measurements on parallel divided routes.

With regards to the results of the data collected at RWIS stations and adjacent roads treated with prewet salt, the measures of Friction Deficit (FD) and Travel Disruption (TD) significantly contributed to assess the impact of weather conditions and winter maintenance treatments. Continuous friction measurements from RWIS stations and AVL data also provided valuable information about trends in friction, impact of storm, impact of treatment, and thresholds of operation during a storm.

This study lays out a methodology to estimate the performance metrics of FD and TD which quantify the impact of winter storms on roadway safety and mobility and assess the effects of maintenance treatments on road conditions. Using these field performance metrics, agencies can monitor existing conditions or test alternative chemical materials, conventional or novel strategies in winter maintenance operations, and thereby optimize practices to reduce impacts on the environment, costs, and roadway safety and mobility. However, the challenges in recruiting agencies to participate in field data collection limited the number of participants and data samples. Additionally, data quality issues associated with the RWIS stations and limited speed data in NPMRDS during winter storms further limited the data for analyses. To expand the findings, future research efforts can implement the methodology presented in this study with a larger dataset of field observations under diverse storm and road conditions.

Chapter 7: Conclusions

The objectives of the project were to synthesize information about the differences between direct liquid application (DLA) of salt brine and granular salt with operational performance and safety metrics, develop a field data collection protocol, and conduct field experiments to compare the performance of DLA of salt brine with granular salt.

Towards these objectives, the research team conducted a thorough literature review of performance measures in winter maintenance, effects of winter weather on traveling speed, recovery time, delay, volume, capacity, friction, and crashes. Key findings of existing literature indicate that winter storms have an impact on roadway operations and safety, and quantifying the effectiveness of winter maintenance treatments is very challenging. Performance measures that have been traditionally used focus on materials used, cost, time to accomplish specific roadway pavement surface conditions, storm severity, and crash rates. Alternatively, roadway surface friction measurement has also been considered as a feasible performance measure to evaluate performance. Operational measures such as travel speed also seem to be feasible alternative to consistently monitor performance and quantify the effectiveness of treatments during winter storms since there are automated processes for data collection and historical records. Databases such as the National Performance Management Research Data Set (NPMRDS) are available and provide a comprehensive nationwide database derived from probe vehicles containing information on speed and travel time with an extensive coverage of the roadway network in the United States.

To evaluate the performance of salt brine DLA applications and granular salt, a field based data collection protocol for study and control routes was developed. Jefferson and Sheboygan counties in Wisconsin were able accommodate the field testing protocol and collected field data during storms at parallel study and control routes during the 2024-2025 winter season. To supplement the analysis in this project, the research team obtained data from roadways adjacent to Road Weather Information System (RWIS) stations in Iowa and Wisconsin with prewet salt treatments to evaluate roadway friction and vehicular speed as a function of storm conditions.

This is the first time that a study conducted the evaluation of DLA of salt brine and dry solid salt simultaneously under the same weather conditions and friction measurements on parallel divided routes. Key findings of this study indicate that there friction measurements between control and study routes were statistically similar. Travel Disruption (TD) and time to bare/wet were similar for study and control routes. Since control route applications were 200-300 pounds per lane-mile, and study route applications ranged from 35 to 50 gallons per lane-mile, a difference in salt usage of between 40% and 72% would be expected, accomplishing similar roadway conditions as measured by friction and other performance measures.

In terms of RWIS stations and adjacent roads treated with prewet salt, the measures of Friction Deficit (FD) and Travel Disruption (TD) significantly contributed to assess the impact of weather conditions and winter maintenance treatments. Continuous friction measurements from RWIS stations and AVL data also provided valuable information about trends in friction, impact of storm, impact of treatment, and thresholds of operation during a storm.

Limitations identified in this project include the challenges in recruiting agencies to participate in field data collection, which limited the number of participants and data samples. Additionally, data quality issues associated with the RWIS stations and limited speed data in NPMRDS during winter storms further limited the data for analyses. To expand the findings, future research efforts can implement the methodology presented in this study with a larger dataset of field observations under diverse storm and road conditions.

