Comparative Analysis of Performance of Different De-Icing Materials

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Abstract

Canada's Code of Practice for Environmental Management of Road Salts assists road agencies to use road salt effectively. The Ontario Ministry of Transportation is addressing the Code in part by evaluating and implementing improved salting practices. Recent efforts developed methodologies to compare the relative performance of dry salt, pre-wetted salt, and pre-treated salt under operational conditions during winter storms. Relative performance of these application practices was measured on the road using mobile and fixed technologies. The data were integrated with highway maintenance, weather and traffic data and analysed graphically and statistically to compare the effectiveness of the applied treatments with a view to recommending application rates with comparable performance.

1 Introduction and Objectives

Winter weather conditions have significant impacts on the safety and mobility of roadways across Canada. Road agencies manage the impacts of snow and ice by plowing and applying road salt or winter sand, depending on the temperature and traffic conditions. Concerns emerged with growing use of road salt associated with historical periods of rapid highway expansion, and growth in traffic speed and volume. The concerns were initially related to perceived effects of salt on vehicles and infrastructure, and later on the roadside environment. Environment and Health Canada initiated a review of road salt in response to perceived environmental effects, resulting in a Code of Practice for Environmental Management of Road Salts being adopted by all significant users of road salt in Canada (1). Among the recommendations of the Code is the investigation and implementation of best management practices, including those for salt application.

Effective application practices have other benefits such as reducing expenditure on materials and spreading equipment and, reducing greenhouse gas emissions from operation of plows and spreaders when the number of applications can be reduced. Effective practices also provide a faster return to normal driving conditions following winter storms, resulting in reduced accident risk and improved traffic throughput (2).

The Ontario Ministry of Transportation (MTO) addresses recommendations of the Code of Practice through its own Salt Management Plan (3) and an ongoing program of research in Winter Maintenance. Previous research identified pre-wetting of rock salt and the direct application of brine as possible methods to reduce overall salt use (4,5,6). Operational trials with clear performance measures were used to compare the effectiveness of these practices against conventional methods, resulting in the adoption of application rates lower than dry rock salt (7,8).

While widespread and shown to be effective in Ontario and other jurisdictions, pre-wetting of road salt incurs added capital and operating costs due to the requirement for on-site and on-board storage, pumping and metering of winter liquids. In efforts to reduce the cost while maintaining the benefit of added brines, operators suggested the addition of brine to rock salt during stockpiling in the patrol yard, eliminating the need for separate liquid storage and spreading equipment. Since earlier experience with this concept was troublesome when brine leaked from the stockpile (9), it was proposed to use brine at a lower ratio where it would remain suspended in the stockpile through capillarity. The proposed ratio of 1 to 3% mass of brine to granular salt is significantly lower than the established ratio of 5% used for pre-wetting in Ontario (7) and elsewhere, and raised concern whether the effectiveness would be equal to pre-wetting at the same application rates.

The objective of the current study was to compare the effectiveness of pre-treated salt with that of pre-wet salt and conventional dry rock salt, and if possible to recommend application rates for pre-treated salt that provide equivalent snow removal performance to the established application rates for pre-wet and dry salt.

The details of the conducted field study are discussed in this paper. First, the data acquisition process is explained. Then, the data processing, integration and quality control efforts are discussed. Further, the elements of the adopted methodology including types of analyses, measures of effectiveness, modelling structures, modelling calibration approach, and modelling diagnosis are detailed. Later, the results of the conducted comparative analyses are discussed. Finally, the conclusions and recommendations for future research are provided.

1.1 Approach

A series of field experiments were used to compare the effectiveness of different salt application methods and rates. Field experiments have the advantage that real-world influences can be accounted for using multiple regression analyses, to the extent that relevant factors can be measured or observed. Examples of real-world factors that are difficult to reproduce in a lab setting include snowfall rate, temperature, wind, sunlight, pavement texture and temperature, traffic, and plowing in addition to the material application factors.

The experiments were spread across maintenance routes in four of MTO's contract areas to provide a variety of weather, traffic and terrain conditions (Table 1). At each location a winter maintenance route was divided into two or three sections, with one section acting as control using conventional material (either dry or pre-wet salt) and application rates, and one or two adjacent sections where the test material (pre-treated salt) was used. Application rates were held constant through a storm and varied in a regular manner through successive storms at each location as experience was gained. Identical plowing and spreading equipment was used on all sections in a test area (Figure 2).. [

The relative performance of the materials was assessed from road surface measurements factoring in material application quantities, and from qualitative patroller observations. Road surface measurements were obtained from roadside cameras or from a mobile data collection unit equipped with a friction trailer, spectral sensor or a dash-cam, depending on the location and time (Figure 3). The roadside cameras recorded the surface continuously at a fixed location while the mobile unit traversed the sections repeatedly during significant parts of selected storms. Each of the measuring approaches contributed to a specific type of analysis and performance measure.

2 Data Collection

Data were collected to characterize the weather conditions, the maintenance inputs (plowing, salting, sanding), and outputs (road surface condition) independently for each test section through each monitored winter storm. This allowed comparisons within a storm and between storms, and ultimately between test areas.

2.1 Maintenance Operations

The tests were undertaken on two-lane and four-lane divided highways and a range of weather conditions (Table 1). The same material and application rate was used in both directions of two or four lane highways such that tests compared adjacent locations along the route rather than on different sides of the highway. A map of the four test areas is illustrated in Figure 1.

