Evaluation of Winter Maintenance with Salt Brine Applications in Wisconsin

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16. Abstract

Salt has traditionally been used in winter roadway maintenance. Due to driver expectations and level of service, use of salt and cost have significantly increased over the years. Transportation agencies have been introducing responsible and sustainable winter maintenance practices to alleviate impacts on the environment, human health, vehicles, infrastructure, and reduce costs. Salt brine has been implemented in Wisconsin for several years and there is a need to evaluate its performance. Previous research indicated that there may be a significant reduction of salt and time to bare/wet when using salt brine compared to solid salt in Wisconsin.

In this research project, data collection and analysis were expanded from previous research efforts to evaluate salt brine performance in terms of amount of salt used, time to bare/wet, pavement friction, and benefit-cost. The methodology consisted of route selection, route and equipment data collection, winter storm event field data collection, and pavement friction data collection and data analysis. Field data was collected from 10 counties in Wisconsin; there were 143 storms evaluated during the 2020-21 winter season. Field data was collected from study and control routes at the same time and under the same weather conditions. Pavement friction data was collected from two counties.

Key findings of this research indicate that salt brine applications reduced the amount of salt used, improved time to bare/wet, present better pavement friction conditions, and benefits outweighed the cost of investment to introduce salt brine to existing solid salt applications.

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Final Report

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EXECUTIVE SUMMARY

Salt has been traditionally used in winter roadway maintenance. Due to driver expectations and level of service, use of salt and cost have significantly increased over the years. Transportation agencies have been introducing responsible and sustainable winter maintenance practices to alleviate impacts on the environment, human health, vehicles, infrastructure, and reduce costs. Salt brine has been implemented in Wisconsin for several years and there is a need to evaluate its performance. Previous research indicated that there may be a significant reduction of salt and time to bare/wet when using salt brine compared to solid salt in Wisconsin.

In this research project, data collection and analysis were expanded from previous research efforts to evaluate salt brine performance in terms of amount of salt used, time to bare/wet, pavement friction, and benefit-cost. The methodology consisted of route selection, route and equipment data collection, winter storm event field data collection (weather, material, application rates, and performance), pavement friction data collection, and data analysis (comparison between study and control routes). Field data was collected from 10 counties (Brown, Dane, Jefferson, Marathon, Marquette, Outagamie, Price, Shawano, Washington, and Wood) in Wisconsin and there were 143 storms evaluated during the 2020-2021 winter season. Field data was collected from study and control routes at the same time and under the same weather conditions. Pavement friction data was collected from two counties (Jefferson and Wood).

Key findings of this research indicate that salt brine applications reduced the amount of salt used, improved time to bare/wet, presented better pavement friction conditions, and benefits outweighed the cost of investment to introduce salt brine to existing solid salt applications.

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1. INTRODUCTION

Salt has been traditionally used as a deicer material in roadway maintenance treatments during winter storms. Driven by driver expectations and level of service, use of salt and cost have significantly increased over the years. Therefore, transportation agencies have been introducing responsible and sustainable winter maintenance practices to alleviate impacts on the environment, human health, vehicles, infrastructure, and reduce costs. Salt brine is an alternative to reduce the amount of salt used in winter maintenance. Salt brine is a solution of sodium chloride (salt) in water which typically has a 23.3% concentration of the chemical material. Laboratory tests have provided evidence of benefits and effectiveness of salt brine. However, laboratory findings may not reflect complex dynamics in the field.

Salt brine has been implemented in Wisconsin for several years and there is a need to evaluate its performance. In the first phase of the research project, field data was collected from four counties during the 2018-2019 winter season in Wisconsin. Results of the initial evaluation indicated that there may be a significant reduction of salt and time to bare/wet when using salt brine compared to solid salt. Unfortunately, data was limited, and further analysis was required.

In this second phase of the research project, data collection and analysis were expanded to evaluate salt brine performance in terms of amount of salt used, time to bare/wet, pavement friction, and benefit-cost. Field data was collected from 10 counties in Wisconsin and there were 143 storms evaluated during the 2020-2021 winter season. This report provides a summary of the methodological approach and focuses on the key findings of the research. For more details about existing literature on liquid chemical products, blending, agro-based products, application rates, performance measures, environmental impacts, corrosion, impacts on concrete and asphalt, and benefit-cost, the reader may refer to the final report of the first phase of the research project.

2. METHODOLOGY

Winter maintenance practices vary across northern states in the United States with predominant winter conditions. In Wisconsin, winter maintenance is managed by county highway departments. Wisconsin Department of Transportation (WisDOT) contracts with all 72 county highway departments for maintaining interstate, federal, and state highways. Several counties have acquired and adapted equipment and facilities to enable the use of salt brine in winter maintenance. Historical data does not provide accurate data since winter events have different severities and conditions. Therefore, field data collection was conducted on study and control routes at the same time and under the same weather conditions. Field data by storm event was collected during the 2020-2021 winter season from 10 counties (Brown, Dane, Jefferson, Marathon, Marquette, Outagamie, Price, Shawano, Washington, and Wood). Pavement friction data was collected from two counties (Jefferson and Wood). Figure 1 illustrates the location of each county in Wisconsin that provided field data (red = storm data, blue = storm and pavement friction data).

The methodology consisted of route selection, route and equipment data collection, winter storm event field data collection (weather, material, application rates, and performance), pavement friction data collection, and data analysis (comparison between study and control routes).

2.1. Route Selection

Selection of study and control routes consisted of homogeneous and comparable segments. The study design required routes treated with salt brine and/or solid salt. Selection of routes was a difficult task since there were established winter maintenance operations. In order to conduct a rigorous controlled study, the research team provided route selection guidelines.

