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Winter Maintenance Field Evaluation of Salt Brine Applications

--Manuscript Draft--

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WINTER MAINTENANCE FIELD EVALUATION OF SALT BRINE APPLICATIONS

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ABSTRACT

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 implementation is an alternative to reduce the amount of salt used in winter maintenance. Laboratory tests have provided evidence of benefits and effectiveness of salt brine. However, laboratory findings may not replicate complex dynamics in the field. Thus, field data was collected in four counties in Wisconsin to evaluate pairs of study and control roadway segments and quantify material usage, cost, and performance. Study routes were mainly treated with salt brine and control routes were treated with conventional solid salt. Data collection consisted of route, equipment, and storm data (weather, materials, time to bare/wet, and travel speed). The focus of the analysis was to compare total salt and cost per lane-mile, time to bare/wet, and travel speed. Statistical tests were used to compare population means of paired observations of study and control routes. Storm data analysis included 70 winter storms. The results of this research show a 34% reduction in overall salt while there was no difference in material costs between study and control groups. However, lesser times to bare/wet with salt brine indicates that less operations/labor time and improved level of service may reduce total costs compared to solid salt. This paper contributes to exiting literature by providing a systematic field data collection process and analysis of winter maintenance performance measures using study and control routes under the same weather conditions.

Keywords: Salt brine, winter, maintenance, cost, speed.

INTRODUCTION

Salt has been traditionally used as a deicer material in roadway maintenance treatments during winter storm conditions. Driven by driver expectations and level of service, the use of salt has significantly increased over the years. With the increasing cost of salt, high demand, and limited budgets (*1*); agencies have been introducing alternative materials in liquid form for winter maintenance. At the same time, there is a growing concern over the impact of winter maintenance practices on the environment (including soil, flora, fauna, surface/ground water), human health, and damage to vehicles and infrastructure (*2-10*).

Salt brine implementation is an alternative to reduce the amount of salt used in winter maintenance. Salt brine is a liquid solution of water and salt in which salt concentration is usually 23% of the aqueous solution. Since salt brine has a lower concentration of salt, less salt is released into the environment. The use of salt brine in winter maintenance is not a recent practice and it has been implemented over the last couple of decades. Laboratory tests have provided evidence of benefits and effectiveness of salt brine (*11-16*). However, laboratory tests may not directly translate to complex dynamics in the field.

The primary objective of this research was to compare the usage of liquid brine with solid salt in winter maintenance, using data from four counties in Wisconsin during the 2018-2019 winter season. The experiment design consisted of evaluating pairs of study and control roadway segments to quantify material usage, cost, and performance. Study routes were mainly treated with salt brine and control routes were treated with conventional solid salt. Data collection consisted of route, equipment, and storm data (weather, materials, time to bare/wet, and speed). The focus of the analysis was to compare study and control routes total salt and cost per lane-mile, time to bare/wet, and travel speed. Paired t-tests were used to compare population means of the two samples—study and control routes paired observations. Storm data analysis included 70 winter storms from four counties located in different geographical regions across Wisconsin.

LITERATURE REVIEW

There is a growing concern over the impact of winter maintenance practices on the environment including soil, flora, fauna, surface/ground water, and human health. Conclusive evidence shows that chloride salts have a negative effect on the environment (*2-8*). Since there is a predominant use of chlorides in winter maintenance, much of the material ends up in nearby water bodies (*4, 5*). Dugan et al. (*4*) reported that 44% of 371 freshwater lakes in North America had undergone long-term salinization. Extrapolating the results, 47 lakes are in track to reach chloride concentrations of 100 mg/l and 14 are expected to surpass 230 mg/l (EPA's aquatic life criterion concentration) by year 2050—concentration level at which drinking water deterioration is perceptible (*4*). Although the effects of other chemicals have been less investigated (i.e. urea, glycols, acetates, agro-based products), there are still environmental concerns with impacts on aquatic ecosystems (*3*, *7*). Ecosystems such as surface waters have physical, biological, and chemical seasonal cycles that adapt to changes at a slow pace (*8*). Short events such as spring snowmelt and storm water runoff can lead to pulse discharges of deicers and abrasives into surface waters (*3*).

According to a study on corrosion in the United Sates, the direct cost of metallic corrosion is $276 billion per year (*9*). Cost of corrosion by industry indicates that transportation and infrastructure account for 21.5% and 16.4%, respectively. For the cost of corrosion in infrastructure, 37% of the cost was from highway bridges. Corrosion is a natural process and takes many forms, its occurrence and associated costs cannot be completely eliminated. However, it was estimated that 25-30% of annual corrosion costs could be reduced with optimal management and engineering practices (*9*).

A vast amount of research has been conducted on the damaging effects of deicers on concrete. Deicers should be of concern with marginal quality concrete. Laboratory tests expose concrete samples to accelerated and aggressive conditions which may not translate to real field conditions and the effects of deicers may be negligible in the durability of properly produced, cured, and finished concrete (*17, 18*).

Agro-based products are increasingly being used for anti-icing and deicing winter maintenance activities. Performance of agro-based products has mostly been documented from anecdotal field observations. Despite reported advantages, there are still concerns regarding their toxicity to aquatic ecosystems, attraction of wild animals, increased cost of winter maintenance, effectiveness, and quality control (consistency of product). Little is known about the mechanisms that may lead to the observed benefits. Commercial agro-based products may contain additional chemicals which may be attributed for enhanced product performance. Products with sugar beet exhibited lower ice melting capacities suggesting that agro-based products are not suitable as liquid deicers at low temperatures (*12*).

Selection of deicer products directly influences the cost of winter maintenance operations. Direct cost of winter maintenance includes cost of material (chemicals, number of storms, and severity of storms), equipment (brine maker, storage, operating hours, fuel, maintenance, etc.), and staffing (wages, benefits, overtime, standby, training, etc.). Indirect costs may be associated with negative impacts on motor vehicles, transportation infrastructure, and the environment (*13*). It is a complex task to estimate the overall cost of winter maintenance—type, amount, and cost of material.