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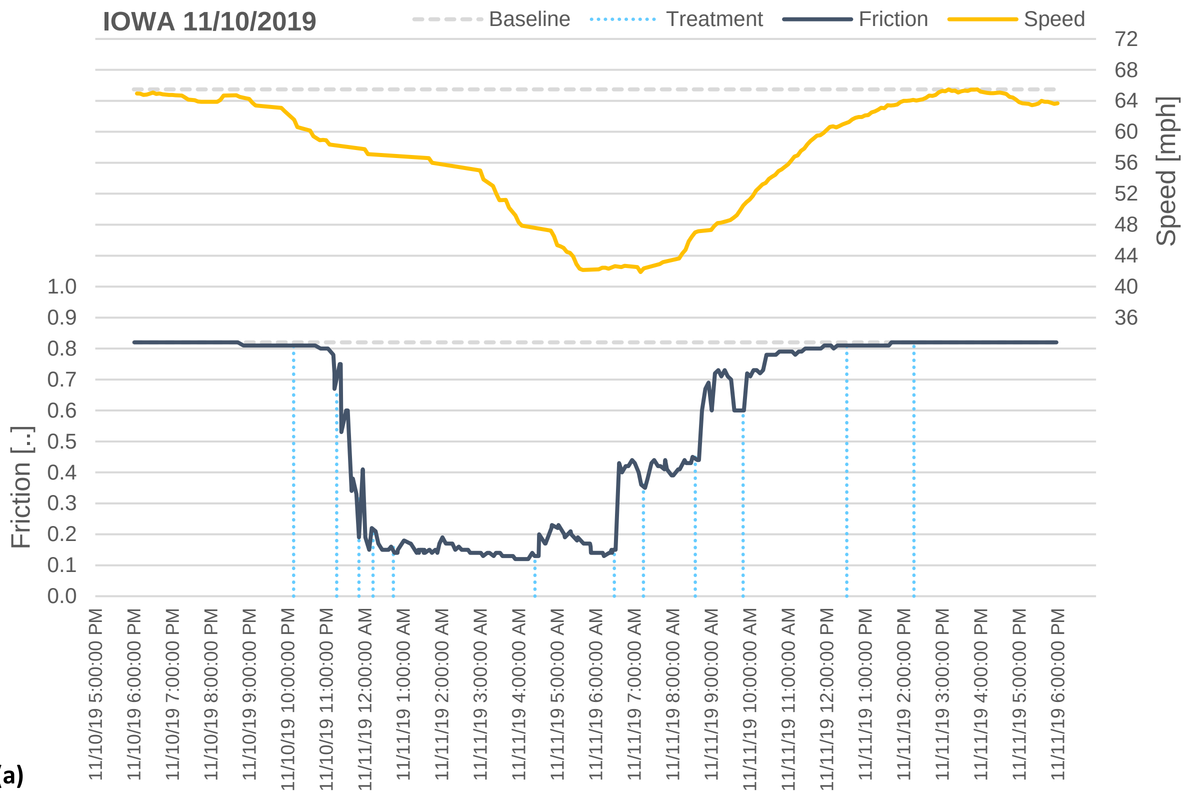
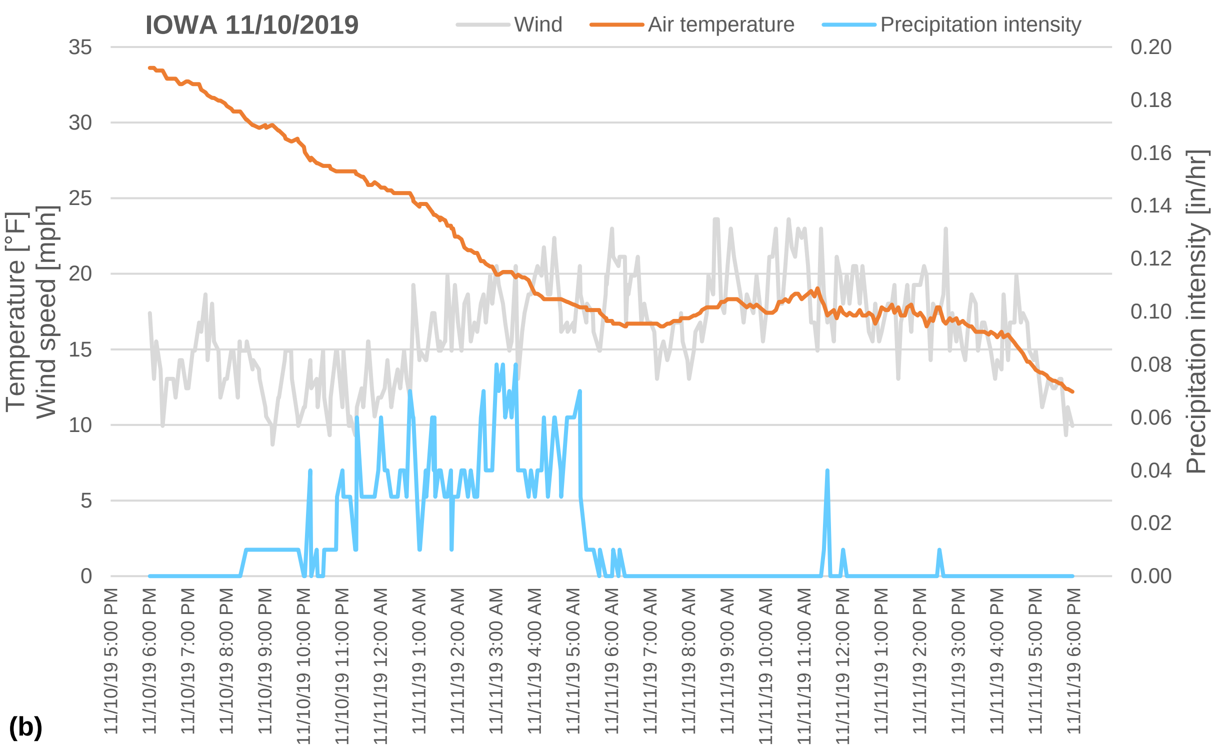
Appendix A
RWIS Station Storm Analysis