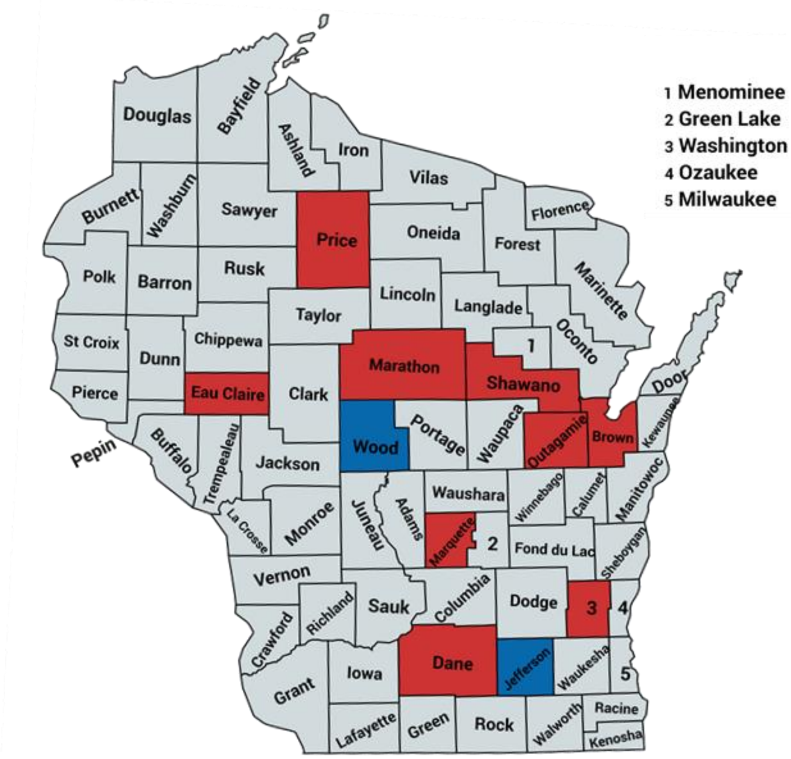

Figure 1. Counties that submitted storm and pavement friction data

Each study site (salt brine only, or salt brine and solid salt) had a control site (solid salt route) pair. Although the study site was designated as a route with salt brine application, solid materials such as dry salt may have been used in addition to salt brine as required by storm conditions. Each pair of sites were in the vicinity and had similar roadway geometric, traffic, and weather characteristics. Segments were five to 25 miles long with one to three lanes by direction. In order of priority, three site selection criteria were considered.

2.1.1. Parallel Routes

For ideal conditions, multilane divided roadway segments may be used as study and control sites. One direction of travel may be treated with salt brine and the opposite direction with solid salt—ensuring data collection under the same geometric, traffic, and environmental conditions for an ideal comparison.

2.1.2. Split Routes

The split design consisted of dividing a route into two segments. One segment of the route may be treated with solid salt and the other segment with salt brine. This study approach provided proximity between study and control routes with similar conditions.

2.1.3. Independent Routes

Study and control routes in the same area may not be available, so routes were selected based on the similarity of geometric/operational characteristics and weather conditions within the same county. The independent study approach was only considered when all efforts to select parallel or split routes had been exhausted.

2.2. Data Collection

Data was collected from each county through **report forms** and an **online winter storm report** system hosted in the WisTransPortal (TOPS 2020). All 72 counties already report overall county level material, labor, and operations for every storm. Thus, for the 10 counties participating in the study, an additional online report form was provided to submit data for study and control routes by winter storm. Data collected consisted of route, equipment, and storm data (weather, materials, and performance). Through the **online report form**, each county submitted information regarding individual storms for study and control routes. The storm report included the following information:

- **Environmental Conditions**
  - Storm start/end date
  - Storm start/end time
  - Type of precipitation (wet snow, dry snow, freezing rain, sleet, lake effect)
  - Snowfall (in)
  - Pavement temperature (when crew OUT and IN) (°F)
  - Air temperature (when crew OUT and IN) (°F)
  - Humidity (when crew OUT and IN) (%)
  - Wind speed (when crew OUT and IN) (mph)
  - Wind direction (when crew OUT and IN) (mph)
  - Crew OUT and IN time
- **Study/Control Routes**
  - Treatment type (anti-icing, plow, salt brine, pre-wetted salt, dry salt)
  - Materials (study route)
    - Brine solution
      - Sodium Chloride (NaCl)
      - Calcium Chloride ($CaCl_2$)
      - Magnesium Chloride ($MgCl_2$)
      - Calcium Magnesium Acetate (CMA)
      - Potassium Acetate (KAc)
    - Brine concentration in solution (%)
    - Brine solution used (gal)
    - Other agents (i.e., Beet Heet®, Geo-melt®, etc.)
    - Other agents amount used (gal)
  - Materials (control route)
    - Solid salt used (ton)
    - Other agents (i.e., salt brine for pre-wet, Beet Heet®, etc.)
  - Winter treatment operations
    - Salt brine or solid salt application rate (gal or lb/ln-mi)
    - Application frequency (min)
  - Performance measures
    - Bare/wet time

In terms of **pavement friction data collection**, Jefferson and Wood counties acquired the Mobile Advanced Road Weather Information Sensor (MARWIS), which collects measurements of road surface, ambient, 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. Pavement friction data were collected before, during, and after the storm and application of materials according to the estimated beginning of the storm, end of storm, and period of application of material. All measurements were automatically uploaded to the online application ViewMondo (Lufft 2021) right after data collection. Figures 2 and 3 provide images of the MARWIS device including Jefferson County installation.

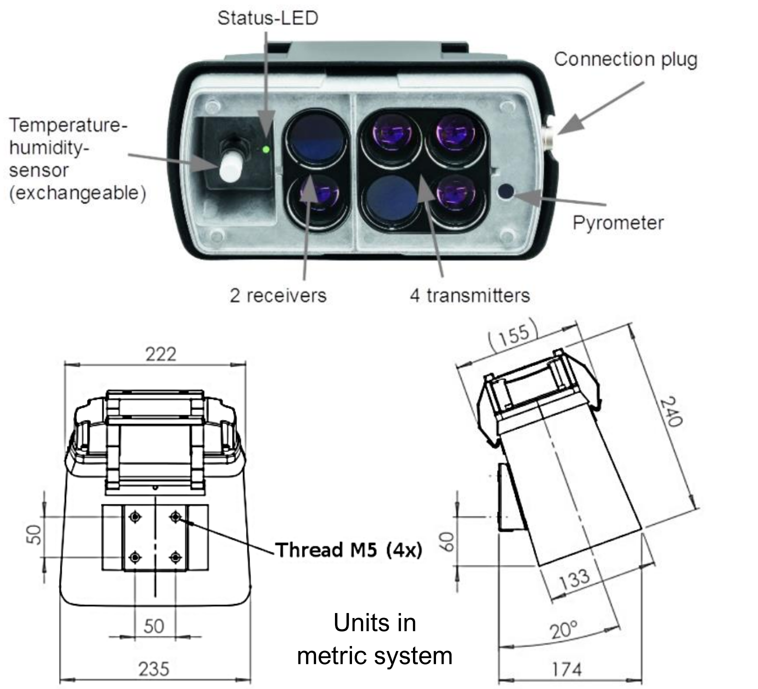

Figure 2. MARWIS friction data collection device (Lufft 2019)

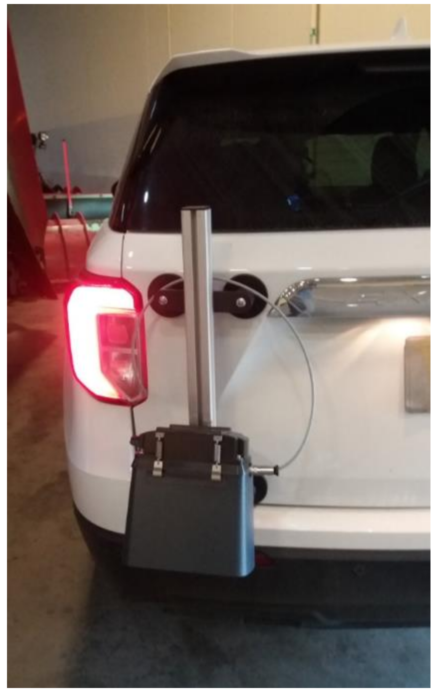

Figure 3. Jefferson County installation

Table 1 provides a summary of storm and friction data collected. One friction data collection run means that the device collected data from beginning to end of the route.