Liquid applications have become more common in winter maintenance and in-house production is practical. In the case of salt brine, true cost of in-house salt brine should include capital costs (brine maker, storage, and entire system components). Reported costs of brine per gallon were between $0.05-0.35 (*19*); however, little information on equipment, labor, and material costs were considered. Crow et al. (*20*) conducted a case study in Ohio to estimate the true cost of salt brine. Using Mote Carlo simulation, equations of brine, salt, electric, and capital cost were simulated one million times to find the average cost of brine and range of variation. Since the cost is highly dependent on the cost of salt per ton, a range of costs was estimated. The true cost of salt brine was between $0.13-0.17/gal (for $45.3-82.72 per ton of salt). Cost of storage was not accounted for in the calculations (*20*).

As mentioned previously, calculation of the true cost of salt brine is complex and varies based on the production capacity/storage and unit costs considered. For instance, Keep (*21*) argued that estimated true costs of salt brine in the range of $0.08-0.10/gal omit and underestimate in-house costs associated with labor, equipment, and material. Assumed costs of a brine maker and complete new system were $60,000, and repairs and maintenance over 10 years was $10,000, in addition to indirect costs and residual value of equipment. Keep (*21*) estimated that the true cost of salt brine per gallon was $0.22.

Estimating the cost of material used in winter maintenance is just one aspect of the process of decision making for effective operations. It is important to consider the most effective treatment at a reasonable cost. Fitch et al. (*22*) reported that the cost of winter maintenance with solid salt was $3,149 and with salt brine $3,343 per typical 100 lane miles (insignificant difference of cost per storm basis). From a survey conducted by Ye et al. (*23*), the weighted average application rate of 28 gallons per lane mile with salt brine was estimated to be $0.14/gal and for $MgCl_2$ was $0.72/gal, indicating a considerable difference in cost per gallon. Estimates of average annual direct costs (material, equipment, and staffing) in lanes per mile were $123 (solid salt), $121 (salt brine), and $263 ($MgCl_2$). Salt brine was slightly more cost effective than solid salt. $MgCl_2$ based products had higher cost likely due to the inclusion of corrosion inhibitor (*23*). Sand is relatively inexpensive, but environmental impacts and cleanup activities can make it less cost-effective (*13*).

A comprehensive benefit-cost analysis of several winter maintenance strategies was conducted by Fay et al. (*19*). Information considered were reported costs, benefits, effectiveness of achieving level of service, performance, pros and cons, and environmental impacts. The analysis was divided into winter activities and strategies (basic, intermediate, and advanced). Basic strategies consisted of initiatives to maintain traveler mobility and safety (i.e. plowing, abrasives). Intermediate strategies focused on mechanical snow removal through plowing and application of conventional chemical materials (solid salt or salt brine). Advanced strategies considered more expensive and chemically enhanced materials for applications in lower temperatures and corrosion prevention (magnesium chloride, calcium chloride, corrosion inhibitor, blended products). Overall, the most cost effective activities for basic and intermediate strategies were plowing and salt brine application. In more advanced winter activities, all maintenance strategies proved to be cost effective alternatives such as the use of corrosion inhibitors, $MgCl_2$, or $CaCl_2$. When comparing maintenance strategies of solid salt and salt brine applications, salt brine was 1.58 times more cost effective than solid salt (*19*).

METHODOLOGY

Winter maintenance practices vary across northern 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, data collection was conducted on study and control routes (in each county) at the same time and under the same weather conditions to quantify material usage, costs, and performance. Field data by storm event was collected during the 2018-2019 winter season from four counties (Brown, Eau Claire, Jefferson, and Wood).

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

Route Selection

Selection of study and control routes consisted of homogeneous and comparable segments. The study design required routes treated with salt brine and 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 the following guidelines.

Each study site (liquid brine route) had a control site (solid salt route) pair. Although the study site was designated as a route with salt brine application, dry or pre-wetted salt may have been used as required by storm conditions. Each pair of sites (study and control) 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.

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.

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

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

Data Collection
Data was collected from each county through report forms and an online winter storm report system hosted in the WisTransPortal (*24*). All 72 counties already report overall county level material, labor, and operations for every storm. Thus, for the four 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). Disaggregated data included speed from sensors in 5-minute intervals from the WisTransPortal (*24*) and weather from the MDSS (*25*).

Routes
Study and control routes data were collected from each participating county. The following information was collected:

- County
- Roadway name
- Direction
- Beginning of route
- End of route
- Length of route (mi)
- Number of lanes by direction
- Map

Winter Storm Report
Through the online report form, each county submitted information regarding individual storms for study and control routes during the 2018-2019 winter season. 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)
    - Air temperature (when crew OUT and IN)
    - Humidity (when crew OUT and IN)
    - Wind speed (when crew OUT and IN)
    - Wind direction (when crew OUT and IN)
    - Crew OUT and IN time
- Study/Control Route

- 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
  - Effective truck hours on the road
  - Salt brine or solid salt application rate (gal or lb/ln-mi)
  - Application frequency (min)
  - Cycle of truck (min)
  - Unused material in truck at the end of cycle/storm (gal, lb)
- Performance measures
  - Bare/wet time
  - Video (optional)
  - Traffic speed (mph) (optional)

- Comments

Data Analysis

Data evaluated consisted of storm data which included materials, weather conditions, application rates, costs, and performance measures observed at study and control routes. Pairwise comparison was conducted to quantify the difference between control and study routes.

Materials

Primary materials used were salt brine on study routes and solid salt on control routes. Other materials used were calcium chloride ($CaCl_2$), Beet Heet®, and Geo-melt®. The analysis of material focused on the overall amount of salt used by route. Thus, 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 on the corresponding route for comparison between study and control routes. It should be noted that material per lane-mile is a function of the number, duration, and intensity of storms; so it is not comparable to application rates.

Cost of Material

The average cost of salt in Wisconsin was $73.51/ton for the 2018-2019 winter season. Counties reported cost of salt brine between $0.13-0.15/gal. For this study, two costs of salt brine were considered: $0.08/gal (only considering cost of salt in brine) and $0.14/gal (including material and production cost). The cost of other agents used were calcium chloride ($CaCl_2$) at $0.63-0.84/gal, Beet Heet® at $1.60/gal, and Geo-melt® at $2.00/gal. Overall treatment costs included all materials provided per lane-mile for the corresponding route.