A.1 Iowa Storm 11/10/2019



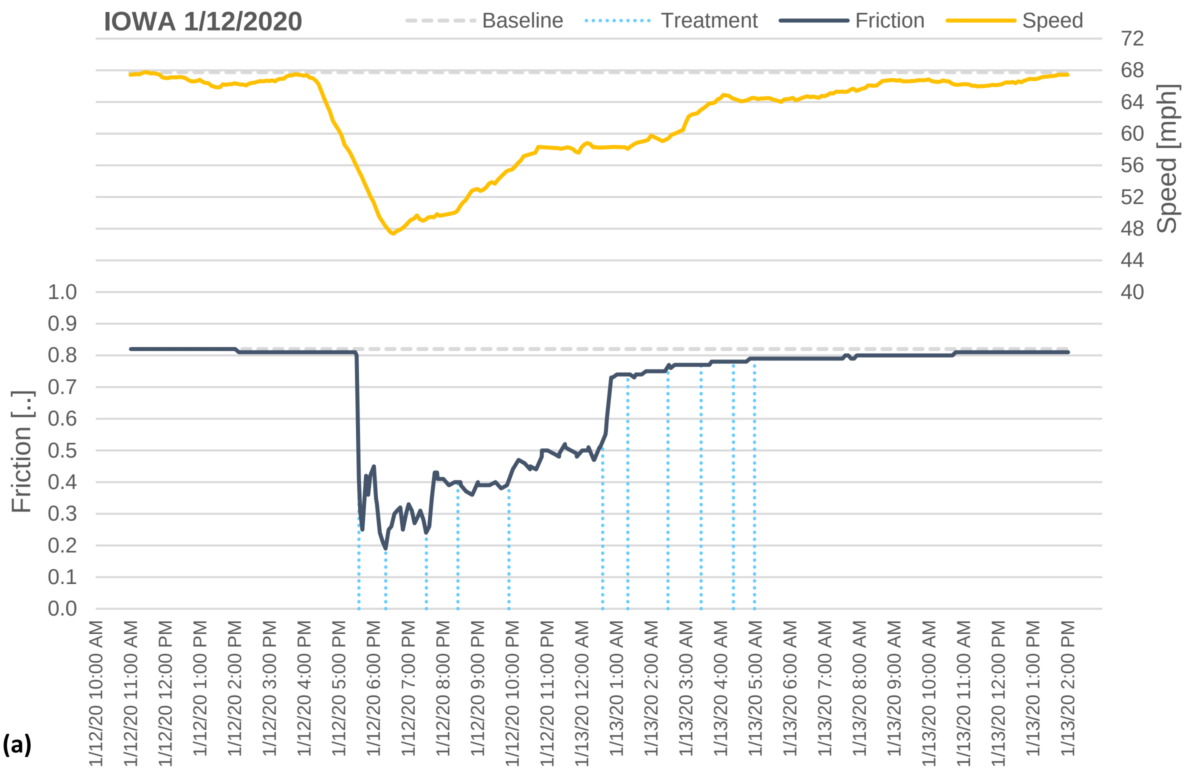
(a)



(b)

Figure A.1 Iowa storm 11/10/2019 (a) speed and friction, and (b) weather in time series.

A.2 Iowa Storm 1/12/2020



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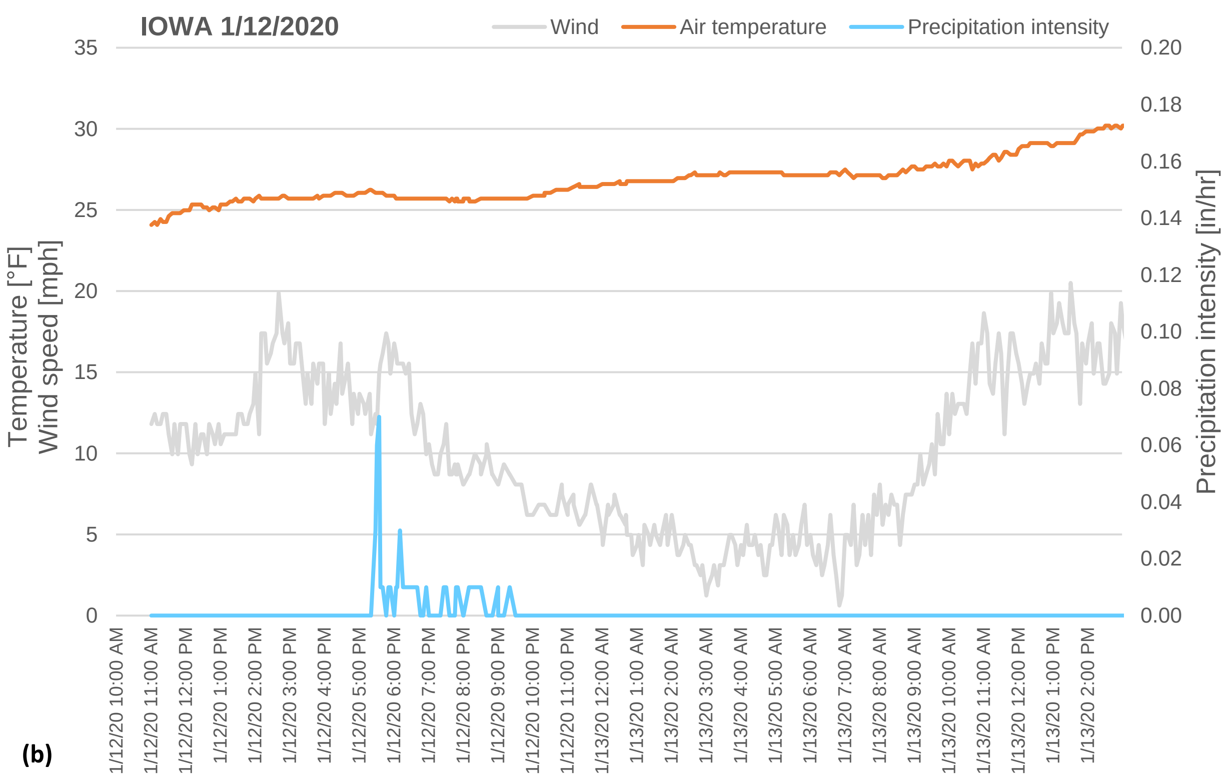


(b)

Figure A.2 Iowa storm 1/12/2020 (a) speed and friction, and (b) weather in time series.