Table 1. Data collection summary

County	Storm Data Reports	Friction Data Runs
Brown	11	
Dane	18	
Jefferson	20	152
Marathon	14	
Marquette	13	
Outagamie	16	
Price	2	
Shawano	18	
Washington	18	
Wood	13	120
Total	**143**	**272**

2.3. Data Analysis

Data analysis focused on comparing performance of study and control routes. Study routes were treated with salt brine only, or salt brine and solid salt (pre-wet salt or Shake and Bake). Control routes were treated with solid salt. Shake and Bake is defined as the spraying of liquid and application of solid materials at the same time, liquid immediately followed by solid, or solid immediately followed by liquid. The analysis consisted of salt use, time to bare/wet, pavement friction, and benefit-cost.

For comparison of study and control route measures, statistical paired t-tests were used to compare the population means of two samples in which the observations in the study route were paired with the observations in the control route. The test is appropriate in experiments where observations of treatments (salt brine and solid salt) over subjects (study and control sites) are collected under the same conditions. The null hypothesis considered no difference between means of both treatments. If p-values were less than 0.05 (two-tailed, 95% confidence interval), the null hypothesis was rejected, and the difference between study and control routes was statistically significant. Along with the results, corresponding p-values of the paired t-test are provided. The analysis was conducted at the route and aggregated level.

2.3.1. Salt Use

The approach consisted of estimating the overall amount of salt used by route. Salt present in salt brine was quantified through the conversion factor of 2.29 lb/gal. Salt in salt brine for pre-wet was also considered. The amount of salt was then normalized per lane-mile for comparison between study and control routes.

2.3.2. Time to Bare/Wet

Time in hours to reach pavement bare/wet conditions since the beginning of the storm were compared for study and control routes. WisDOT expects 24-hour maintained roads to be clear within four hours of the end of the storm and 18-hour maintained roads to be clear within six hours (WisDOT 2020).

2.3.3. Pavement Friction

Since the MARWIS device is capable collecting data up to 100 times per second, the mean pavement friction during a storm was compared between study and control routes. In addition to collecting friction data, the MARWIS device collects dew point temperature, relative air humidity, water film height, and ice percentage. Using these data, the ViewMondo application computes a roadway condition rating with a scale from zero to eight, with zero representing poor conditions and eight representing great conditions. Similar to the roadway friction analysis, the mean roadway condition rating during a storm was compared between study and control routes.

Friction data was integrated with Automatic Vehicle Location (AVL) data of trucks and weather data from Maintenance Decision Support System (MDSS) for time series analysis (Iteris 2021). Data was evaluated for several storms to visualize the different variables that have a significant effect on roadway conditions such as pavement temperature and application of material over time.

2.3.4. Benefit-Cost

In this study, the cost of salt brine per gallon was not estimated. Instead, the benefit-cost of introducing salt brine applications into existing solid salt applications was quantified for a horizon of 10 years. Figure 4 illustrates the cost components assumed for the benefit-cost (B/C) analysis. The following sections will carefully describe assumptions made and costs adopted.

$$\text{B/C} = \frac{\underset{(\$/\text{ln-mi/storm})}{\textbf{BENEFIT}} \times \underset{(\text{ln-mi})}{\textbf{SALT BRINE ROUTES}} \times \underset{(\text{storms over 10 years})}{\textbf{STORMS}}}{\underset{(\$\text{ over 10 years})}{\textbf{COST}}}$$

Figure 4. Illustration of costs components considered for calculation of the benefit-cost

2.3.4.1. Benefit

The benefit is defined as the difference of treatment cost between study and control routes. The research team realizes that there could be many other benefits including environmental benefits, reduction in corrosion, less chlorides in subsurface and surface water bodies, reduction in crashes, improved friction, etc. However, in this analysis the benefits estimated are only the savings in application of materials. Equation 1 provides the elements used to calculate the cost of treatment per route in $ per lane-mile per storm ($/ln-mi/storm). For study routes, the overall amount of salt in salt brine and dry salt used in tons were estimated, and the costs associated with the production of salt brine per gallon was added separately with the costs of water and electricity. Counties provided cost estimates of salt brine production which ranged from $0.0018-$0.0055 of water cost per gallon and $0.001 of electricity per gallon of salt brine. The cost of trucking and applying material was estimated based on the number of trips made, length of route, and truck cost of operation. Based on average national costs (ATRI 2020), cost of truck operation including fuel cost, maintenance, insurance, permit/licenses, tires, wages, benefits, and administration, truck operations were assumed to be $1.38 per mile. For control routes, salt brine production cost component in Equation 1 was not considered and the rest of the cost elements remained the same. Since treatment costs are a function of the number of storms and intensity, costs were normalized per lane-miles and number of storms with data available. It is important to mention that a sample of all storms during the winter season were analyzed in this study, so estimates need to reflect entire winter seasons which will be explained in more detail in sections 2.3.4.3. Salt Brine Routes and 2.3.4.4. Storms.

$$\begin{array}{c}Treatment\\ (\$/ln-mi/storm)\end{array} = \frac{Salt\ (ton) \times Cost\ Salt\ (\$/ton) + Brine\ (gal) \times [Water\ (\$/gal) + Electricity\ (\$/gal)] + Trips\ (n) \times Length\ (mi/n) \times Truck\ Ope.\ (\$/mi)}{Route\ (ln-mi) \times Storms} \quad (1)$$

With the computed cost of treatments at study and control routes, the benefit can be estimated. The benefit was calculated as the difference in cost of treatment between study and control routes. Figure 5 illustrates the cost components covered in Equation 1 for each route and calculation of the benefit.

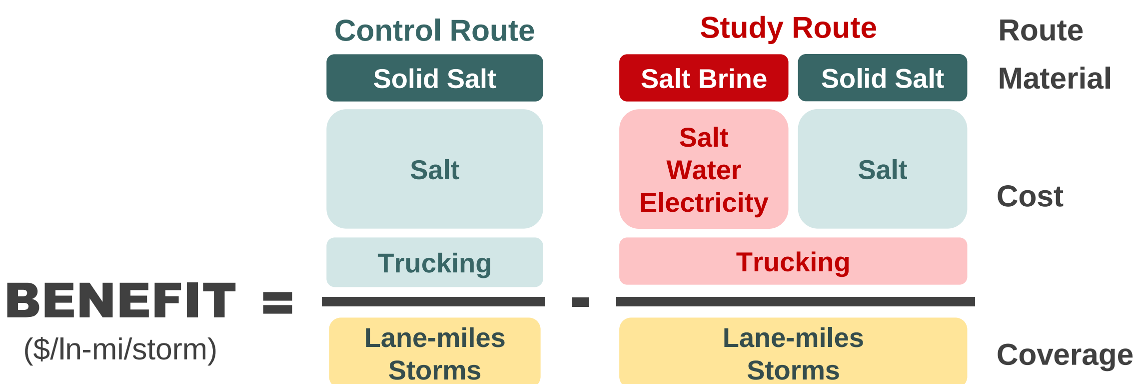

Figure 5. Illustration of costs considered for computation of the benefit

Since the benefit may be different by storm, it was crucial to capture the effect of storm conditions in the benefit estimation. With data available, it was possible to estimate the benefit as a function of pavement temperature and snow intensity. Benefit estimates were obtained for storms with pavement temperatures between 15°-19°F, 20°-25°F, and above 24°F and snow intensity categories defined as light (≤ 5 inches in 24 hours) and moderate/heavy (> 5 inches in 24 hours).