As discussed in the literature review, there are strong arguments about the true cost of salt brine as a material. One side of the argument is that the production cost of salt brine is negligible and therefore should include only the cost of salt in brine. The other side of the argument states that the true cost of salt brine should include capital, material (salt and water), and production/operation (labor and electricity) costs. However, the focus on the cost of material may be misleading since the cost of winter treatments with salt brine and solid salt may significantly differ based on equipment, operations, and effectiveness in the field (reducing operation and labor costs). Also, unmeasurable benefits and cost savings in vehicle corrosion, damage to infrastructure, and less salt released into the environment should be acknowledged. Therefore, the overall cost of material should be interpreted with caution and associated with the effectiveness and performance of the treatment.

Application Rates and Frequency

Reported application rates and frequency were plotted in relation to pavement and air temperatures to identify trends. Application rates and frequency were also interpreted along with the amount of snow and duration of storm.

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 (*1*).

Paired t-test

Statistical paired t-test was used to compare the population means of two samples in which the observations in the study site/group were paired with the observations in the control site/group. 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 sites/groups was statistically significant. Along with the results, corresponding p-values of the paired t-test were provided. The analysis was conducted at the site (paired routes) and aggregated group level (paired route groups).

RESULTS

Study and control routes were used to compare material, cost, application rates, time to bare/wet, and travel speed. Four counties provided storm data for analysis—Brown, Eau Claire, Jefferson, and Wood counties. From the overall 84 winter storms submitted for analysis, 14 storms were dropped (due to insufficient or inconsistent data), leaving a total of 70 winter storms for the evaluation. Results are provided by comparison group (paired routes) and county (paired route groups) for the winter season of 2018-2019.

Comparison of Routes by Group

Experimental group was composed of study routes with salt brine treatment and comparison group was composed of control routes with solid salt treatment. Each study route had a comparable pair route in the control group. Some assumptions were required for some sites that did not have available data. For instance, Eau Claire routes did not have time to bare/wet data, and the comparison group analysis for time to bare/wet only included routes from Brown, Jefferson, and Wood counties. Also, Jefferson County had two control routes, so control route 1 was selected since it had the most consistent and complete data (control route 2 did not have time to bare/wet data). The aggregated data for the experimental and control groups were used for comparison and the results of the analysis are presented in Table 1.

TABLE 1 Comparison Group Analysis Results

Description	Study Group	Control Group	Comparison		p-value
Average Salt (lb/ln-mi)	870	1,313	-443	-34%	< 0.001
Average Cost Material (Salt Brine $0.08/gal) ($/ln-mi)	$38	$49	-$11	-22%	0.002
Average Cost Material (Salt Brine $0.14/gal) ($/ln-mi)	$51	$49	+$2	+4%	0.601
Average Time to Bare/Wet (hr)	11.2	16.3	-5.1	-31%	< 0.001

During 70 reported storms, total salt per lane-mile in the study group was 870 lb/lane-mile and 1,313 lb/lane-mile in the control group. The comparison group analysis results showed that there was an overall reduction in salt use of 34% for study routes compared to control routes.

In terms of material costs, considering the price of salt brine at $0.08/gal, the average cost of material per lane-mile per storm on the study group was reduced by 22% compared to the control group ($38 and $49 per lane-mile, respectively). When the cost of salt brine was considered $0.14/gal, there was no statistical difference in cost between study and control groups. Brown and Eau Claire county routes showed an increase in cost when the cost of salt brine included material and production costs.

On average the study route reached bare/wet conditions 5.1 hours earlier that the control route which resulted in 31% less time required in operations and labor. Although the aggregated analysis of cost of material alone may suggest similar material costs, time to bare/wet indicates that less operations/labor time may reduce overall treatment costs when using salt brine compared to solid salt.

Comparison of Routes by County

More detailed information of study and control route is provided by county and storm. Comparison of routes by county consisted of pairwise comparisons of material, costs, and performance measures. A summary of the results is provided in Table 2.

All four counties had statistically significant reduction in salt usage on study routes compared to control routes. There were mixed results with the analysis of cost of material based on the assumed cost of salt brine. Brown and Eau Claire county routes showed an increase in cost when the cost of salt brine included material and production costs. Jefferson and Wood county routes showed reduction in cost of material between study and control routes. Brown, Jefferson, and Wood county study routes, on average, reached bare/wet conditions 3-7 hours before control routes.

The following sections provide detailed description of county routes characteristic, materials usage, costs, weather, application rates/frequency, and time to bare/wet by storm (Figures 1-4).