A.3 Iowa Storm 1/17/2020

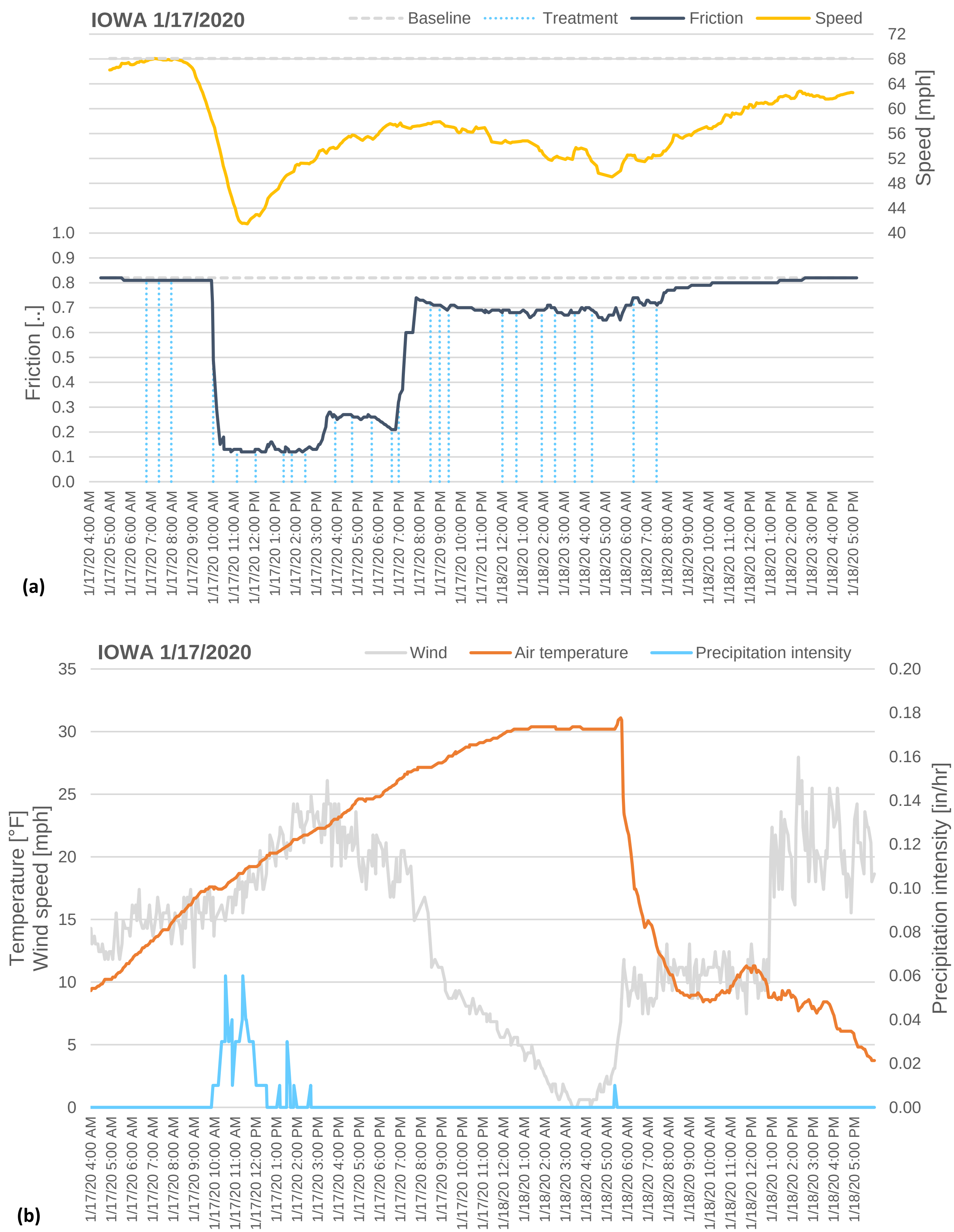