2.3.4.2. Cost

Investment was defined as the cost associated with introducing salt brine to existing and established solid salt applications. Three main components were considered for investment cost to introduce salt brine: salt brine production, trucks, and maintenance.

Salt brine production requires the acquisition of a brine maker, storage tanks, and related production/storage/loading equipment and facility (pumps, pipeline, etc.). In terms of trucks, counties regularly upgrade and purchase trucks based on life cycle, residual value, and other requirements. Thus, investment costs associated with trucks were the difference between the purchase of salt brine equipped trucks and solid salt trucks. Also, counties may not necessarily need to purchase new trucks, existing solid salt trucks may be retrofitted with salt brine add-ons which were considered as an investment. Maintenance is crucial for production and application of salt brine. Maintenance cost estimates were provided by counties which ranged from $15,000 to $31,484 per year, which included maintenance of brine maker, production/storage/loading system, and trucks. The benefit-cost analysis was conducted for a period of 10 years, so maintenance cost was also included for 10 years of analysis. Figure 6 illustrates the costs considered as an investment with the introduction of salt brine to existing solid salt practice.

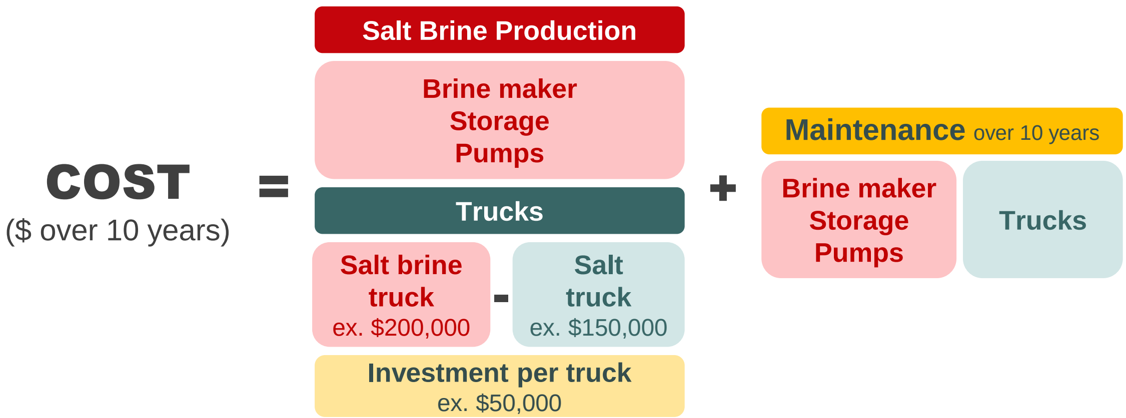

Figure 6. Illustration of the costs considered as an investment

2.3.4.3. Salt Brine Routes

Benefits were estimated based on the study and control routes data from a sample of storms during the 2020-2021 winter season. Thus, benefits needed to be normalized to overall lane-miles treated with salt brine in each county to estimate the overall benefit associated with the investment. Counties provided estimates of the number of interstate (IH), state (STH), and county (CTH) highway lane-miles maintained with salt brine, including direct liquid application, pre-wet, or Shake and Bake. Although state funding may target state highways (IH/STH), equipment has the capacity to cover significantly more lane-miles than just state highways. Consequently, benefit-cost (B/C) estimates were obtained separately for IH/STH highways only and IH/STH/CTH highways treated with salt brine in each county.

2.3.4.4. Storms

Benefits also needed to be estimated for the 10-year period of analysis according to the number of storms per year in each category of pavement temperature and snow intensity. Initially, historical winter severity index and number of storms per winter season were used in an exploratory analysis. However, the results did not provide B/C estimates that reflected the frequency of storms according to storm conditions. The research team collected additional historical data for each county based on the number of storms observed in each winter season since 2013. The mean number of storms per season according to pavement temperature and snow intensity were obtained, capturing the variation and types of storms frequently observed during a winter season. This approach matched pavement temperature and snow intensity categories used to estimate the benefits.

2.3.4.5. Unit Cost Variation Over Time

When conducting an analysis over a period of 10 years, unit costs such as the cost of salt per ton may change over the years (increase most likely). Unit costs may also be influenced by inflation, higher costs of equipment parts, and higher labor costs which may result in higher maintenance costs. The research team evaluated these potential changes in unit costs over time which cannot be estimated with any degree of certainty and would only be a guess. Therefore, unit costs observed during the period of data collection (2020-2021) and reported by counties were assumed to remain fixed over the years for the benefit-cost analysis.

3. RESULTS

Analysis consisted of comparing performance measures at study and controls routes. The results of the analysis consist of salt use, time to bare/wet, pavement friction, and benefit-cost. Although data from 10 counties were collected, data for some of the counties were not used due to limited data, missing data, or conditions in which the analysis was not consistent with other counties. For instance, in the evaluation of salt use, data from Marathon, Outagamie, and Price were not included for that specific analysis. Also, some storms included chemical materials other than salt brine and dry salt (i.e., Calcium Chloride). The evaluation focused exclusively on data from storms with salt brine application, consistent, and complete data.

3.1. Salt Use

Data from three counties were not included in this analysis because of limited storm data or other chemical materials were used (Marathon, Outagamie, and Price). Dane County data was used as a control route for Jefferson County. Results of the evaluation of salt use by county indicate that each of the six counties had an average reduction in salt use between 16.4%-26.8% when using salt brine in comparison to solid salt. From all counties, there was a statistically **significant average reduction in salt use of 23.0%**. The aggregated estimate was weighted based on the number of storms available and magnitude of difference by county.