TABLE 2 Summary of Results by County

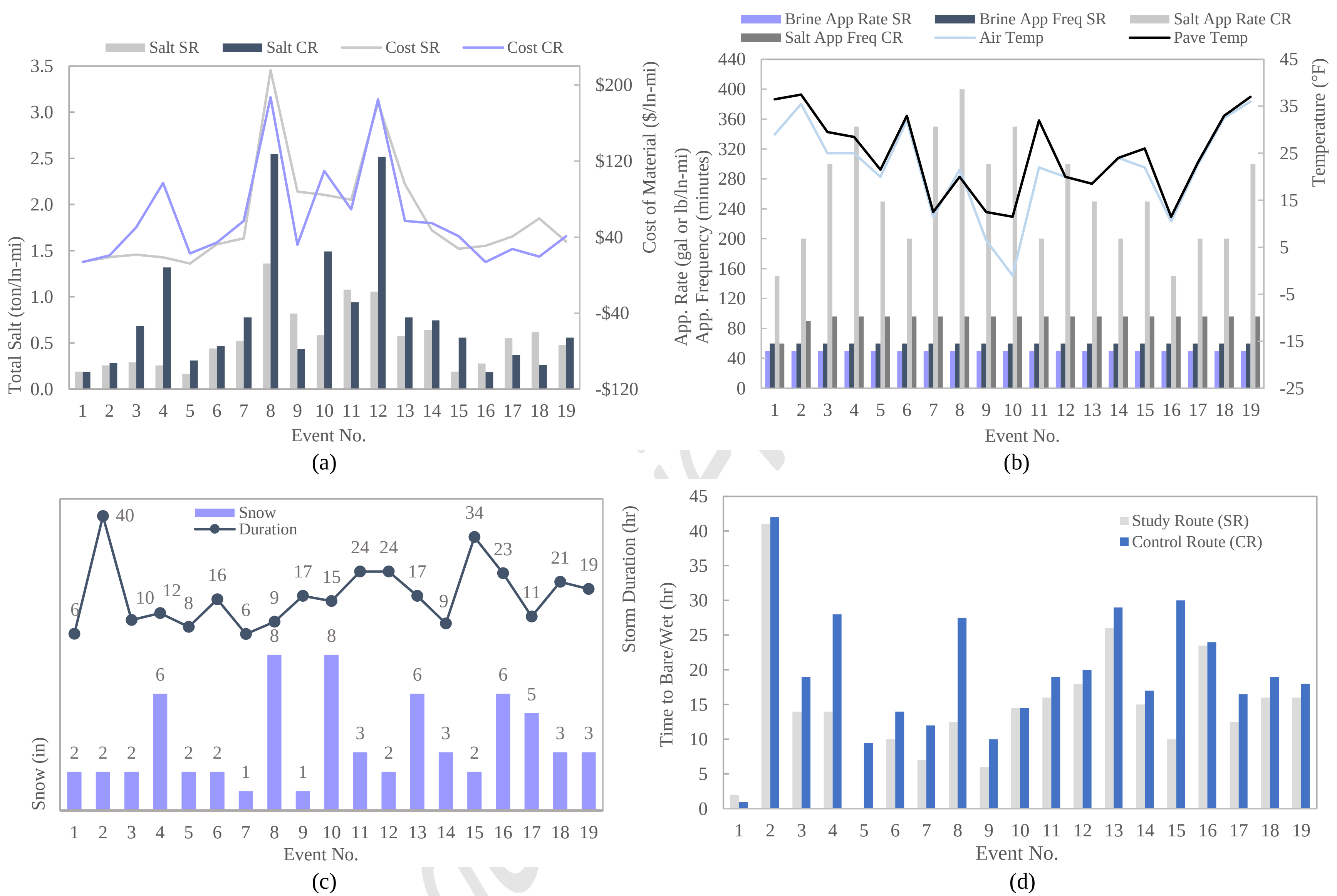
County	Description	Study Route	Control Route	Comparison		p-value
Brown	Length (mi)	13.3	8.7			
	Lane-mile (ln-mi)	29.0	32.2			
	Study Design	Independent Routes				
	Storm Events	19				
	Total Salt Used (ton)[1]	301	496			
	Total Salt (ton/ln-mi)	10.4	15.4			
	Total Cost of Material	$33,124	$36,497			
	Total Cost Material ($/ln-mi)[2]	$1,142	$1,133			
	Average Salt (lb/ln-mi)	1,093	1,623	-531	-33%	0.040
	Average Cost Material ($/ln-mi)	$60.1	$59.7	+$0.4	+0.8%	0.948
	Average Time to Bare/Wet (hr)	14.4	19.5	-5.1	-26%	0.001
Eau Claire[3]	Length (mi)	5.8	6.7			
	Lane-mile (ln-mi)	17.0	18.9			
	Study Design	Parallel Routes				
	Storm Events	10				
	Total Salt Used (ton)[1]	87	122			
	Total Salt (ton/ln-mi)	5.1	6.5			
	Total Cost of Material	$1,024	$1,296			
	Total Cost Material ($/ln-mi)[2]	$6,395	$9,401			
	Average Salt (lb/ln-mi)	376	497	-121	-24%	0.040
	Average Cost Material ($/ln-mi)	$37.6	$49.7	-$12.1	-24.4%	0.948
Jefferson[4]	Length (mi)	25.0	14.0/13.0			
	Lane-mile (ln-mi)	100.0	65.6/52.0			
	Study Design	Split Routes				
	Storm Events	23				
	Total Salt Used (ton)[1]	1,285	1,313/776			
	Total Salt (ton/ln-mi)	12.9	20.0/14.9			
	Total Cost of Material	$1,118	1,740/1,297			
	Total Cost Material ($/ln-mi)[2]	$96,514	$96,501/$57,034			
	Average Salt (lb/ln-mi)	965	$1,471/$1,097	-622/-180	-36%/-14%	0.001/0.239
	Average Cost Material ($/ln-mi)	$42.0	$63.9/$47.7	-$22/-$6	-46%/-12%	0.001/0.300
	Average Time to Bare/Wet (hr)	9.7	16.8	-7.1	-42%	0.001
Wood	Length (mi)	24.0	28.3			
	Lane-mile (ln-mi)	48.0	56.6			
	Study Design	Split Routes				
	Storm Events	18				
	Total Salt Used (ton)[1]	101	229			
	Total Salt (ton/ln-mi)	2.1	4.0			
	Total Cost of Material	$234	$450			
	Total Cost Material ($/ln-mi)[2]	$7,432	$16,840			
	Average Salt (lb/ln-mi)	155	298	-143	-48%	0.019
	Average Cost Material ($/ln-mi)	$8.6	$16.5	-$7.9	-48.0%	0.019
	Average Time to Bare/Wet (hr)	9.8	12.5	-2.7	-22%	0.001

Notes: [1] Total salt includes salt in brine; [2] cost of material includes cost of solid salt, salt brine at $0.08 gal, and other additives, [3] time to bare/wet were not available in Eau Claire County; [4] two control routes were used for Jefferson County; mi = miles, lb = pounds, ln-mi = lane-mile, hr = hours.

Brown County

Routes followed the independent route selection criteria along suburban collectors. Study route consisted of 29.0 lane-mile road segment compared to a control route of 32.2 lane-mile road segment. On the study route, events 8-10, 12, 13, 15, 16, and 18, Geo-Melt® and/or $CaCl_2$ were used in addition to salt brine. During 19 reported storms, total salt per lane-mile used on the study route was 10.4 ton/lane-mile and 15.4 ton/lane-mile on the control route. On average, there was 33% less salt used on the study route (with salt brine) per storm compared to the control route (with solid salt).

With salt brine at $0.08/gal, the average cost of material per lane-mile per storm was basically the same at study and control routes ($60.1 and $59.7 per lane-mile, respectively). Considering $0.14/gal, there was an increase in cost of 45% at the study route compared to the control route. On average the study route reached bare/wet conditions 5.1 hours earlier that the control route which resulted in 26% less time required in operations and labor. Reported application rates of salt brine were 50 gal/lane-mile and solid salt between 150-400 lb/lane-mile. The frequency of applications was 60 minutes for salt brine and 96 minutes for solid salt. Figure 1 provides total salt, cost of material (salt brine at $0.08/gal), applications rates/frequency, snow and storm duration, and time to bare/wet by storm event.