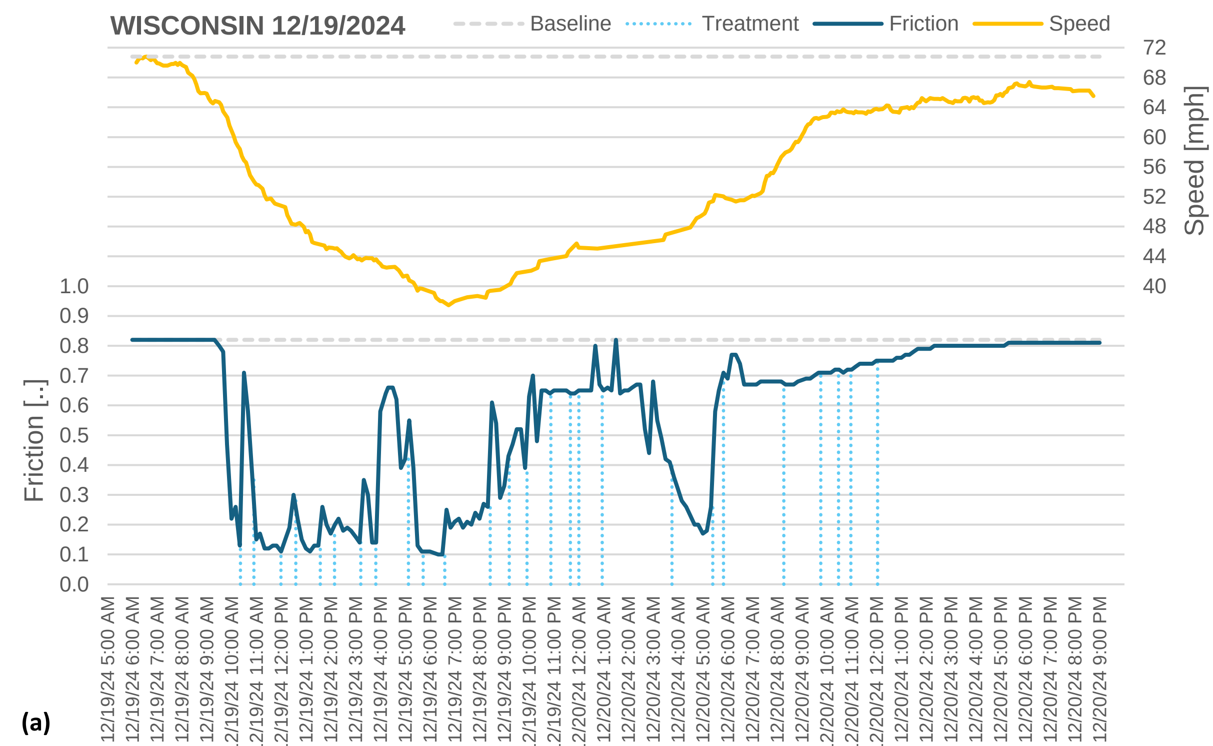
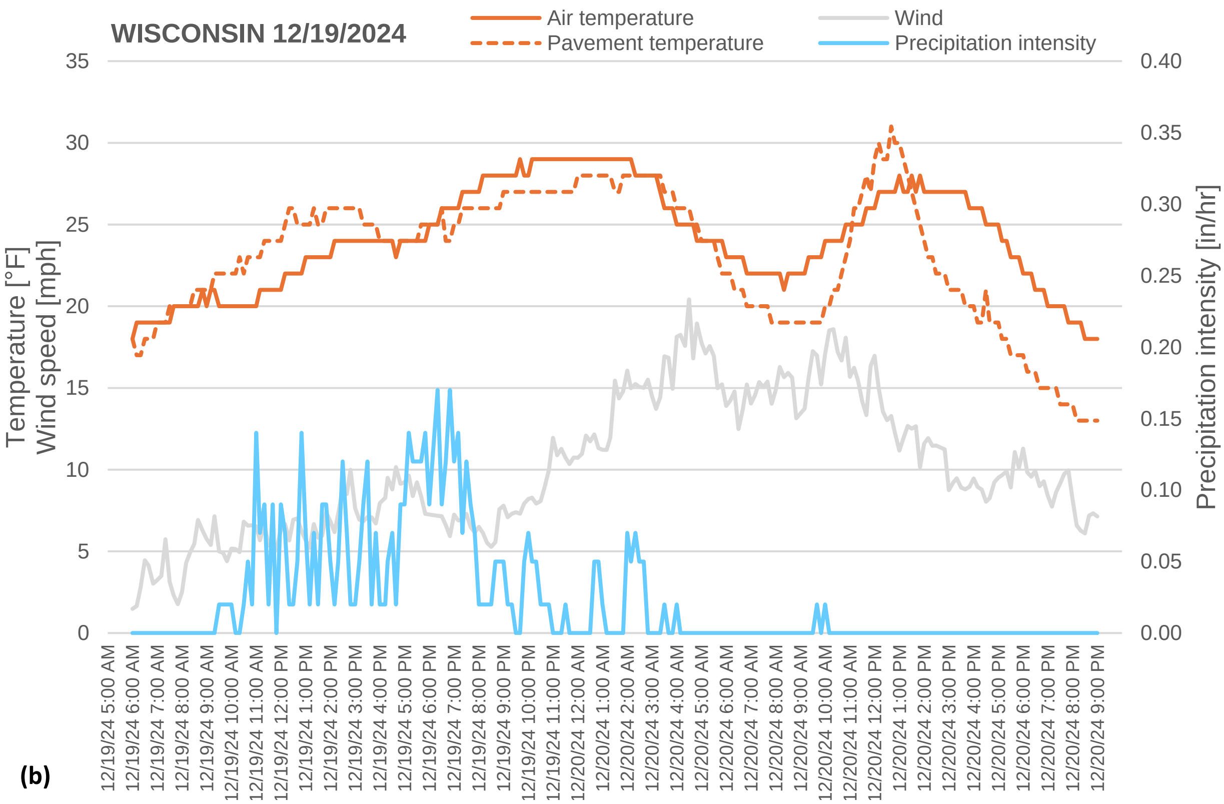