Table 2. Summary of salt use results

County	Storms	Average Salt Use (lb/ln-mi)		Comparison		
		Study	Control	Difference	%	p-value
Brown	10	789	1,037	249	24.0	0.085
Jefferson	8	807	1,035	229	22.1	0.265
Marquette	13	356	426	70	16.4	0.276
Shawano	8	330	463	133	28.8	0.028
Washington	14	744	944	200	21.2	0.072
Wood	21	307	420	113	26.8	0.007
All	**74**	**520**	**675**	**155**	**23.0**	**< 0.001**

3.2. Time to Bare/Wet

Time to bare/wet is expressed in time to reach pavement bare/wet conditions since the beginning of the storm. The results of the comparison between study and control routes from five counties showed that time to bare/wet was reduced between 6.0%-15.2%. From all aggregated counties, there was a statistically **significant reduction in time to bare/wet of 11.9%**. The aggregated estimate was weighted based on the number of storms available and magnitude of difference by county. Data from four counties were not included in this analysis since time to bare/wet information was not available, or there was inconsistent reporting. Dane County data was used as a control route for Jefferson County.

Table 3. Summary of time to bare/wet results

County	Storms	Average Time to Bare/Wet (hr)		Comparison		
		Study	Control	Difference	%	p-value
Brown	10	24.4	26.3	1.9	7.2	0.078
Jefferson	4	28.0	32.2	4.3	13.2	0.077
Outagamie	12	19.0	22.1	3.1	14.0	0.453
Shawano	8	12.6	13.4	0.8	6.0	0.042
Wood	21	14.0	16.5	2.5	15.2	0.039
All	**55**	**17.8**	**20.2**	**2.4**	**11.9**	**< 0.001**

3.3. Pavement Friction

Estimates for pavement friction, road condition rating, and time series analysis were obtained. Friction data was collected by two counties: Jefferson and Wood. Jefferson County collected friction data at the Dane County line to conduct a split study design. The study route was located in Jefferson County on I-94 from Dane County line to WI-89. The control route was a short segment on I-94 in Dane County between Missouri Rd and Jefferson County line. A buffer of 1,000 feet was established between routes to avoid transitional measurements. In the case of Wood County, friction data collection ran into technical issues with the cellular connection of the device, so measurements were recorded intermittently, and locations of the measurements did not continuously track the route evaluated. Also, weather data from MDSS was not available for the Wood County location where friction data was collected since there was an update to the route in the system and weather data was not stored. Despite several efforts to use the collected data, it was not possible to conduct an analysis with Wood County's friction data.

3.3.1. Friction and Road Condition Rating

Results of the analysis with friction data from Jefferson County are illustrated in Figure 7, with friction values between 0-1 (0=low, 1=high). The figure shows a comparison of study and control routes mean friction values for specific periods during storms. **From 50 storm observations, 41 observations had higher mean pavement friction** values on the study route than the control route. Pavement friction values are important during winter storms to allow safe longitudinal and lateral vehicle maneuvers.

Also, as part of pavement friction data collection, other measurements were collected through the MARWIS device and ViewMondo application, and the road condition rating was provided. For specific periods during storms, Figure 8 provides a comparison between study and control routes' rating with a scale from 0-8 (0=poor, 8=great). **From 46 storm observations, 39 observations had higher mean road condition rating** on the study route than the control route.

Figure 7. Mean friction

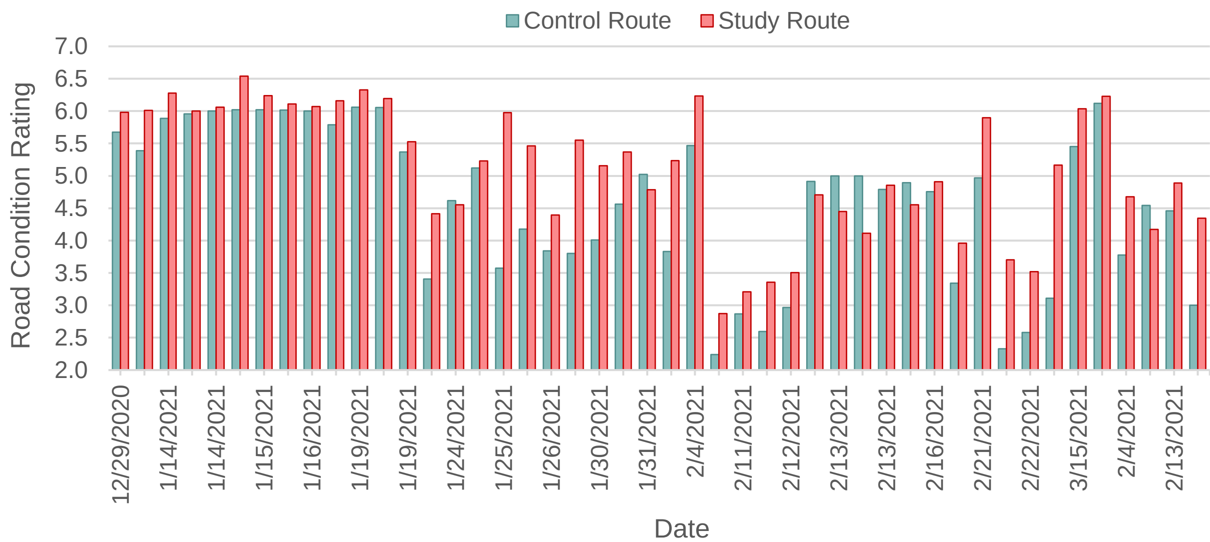

Figure 8. Mean road condition rating

Storm observations were aggregated for analysis, and results provided in Table 4 indicate that on average, **friction was 8.1% and road condition rating was 15.3% higher at the study route than the control route** (both statistically significant). In summary, better roadway conditions were observed in terms of friction data and rating at the study route treated with salt brine than the control route treated with solid salt.

Table 4. Mean friction and road condition rating

Description	Mean Friction	Mean Road Condition Rating
Study Route	0.703	5.339
Control Route	0.651	4.633
Difference	0.052	0.707
% (p-value)	**8.1 (0.017)**	**15.3 (0.002)**

3.3.2. Time Series

Friction data was evaluated in time series format for a selected number of storms for which complete data was available. Data required for the analysis included friction, water film height, pavement temperature, relative humidity, snow accumulation, snow rate, and AVL data. Three storms were evaluated in detail for relatively warm and steady temperature between 30°F-34°F (storm on 01/15/2021, Figure 9), variable humidity and dropping temperature from 29°F to 15°F (storm on 01/19/2021, Figure 10), and frigid temperatures below 3°F with consistent snow accumulation (storm on 02/13/2021, Figure 11). Period of analysis for each storm was based on the first and last friction data collection run during the storm. AVL data was used to identify the time in which the truck entered the route, plowed, and/or applied material.

From the time series analysis, friction is highly correlated to water film height since an increase in friction closely mirrors a decrease in water film height which may be one of the measures the optical device uses to estimate friction values. From observation of the times in which truck entered the route for the storm on 01/19/2021, it appears that there is an effect of improved pavement friction for most of the times that material was applied. Also, for storm on 02/13/2021, frequent application of material (Calcium Chloride and solid salt) under very low temperatures and formation of ice (between 1-3 PM) seemed to result in improved friction conditions and reduction of ice percentage.