Notes: SR = Study Route, CR = Control Route, ln-mi = lane-mile, hr = hours, in = inches, App. = application, Freq. = frequency, Pave. = pavement, Temp.= temperature.

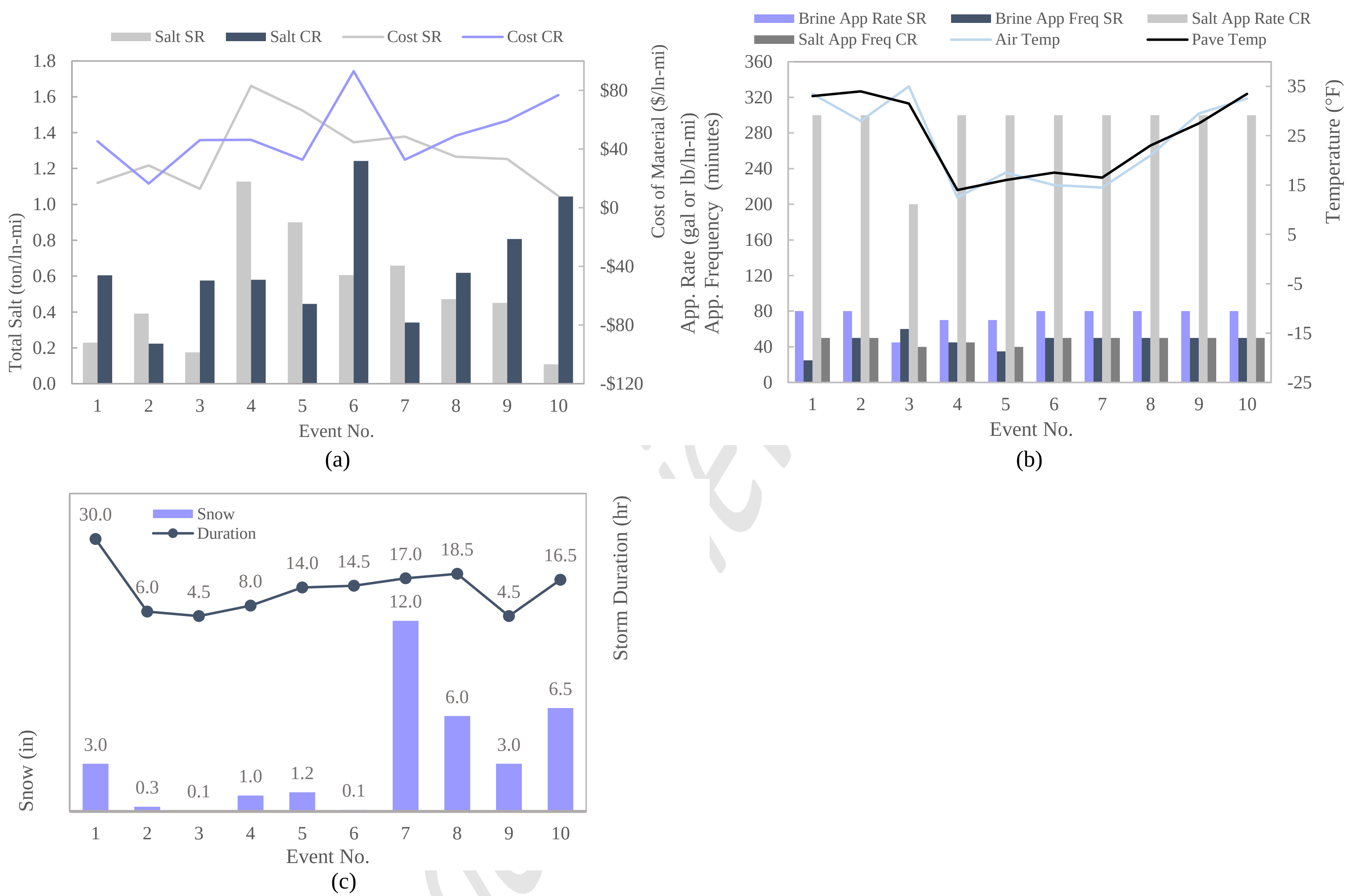
Figure 1 Brown County (a) salt and cost of material, (b) app. rate/frequency, (c) snow and storm duration, and (d) time to bare/wet

Eau Claire County

Routes followed parallel route selection criteria along an urban collector. Study route consisted of 17.0 lane-mile road segment compared to a control route with 18.9 lane-mile road segment. On the study route, in events 2, 4, and 7, solid salt was used in addition to salt brine. On the control route, $CaCl_2$ (events 4, 7, and 8) and Beet Heet® (events 1, 3, and 6) were used in addition to solid salt. During 10 reported storms, total salt per lane-mile on the study route was 5.1 ton/lane-mile and 6.5 ton/lane-mile on the control route. On average, there was 21% less salt used on the study route per storm compared to the control route. There were mixed results that may be attributed to the reduced amount of material used and short segments evaluated (5.4 and 6.7 mile segments).

Considering the price of salt brine at $0.08/gal, the average cost of material per lane-mile per storm was 24% lower on the study route compared to the control route ($38 and $50 per lane-mile, respectively). When the cost of salt brine was considered $0.14/gal, there was an increase in cost of 10% for the study route compared to the control route. Unfortunately, times to bare/wet were not available by route in Eau Claire County.

Reported application rates of salt brine were between 45-80 gal/lane-mile and solid salt between 200-300 lb/lane-mile. The frequency of applications was between 25-60 minutes for salt brine and 40-50 minutes for solid salt. Salt brine to pre-wet solid salt was used at a rate of 15 gal/ton. Figure 2 provides total salt, cost of material (salt brine at $0.08/gal), applications rates/frequency, and snow and storm duration by storm event.



Notes: SR = Study Route, CR = Control Route, ln-mi = lane-mile, hr = hours, in = inches, App. = application, Freq. = frequency, Pave. = pavement, Temp.= temperature.