Figure A.3 Iowa storm 1/17/2020 (a) speed and friction, and (b) weather in time series.

A.4 Wisconsin Storm 12/19/2024



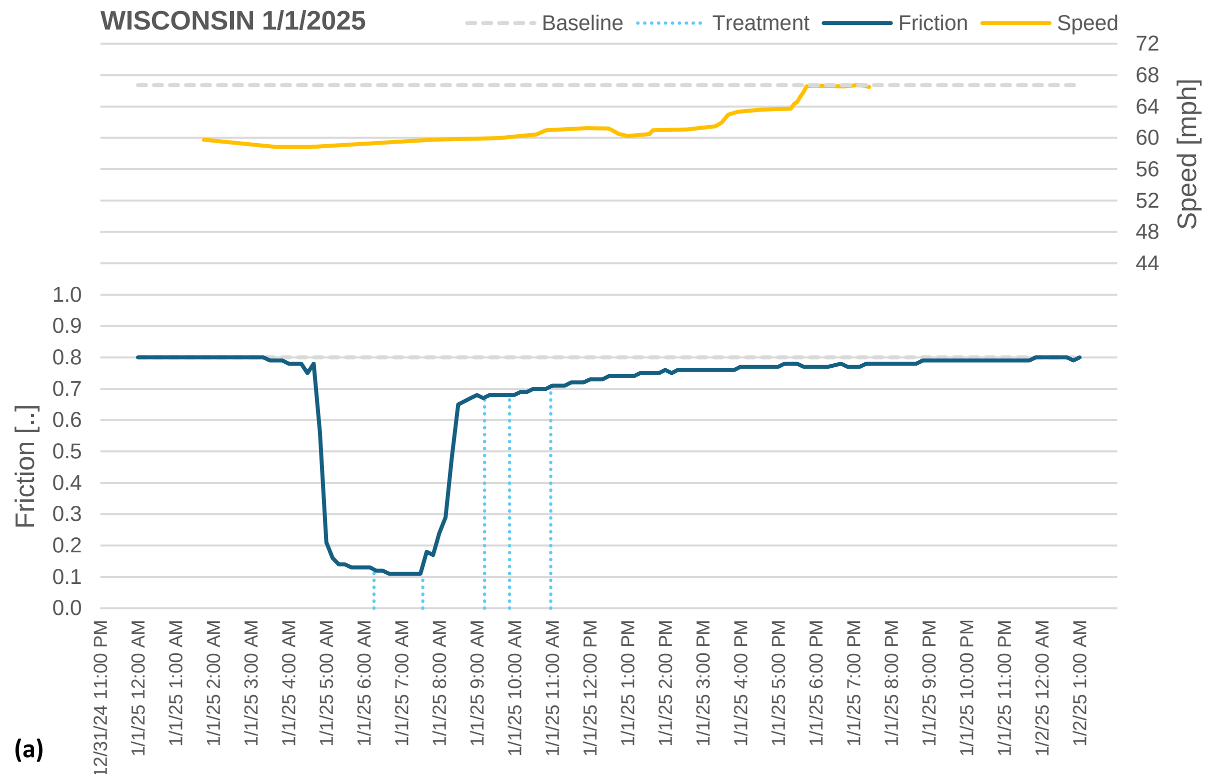
(a)



(b)

Figure A.4 Wisconsin storm 12/19/2024 (a) speed and friction, and (b) weather in time series.

A.5 Wisconsin Storm 1/1/2025



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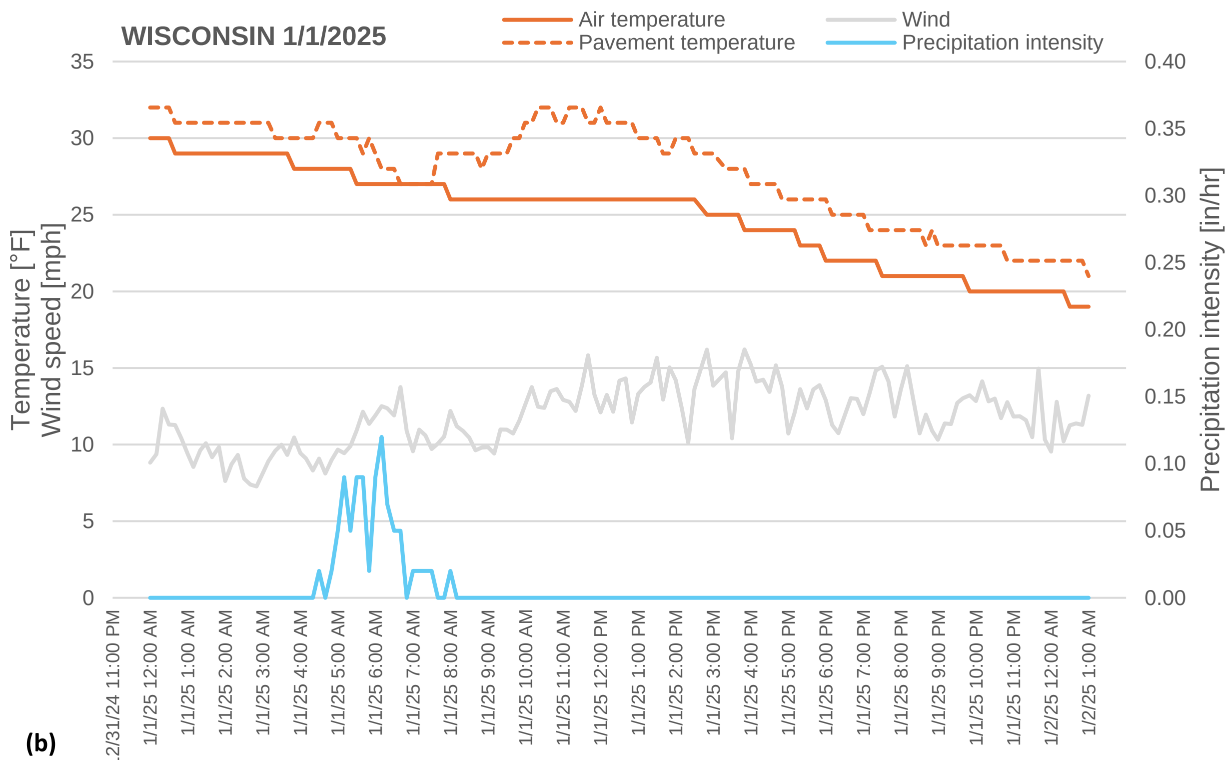


(b)

Figure A.5 Wisconsin storm 1/1/2025 (a) speed and friction, and (b) weather in time series.