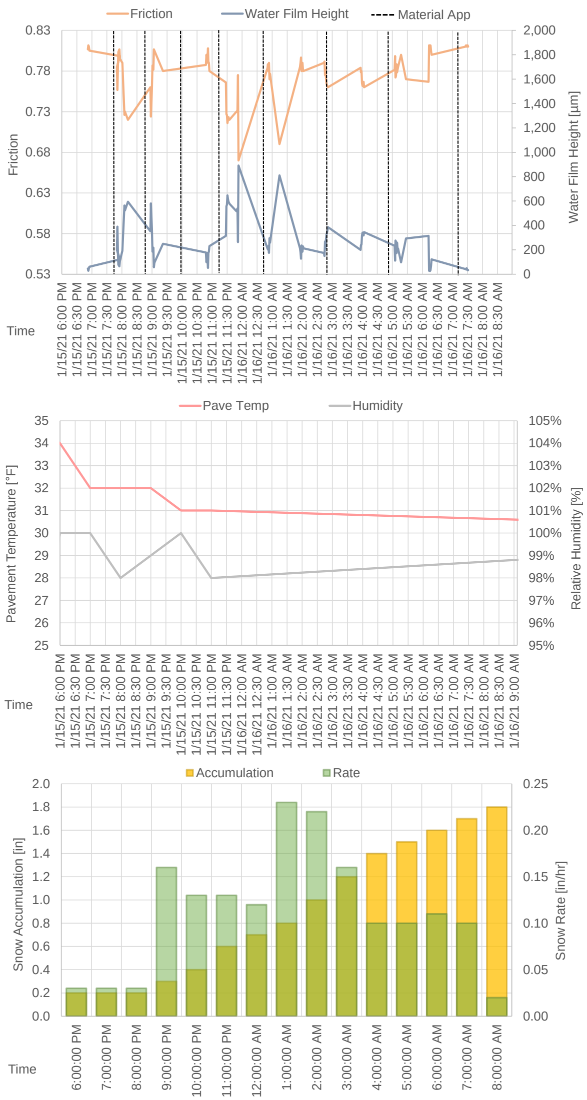

Figure 9. Storm on 01/15/2021

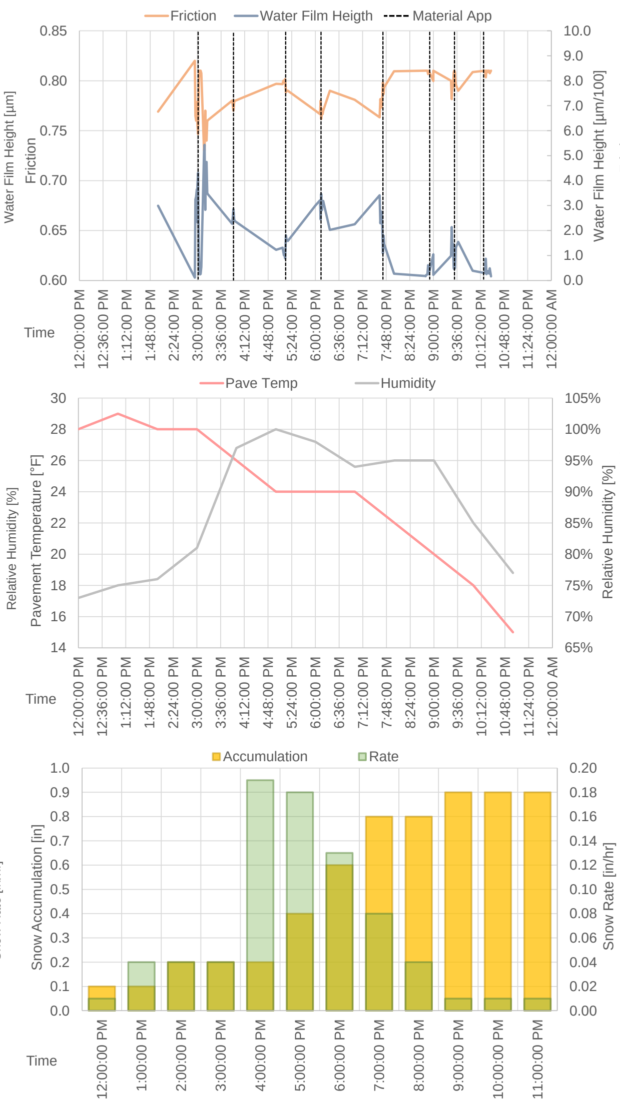

Figure 10. Storm on 01/19/2021

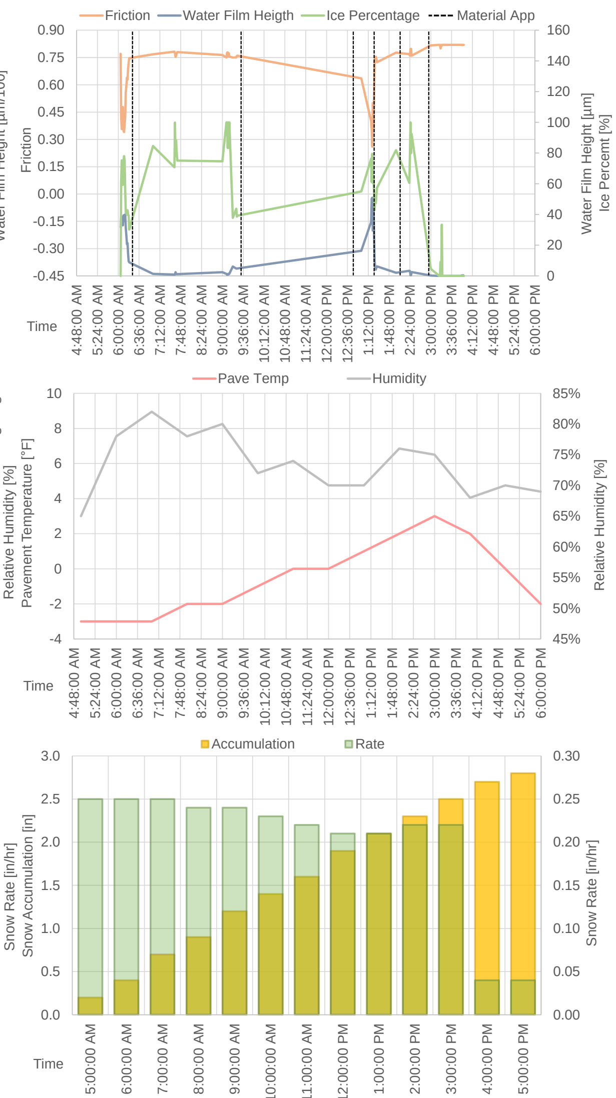

Figure 11. Storm on 02/13/2021

3.4. Benefit-Cost

Benefit-cost of introducing salt brine into existing solid salt applications was quantified for a 10-year horizon. First, benefits according to frequency and storm conditions were estimated. Second, parameters for the number of storms per winter season by pavement temperature and snow intensity were also estimated. Third, cost of investment was quantified, and the number of lane-miles treated with salt brine in each county were obtained. Finally, the benefit-cost ratio (B/C) for state highways (IH and STH) and all highways (IH, STH, and CTH) treated with salt brine were estimated.