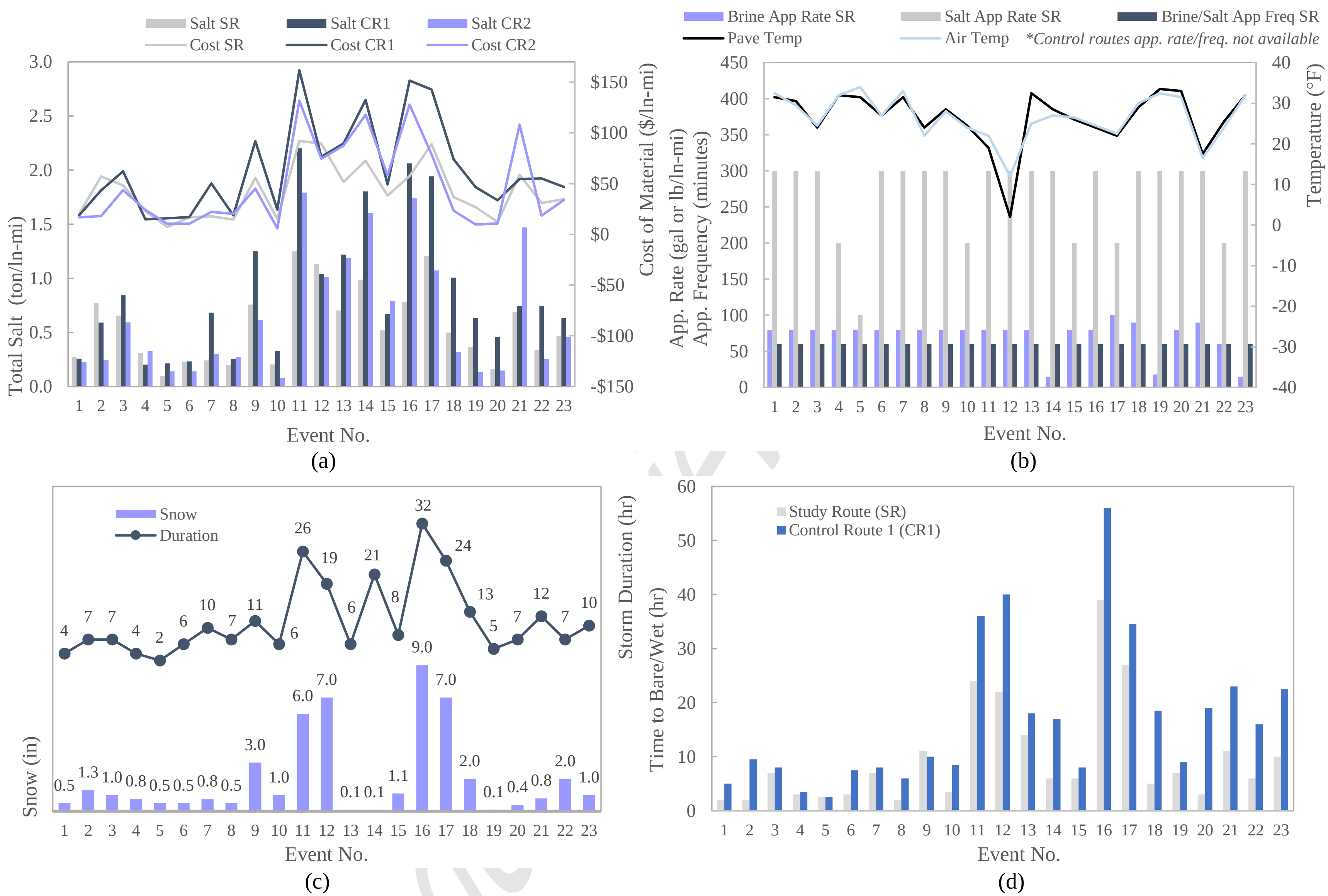
Figure 2 Eau Claire County (a) salt and cost of material, (b) app. rate/freq., and (c) snow and storm duration (time to bare/wet not available)

Jefferson County

Routes followed split route selection criteria along an interstate highway located in rural areas. Study route consisted of 100.0 lane-mile road segment compared to control route 1 with 65.6 lane-mile and control route 2 with 52.0 lane-mile. Control routes were selected from neighboring counties. Salt brine was predominately used in the study route and solid salt on the control routes. On the study route, in events 12, 21, and 22, $CaCl_2$ was used in addition to salt brine or solid salt. On the control routes, due to data availability, only dry salt quantities were available. During 23 reported storms, total salt on the study route was 12.9 ton/lane-mile, 20.0 ton/lane-mile on the control route 1, and 14.9 ton/lane-mile on control route 2. On average, there was 36% and 14% less salt used on the study route (with salt brine) per storm compared to control routes 1 and 2 (with solid salt).

Assuming the cost of salt brine at $0.08/gal, average cost of material per lane-mile per storm was 46% and 12% lower at study route ($42 per lane-mile) compared to the control routes 1 and 2 ($64 and $48 per lane-mile, respectively). When the cost of salt brine was considered $0.14/gal, there was still a reduction in cost of 34% compared to control route 1 and basically the same cost compared to control route 2.

Results showed that on average the study route reached bare/wet conditions 9.7 hours earlier than control route 1 which resulted in 42% less time required in operations and labor. Unfortunately, time to bare/wet data was not available for control route 2. Reported application rates of salt brine were between 15-100 gal/lane-mile and solid salt between 100-300 lb/lane-mile. The frequency of applications was 60 minutes for salt brine and solid salt. Salt brine to pre-wet solid salt was used at a rate of 10-20 gal/ton. Application rates and frequency were not available for control routes. Figure 3 provides total salt, cost of material (salt brine at $0.08/gal), applications rates/frequency, snow and storm duration, and time to bare/wet by storm event.



Notes: SR = Study Route, CR = Control Route, ln-mi = lane-mile, hr = hours, in = inches, App. = application, Freq. = frequency, Pave. = pavement, Temp.= temperature.