A.6 Wisconsin Storm 2/12/2025

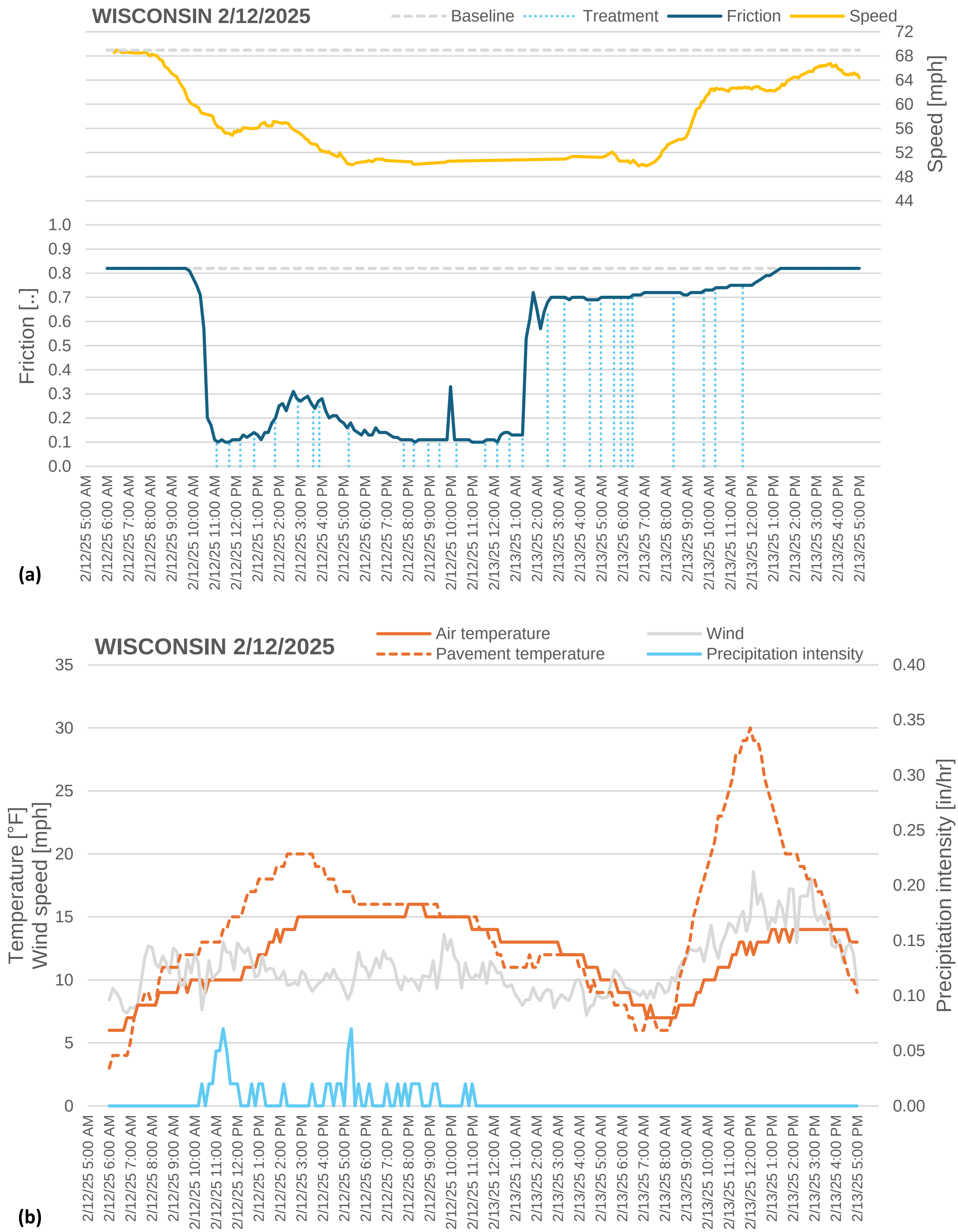
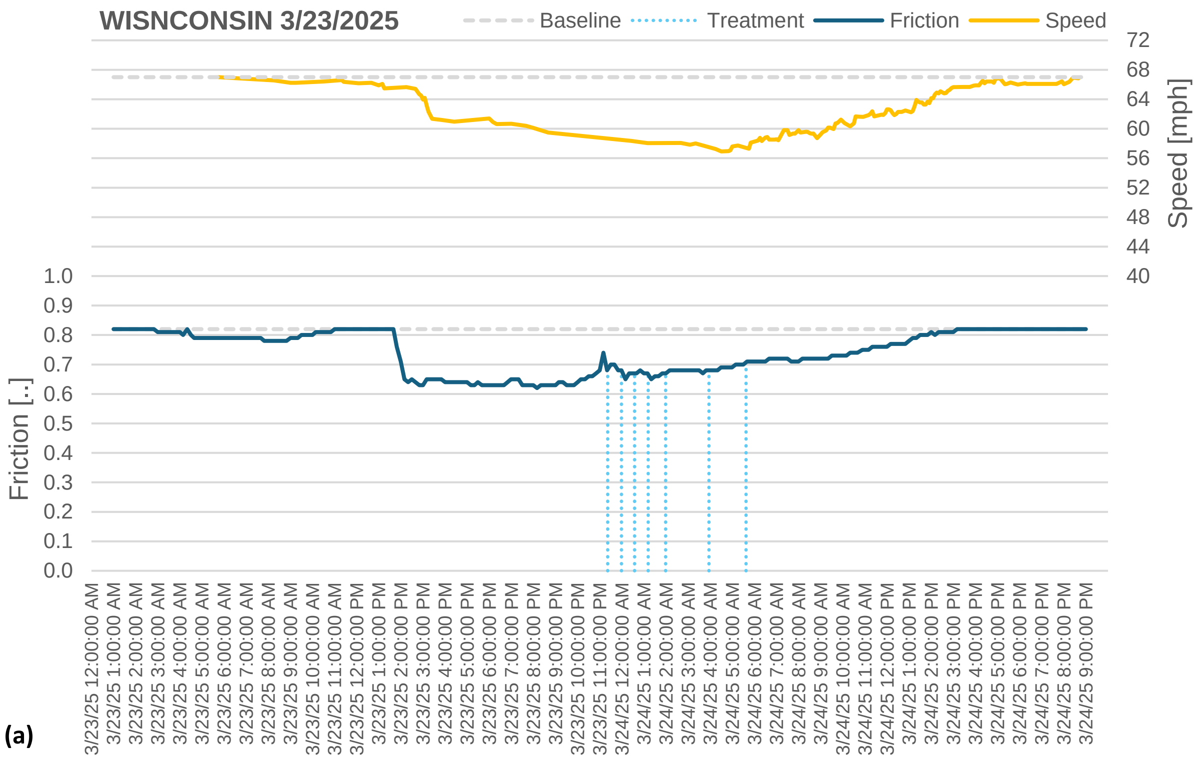
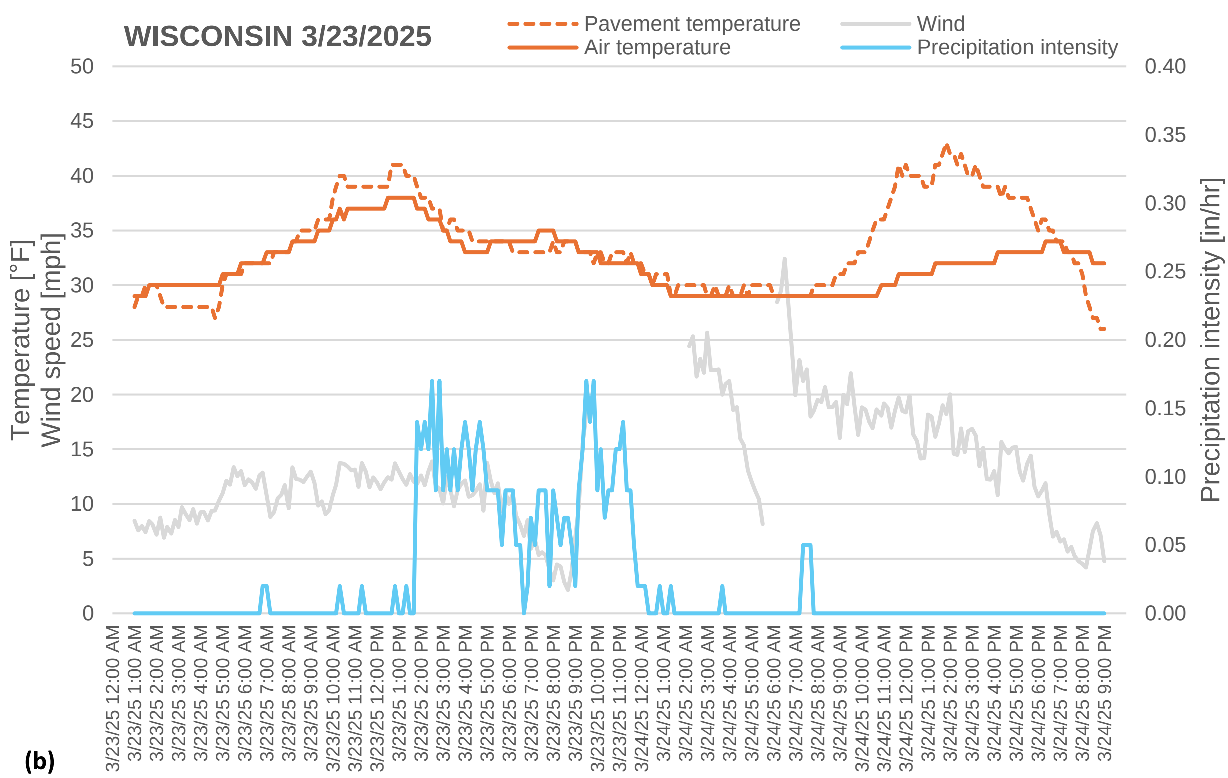


Figure A.6 Wisconsin storm 2/12/2025 (a) speed and friction, and (b) weather in time series.

A.7 Wisconsin Storm 3/23/2025



(a)



(b)

Figure A.7 Wisconsin storm 3/23/2025 (a) speed and friction, and (b) weather in time series.

CLEAR ROADS

research for winter highway maintenance

Lead state:

Minnesota Department of Transportation

Research Services

395 John Ireland Blvd.

St. Paul, MN 55155