3.4.1. Benefit

Benefits were estimated for all storms as illustrated in Figure 12. The distribution of benefits as a function of temperature show that the colder the temperature, there may be lower benefits. A total of 71 storms that were treated with salt brine only, or salt brine and solid salt, were evaluated for the benefit-cost analysis. The rest of the 143 storms used other treatment materials in addition to salt brine and/or solid salt. Based on the results by storm, it was found appropriate to obtain benefit estimates by temperature range and snow intensity to capture storm variations.

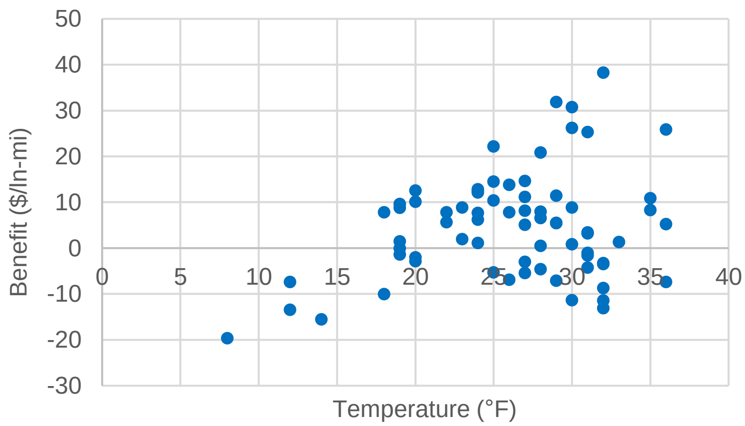

Figure 12. Benefit estimates by storm

Benefit estimates were obtained for storms with pavement temperatures between 15°-19°F, 20°-25°F, and above 24°F and snow intensity categories defined as light (≤ 5 inches in 24 hours) and moderate/heavy (> 5 inches in 24 hours). Table 5 provides the number of storms in each bin. Bins will be referred according to the designated row and column coding. For instance, bin with temperature above 24°F and light snow intensity will be referred as C1. For the benefit analysis, unfortunately, there were not enough storms below 15°F (no observations in bin O2) to complete the analysis for that temperature range. However, benefits were estimated for all the other bins, and results are provided in Table 6.

Table 5. Number of storms in each bin

Temperature		Snow Intensity	
		Light	Moderate/Heavy
	Bins	**1**	**2**
<15°F	**O**	4	0
15°F-19°F	**A**	3	4
20°F-24°F	**B**	8	6
>24°	**C**	31	15
All		**46**	**25**

Benefits by bin provide intuitive and consistent trend in $ per lane-mile per storm ($/ln-mi/storm). All benefits for bins with light snow intensity (A1, B1, C1) were higher than corresponding benefits for bins with moderate/heavy snow intensity (A2, B2, C2). Benefit in $/ln-mi/storm for bin A1 is $3.38 which is higher than bin A2 with $1.49. Also, when comparing benefits for bins according to temperature range, most benefits have an increasing trend from colder to warmer temperatures. For instance, benefits in $/ln-mi/storm for bin A2 is $1.49, for bin B2 is $4.68, and for bin C2 is $5.33—increasing benefits with warmer temperatures. Overall, there was a **mean benefit of $5.95/ln-mi/storm** when implementing salt brine compared to solid salt.

Table 6. Benefit estimated by bin

Bin	Storms	Study ($/ln-mi/storm)			Control ($/ln-mi/storm)			Benefit ($/ln-mi/storm)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
A1	3	7.62	**16.54**	25.43	9.08	**19.92**	25.34	-0.08	**3.38**	8.77
A2	4	11.10	**22.44**	30.37	18.91	**23.94**	28.96	-10.02	**1.49**	9.60
B1	8	0.91	**15.82**	30.76	13.46	**24.12**	38.59	1.97	**8.30**	12.55
B2	6	11.38	**28.17**	38.27	18.85	**32.85**	48.37	-2.83	**4.68**	12.84
C1	31	5.10	**22.09**	62.04	7.38	**28.80**	87.58	-11.34	**6.72**	38.26
C2	15	2.93	**36.72**	79.33	8.01	**42.03**	79.25	-13.08	**5.31**	31.83
All	67	0.91	**24.93**	79.33	7.38	**30.88**	87.58	-13.08	**5.95**	38.26

3.4.2. Winter Storm Parameters

Benefits needed to be estimated for the 10-year period of analysis according to the number of storms per year in each category of pavement temperature and snow intensity. The same binning configuration was used and the mean number of storms in each bin by county was estimated using historic data from the Winter Storm report system (TOPS 2020). Table 7 provides the results of winter storm parameters. Although bins O1 and O2 showed a significant number of storms since it covers all storms below 15°F, those storms were not considered in the benefit-cost analysis because it is not likely that salt brine application alone without any other blending material would be implemented under those conditions. Thus, in concordance with the benefit bin estimates, mean storms per season between 15°-19°F, 20°-25°F, above 24°F, and snow intensity light and moderate/heavy were considered for estimating the B/C ratio.

Table 7. Mean number of storms per season

County	Winter Storms per Season by Bin								
	O1	O2	A1	A2	B1	B2	C1	C2	All
Brown	2	1	2	1	3	3	17	6	**34**
Jefferson	2	3	2	1	2	2	11	7	**29**
Marquette	2	2	1	1	2	2	9	6	**26**
Shawano	3	3	3	2	4	3	8	10	**35**
Washington	4	1	2	1	4	2	16	4	**34**
Wood	4	3	3	1	3	2	13	7	**36**
All	**17**	**12**	**12**	**7**	**18**	**13**	**74**	**40**	**193**

3.4.3. Cost of Investment and Lane-Miles Treated

Additional data were collected from each of the counties considered in the benefit-cost analysis. A set of questions were sent out to each county to estimate the equipment purchased to produce, store, apply salt brine, and associated yearly maintenance costs. Also, counties maintain state, county, and in some cases local roads, so it was necessary to estimate the overall lane-miles treated with salt brine and how material is used (anti-icing, deicing) and applied in each county (pre-wet, direct application, Shake and Bake). Table 8 provides a summary of the estimates of cost of investment for a 10-year period and the lane-miles treated with salt brine in each county. Some costs were not available for some counties, so costs were assumed based on data available from counties with similar operations and equipment.