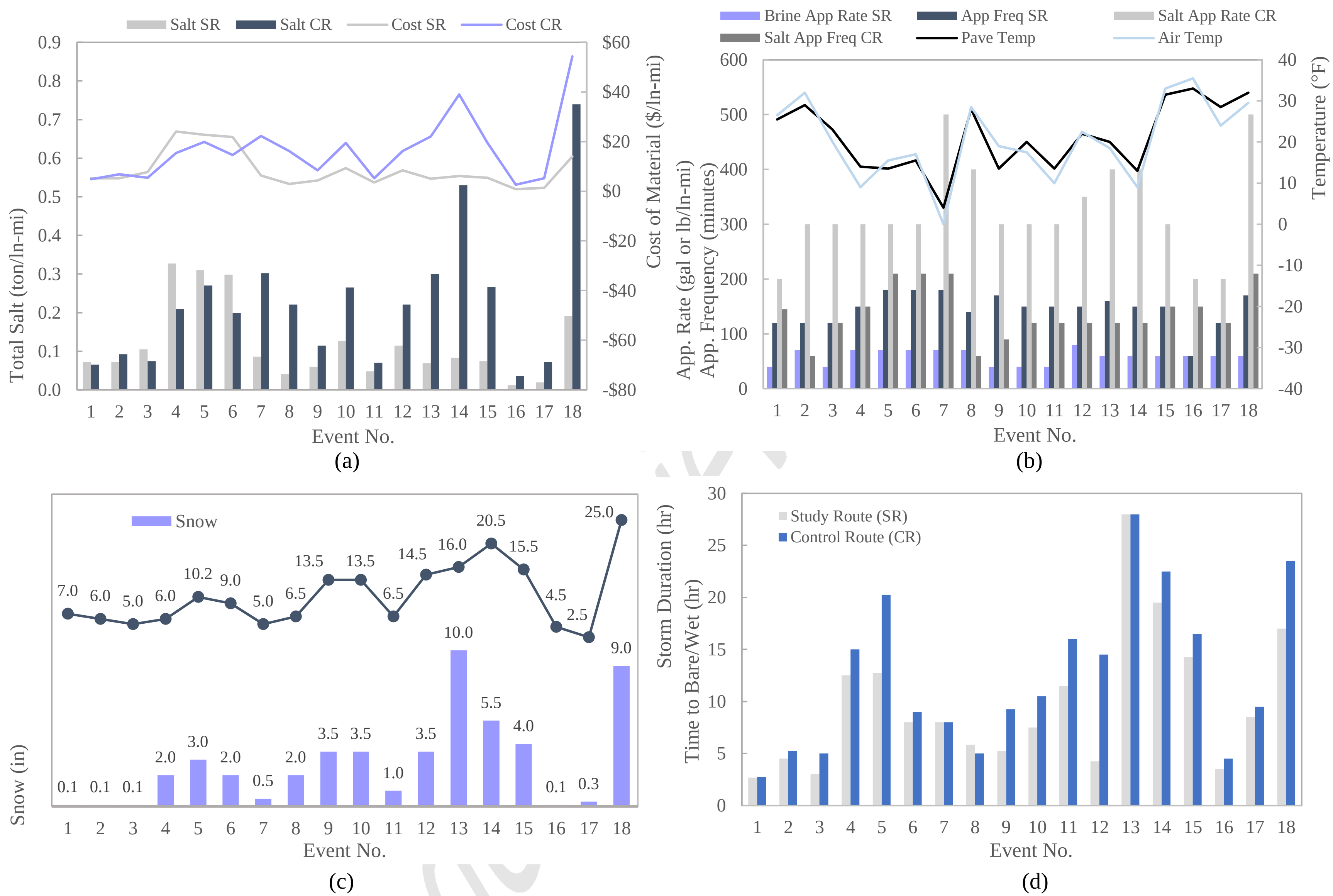
Figure 3 Jefferson County (a) salt and cost of material, (b) app. rate/frequency, (c) snow and storm duration, and (d) time to bare/wet

Wood County

Routes followed split route selection criteria along county roads located in rural areas. Study route consisted of 48.0 lane-miles road segment compared to a control route with 56.6 lane-mile. During 18 reported storms, total salt per lane-mile used on the study route was 2.1 ton/lane-mile and 4.0 ton/lane-mile on the control route. On average, there was 48% less salt used on the study route per storm compared to the control route.

In terms of material costs, considering the price of salt brine at $0.08/gal, the average cost of material per lane-mile per storm at the study route was also reduced by 48% compared to the control site ($9 and $17 per lane-mile, respectively) since there were no additional agents other than salt brine and solid salt used. When the cost of salt brine was considered $0.14/gal, there was still a reduction in cost of 14% compared to control route.

On average the study route reached bare/wet conditions 2.7 hours earlier that the control route which resulted in 22% less time required in operations and labor. Reported application rates of salt brine were between 40-80 gal/lane-mile and solid salt between 200-500 lb/lane-mile. The frequency of applications was between 60-180 minutes for salt brine and between 60-210 minutes for solid salt. Salt brine to pre-wet solid salt was used at a rate of 14 gal/ton. Figure 4 provides total salt, cost of material (salt brine at $0.08/gal), applications rates/frequency, snow and storm duration, and time to bar/wet by storm event.



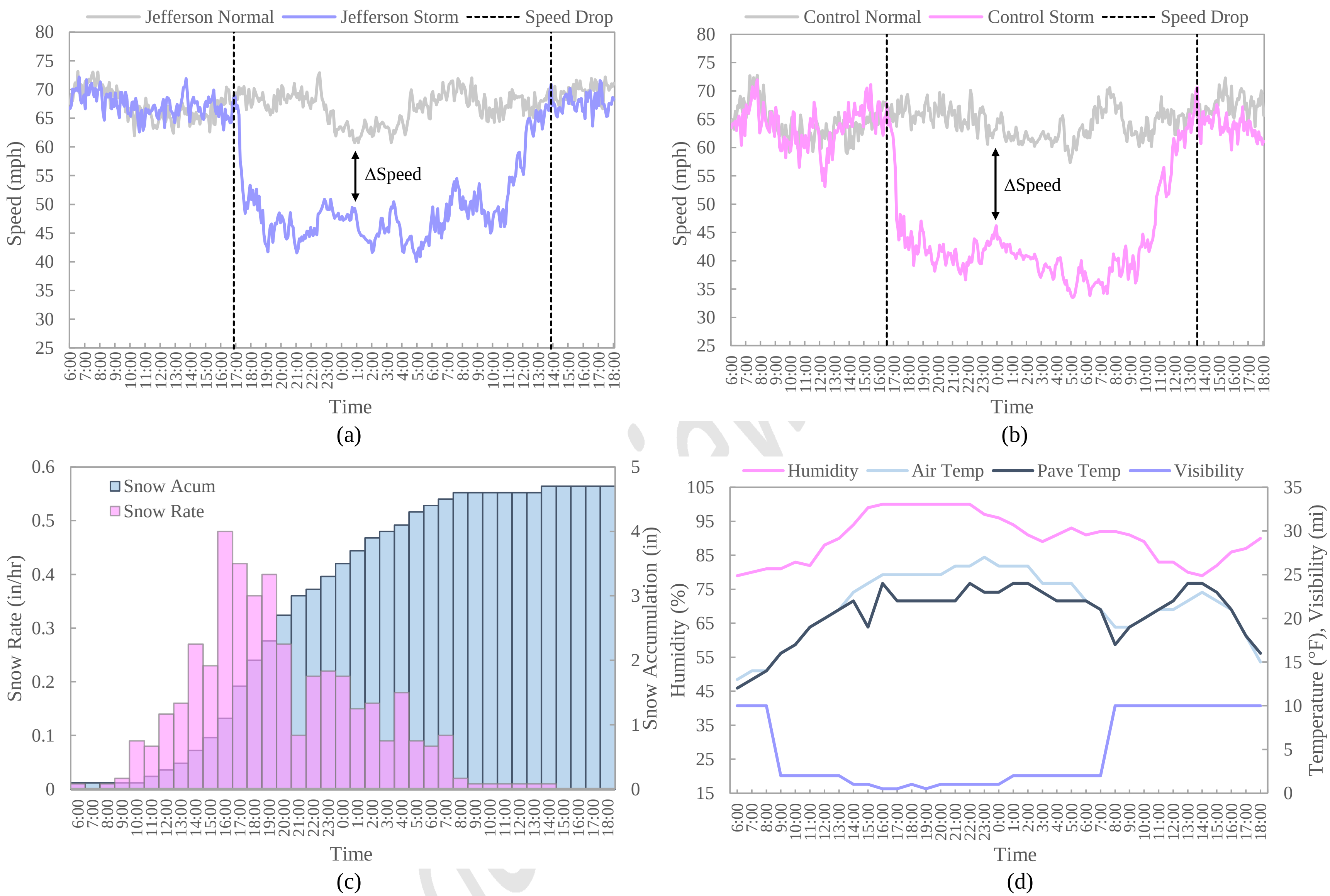
Notes: SR = Study Route, CR = Control Route, ln-mi = lane-mile, hr = hours, in = inches, App. = application, Freq. = frequency, Pave. = pavement, Temp.= temperature.

Figure 4 Wood County (a) salt and cost of material, (b) app. rate/frequency, (c) snow and storm duration, and (d) time to bare/wet

Storm Time Series Analysis

In addition to the analysis of material, costs, and time to bare/wet by storm, microscopic evaluation of travel speed was conducted. Guidelines in the Performance Measures in Snow and Ice Control Operations (NCHRP-889) report, recommend performance measures during storms to determine level of service (LOS). Recommended ways to define LOS during a storm include maximum accumulation of snow, maximum allowable drop in roadway friction, and maximum allowable drop in speeds (*26*). Although determination of the LOS requires levels of maximum acceptability and objective ranges, the microscopic speed analysis in this paper focused on comparing the LOS between a pair of study and control during a storm duration.

Travel speed for a selected storm in Jefferson County was evaluated (event 11). The time series evaluation consisted of quantifying the magnitude of the difference in speed under normal and storm conditions to determine treatment performance at study and control routes. Speed data under normal conditions was collected for a similar day of the week and time. Speed drop period considered was the time in which reduction of speed from normal conditions was observed. In the case of the storm studied, the speed drop duration was approximately 21 hours (started at 5 pm and ended at 2 pm of the next day). Figure 5 provides speed (study and control routes), snow rate and accumulation, temperature, humidity, and visibility data in a time series format. As illustrated in Figure 5, speed drop began at the time in which the snowfall rate reached its highest point and there was an accumulation of 2.0-2.5 inches. Also, visibility was limited in a similar time period. During the speed drop period, the magnitude of the difference of speeds between normal and storm conditions was calculated (ΔSpeed). The average ΔSpeed was 17.5 mph for the study route and 20.8 mph for the control route. Average ΔSpeed for the control route was 19.2% (p-value < 0.001) greater than the study route. Thus, the control route had lower level of service compared to the study route.



Notes: Jefferson = study route, normal = normal weather conditions, storm = storm weather conditions, Speed Drop = period of change in speed from normal conditions.

Figure 5 Time series (a) speed study route, (b) speed control route, (c) snowfall, (d) pavement/air temperature, visibility, and humidity

CONCLUSIONS

There is conclusive evidence of increasing levels of chloride salts having a negative effect on the environment, human health, and damage to vehicles and infrastructure. Salt brine implementation is an alternative to reduce the amount of salt used in winter maintenance. Several counties in Wisconsin have acquired and adapted equipment and facilities to enable the use of salt brine in winter maintenance. Study and control road segments were used to quantify material usage, cost, and performance. Results of this study show that with the use of salt brine, reduced amounts of salt were used, less operational and labor hours were required, and improved level of service were observed in winter maintenance. In terms of material costs, the average cost of material per lane-mile on the study group was reduced compared to the control group when considering the cost of salt material in salt brine. There was no statistical difference in cost between study and control groups when the cost of material and production of salt brine was considered. However, at the route level, Brown and Eau Claire county routes had an increase in cost when the cost of salt brine considered material and production costs. The overall cost of material should be interpreted with caution and associated with performance of treatments in terms of time to bare/wet which provides further insight into effectiveness of treatments. Although the analysis of cost of material alone may suggest similar costs, time to bare/wet indicates that less operations and labor time may reduce costs when using salt brine compared to solid salt.

Both salt brine and solid salt should be available for winter maintenance. Using exclusively salt brine for all winter scenarios is not realistic. Based on temperature, duration, and intensity of storms, both salt brine and solid salt may be used at discretion to reduce the use of salt, operations and labor time, and increase level of service. Future research should expand upon the findings of this paper to collect field data at more study and control routes from different geographical regions in the country and generate a centralized database and develop a comprehensive guide with optimal application rates and winter practices according to the region, roadway type and operational characteristics, predominant weather, equipment, materials, and resources available.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Boris Claros, Madhav Chitturi, Andrea Bill, and David A. Noyce; analysis and interpretation of results: Boris Claros, Madhav Chitturi, and Andrea Bill; draft manuscript preparation: Boris Claros and Madhav Chitturi. All authors reviewed the results and approved the final version of the manuscript.

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