Table 8. Cost of investment and lane-miles treated by county

County	Brine Maker ($)	Storage/ Loading ($)	Add-ons/ Trucks ($)	Maintenance ($/year)	Investment and Maintenance ($/10 years)	Salt Brine Treated Lane-Miles (ln-mi)	
						IH/STH	IH/STH/CTH
Brown	$175,000	$45,000	$195,480	$15,000	$565,480	400	800
Jefferson	$150,000	$45,000	$418,563	$31,484	$928,403	550	1,080
Marquette	$191,100	$49,000	$195,480	$15,000	$585,580	246	674
Shawano	$175,000	$45,000	$195,480	$15,000	$565,480	524	524
Washington	$175,000	$45,000	$195,480	$15,000	$565,480	613	613
Wood	$163,650	$45,000	$418,563	$15,000	$777,213	429	1,079
All	**$1,029,750**	**$274,000**	**$1,619,046**	**$106,484**	**$3,987,636**	**2,762**	**4,770**

Notes: [1] IH=interstate, STH=state, and CTH= county highways.

3.4.4. Benefit-Cost Ratio

The benefit-cost ratios (B/C) for salt brine treated state highways (IH and STH) and all salt brine treated highways (IH, STH, and CTH) were estimated for each county and as an aggregate. The results are provided in Tables 9 and 10. **The aggregate B/C ratio of treating IH/STH highways in each county with salt brine compared to solid salt over a 10-year period is equal to 1.14**. B/C ratios by county ranged from 0.54 to 1.97. It is important to acknowledge that salt brine production capacity is not a limitation, and counties are able to maintain more roads (county highways and local roads in some cases) than just state highways, leading to effective use of resources. Therefore, **the aggregate B/C ratio of treating IH/STH/CTH highways in each county over a 10-year period is equal to 1.92**. B/C ratios by county ranged from 1.48 to 2.61. As expected, the more lane-miles treated with salt brine, the greater the benefit. In both cases, either considering IH/STH or IH/STH/CTH highways maintained with salt brine by each county, the B/C ratio was greater than one for a 10-year horizon.

Table 9. Benefit-cost ratio for IH/STH highways

County	Lane-Miles (ln-mi)	Benefit by Bin ($ over 10-years)[1]						Benefit ($/10-year)	Cost ($/10-year)	Benefit-Cost Ratio (B/C)
	IH/STH	A1	A2	B1	B2	C1	C2			
Brown	400	$25,371	$3,733	$99,597	$49,092	$443,433	$116,914	$738,140	$565,480	1.31
Jefferson	550	$34,865	$10,258	$85,540	$41,762	$401,620	$193,523	$767,567	$928,403	0.83
Marquette	246	$9,353	$3,669	$43,343	$24,416	$152,728	$83,256	$316,765	$585,580	0.54
Shawano	524	$44,330	$15,652	$152,267	$70,458	$290,543	$282,040	$855,290	$565,480	1.51
Washington	613	$49,248	$5,720	$216,218	$46,571	$653,789	$142,515	$1,114,061	$565,480	1.97
Wood	429	$36,305	$8,011	$111,341	$47,668	$382,156	$151,137	$736,618	$777,213	0.95
All	**2,762**	**$199,471**	**$47,043**	**$708,305**	**$279,967**	**$2,324,270**	**$969,386**	**$4,528,442**	**$3,987,636**	**1.14**

Notes: [1] A=15°-19°F, B=20°-25°F, C= above 24°F, 1=light snow (≤ 5 inches in 24 hours), 2=moderate/heavy snow (> 5 inches in 24 hours).

Table 10. Benefit-cost ratio for IH/STH/CTH highways

County	Lane-Miles (ln-mi)	Benefit by Bin ($ over 10-years)[1]						Benefit ($/10-year)	Cost ($/10-year)	Benefit-Cost Ratio (B/C)
	IH/STH/CTH	A1	A2	B1	B2	C1	C2			
Brown	800	$50,743	$7,465	$199,194	$98,184	$886,867	$233,828	$1,476,281	$565,480	2.61
Jefferson	1,080	$68,503	$20,156	$168,070	$82,054	$789,110	$380,236	$1,508,128	$928,403	1.62
Marquette	674	$25,651	$10,063	$118,873	$66,964	$418,877	$228,341	$868,768	$585,580	1.48
Shawano	524	$44,315	$15,647	$152,217	$70,435	$290,449	$281,949	$855,013	$565,480	1.51
Washington	613	$49,250	$5,720	$216,229	$46,573	$653,821	$142,522	$1,114,115	$565,480	1.97
Wood	1,079	$91,253	$20,137	$279,857	$119,814	$960,554	$379,884	$1,851,498	$777,213	2.38
All	**4,770**	**$329,715**	**$79,187**	**$1,134,439**	**$484,025**	**$3,999,676**	**$1,646,761**	**$7,673,803**	**$3,987,636**	**1.92**

Notes: [1] A=15°-19°F, B=20°-25°F, C= above 24°F, 1=light snow (≤ 5 inches in 24 hours), 2=moderate/heavy snow (> 5 inches in 24 hours).

4. CONCLUSIONS

Salt has been traditionally used in roadway maintenance treatments during winter storms. Due to increasing costs and environmental concerns, transportation agencies have been introducing responsible and sustainable winter maintenance practices to alleviate impacts. Salt brine is an alternative to reduce the amount of salt used in winter maintenance while providing similar or better roadway conditions and road user experience. Salt brine has been implemented in Wisconsin for several years and there is a need to evaluate its performance.

In this research project, data collection and analysis were expanded from previous efforts to evaluate salt brine performance in 10 counties. Analyses included amount of salt used, time to bare/wet, pavement friction, and benefit-cost. Field data was collected for 143 storms from the 10 counties during the 2020-2021 winter season. Key findings of this research include the following:

- **Salt Use** Six counties were evaluated and had a reduction in salt use between 16.4%-26.8% when using salt brine in comparison to solid salt. From all six counties, there was a statistically significant reduction in salt use of 23.0%.
- **Time to bare/wet** Five counties evaluated showed that time to bare/wet was reduced between 6.0%-15.2%. From all five counties, there was a statistically significant reduction in time to bare/wet of 11.9%.
- **Friction and Road Condition Rating** From 50 storm observations, 41 observations had higher mean pavement friction values on the study route than the control route. From 46 storm observations, 39 observations had higher mean road condition rating on the study route than the control route. On average, friction was 8.1% and road condition rating was 15.3% higher on the study route than the control route (both statistically significant).
- **Benefits** Estimated benefits according to temperature range have an increasing trend from colder to warmer temperatures. Similarly, benefits for storms with light snow intensity were higher than moderate/heavy snow intensity. Overall, there was a mean benefit of $5.95/ln-mi/storm when implementing salt brine compared to solid salt.
- **Benefit-Cost (B/C)** The aggregate B/C ratio (over a 10-year period) of treating IH/STH highways in each county with salt brine compared to solid salt is equal to 1.14. B/C ratios by county ranged from 0.54 to 1.97. The aggregate B/C ratio of treating IH/STH/CTH highways in each county is equal to 1.92. B/C ratios by county ranged from 1.48 to 2.61.

Through the analysis of diverse data from different sources including field data, the results of this study conclusively indicate that salt brine applications reduced the amount of salt used, improved time to bare/wet, presented better pavement friction conditions, and benefits outweighed the cost of investment to introduce salt brine to existing solid salt applications.

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