Table 1 – Location and Characteristics of Trial Test Areas

Test Area	Roadway Limits	Number of Lanes	WADT (veh/hr)	Average January Temperature	Average Annual Snowfall	Materials Used		
						Dry Salt	Pre-Wet	Pre-Treat
Harriston	**Highway 23** - Ontario Rd to Line 72 Perth County (Pre-Wet) **Highway 23** - Line 72 Perth county to Hwy 9 Harriston (Pre-Treat) **Highway 9** - 750m West of Hwy 23 & Hwy 9 to Kincardine Hwy (Dry Salt)	2	4,500	-8C	305 cm	✓	✓	✓
Huntsville	**Highway 117** - Hwy 118 West to Allensville Rd (Pre-Treat) **Highway 117** - Allensville Rd to Fern Glen Rd. (Dry Salt)	4	10,500	-11C	283 cm	✓	---	✓
Morrisburg	**Highway 401** - Shanly Rd to Morrisburg exit (Pre-Treat) **Highway 401** - Morrisburg exit to Moulinette Rd (Pre-Wet & Dry Salt)	4	15, 000	-9C	180 cm	✓	✓	✓
Verner	**Highway 17** - Ottawa St to Highway 64 (Pre-Treat) **Highway 17** - Highway 64 to Highway 535 (Dry Salt)	2	5,100	-13C	260 cm	✓	---	✓

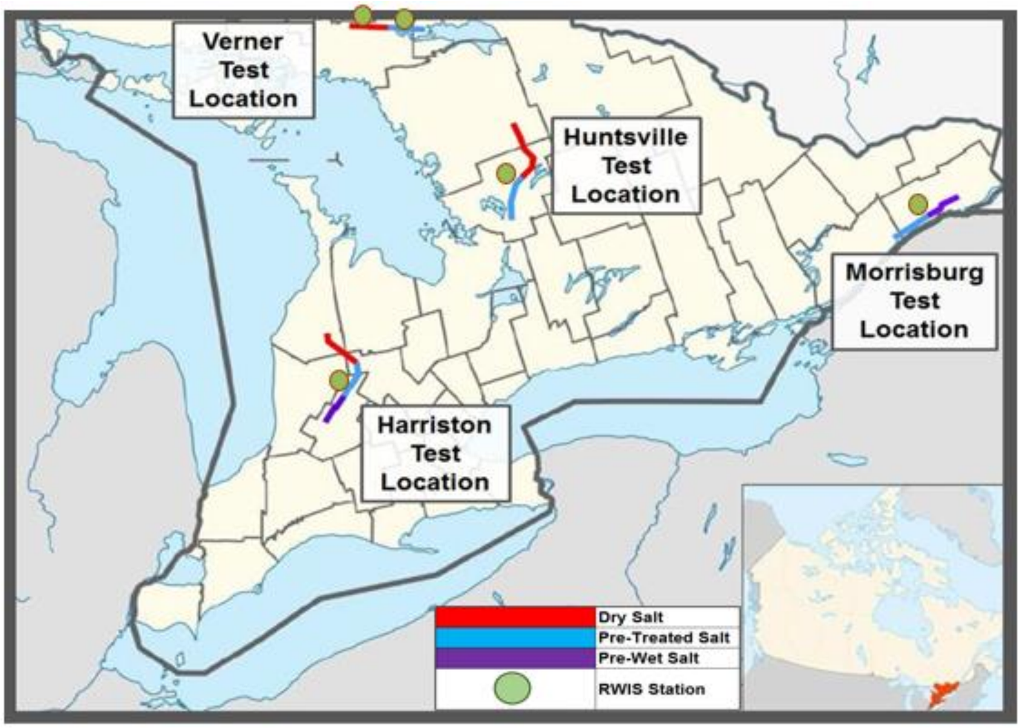


Figure 1 – Map of Test Locations

The three test treatments being compared in this study are the application of dry salt, pre-wet salt and pre-treated salt. The general composition characteristics of the tested salt treatments are provided in Table 2.

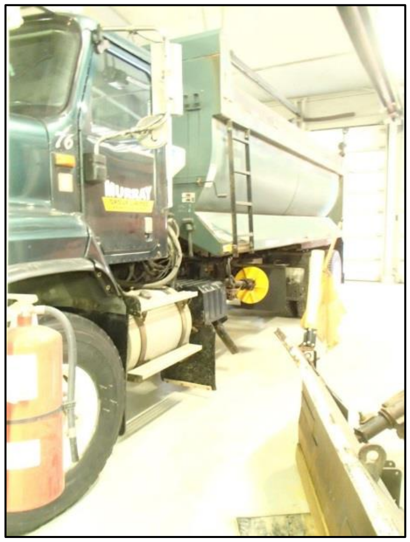
Table 2 – Pre-Wet Tank Test Results

Material Type	Location	NaCl %	Brine %	Insolubles %	$MgCl^2$ to $CaCl^2$ Ratio
Dry Salt	Verner	93.96	-	-	-
	Harriston	94.77	-	0.56	-
	Huntsville	93.12	-	0.57	-
Pre-Treat	Verner	92.56	1.72	-	3 :4
	Harriston	94.01	2.00	0.52	2 :1
	Morrisburg	94.25	1.85	-	3 :4
	Huntsville	92.46	2.11	-	1 :1
Pre-Wet	Harriston	94.77	5.00	-	1 :0
	Morrisburg	95.00	5.00	-	1 :0

Photographs of maintenance equipment used for applying pre-treated salt in different test areas are shown in Figure 2.

a) Huntsville Pre-Treat Salt Combination Unit

b) Verner Pre-Treat Salt Combination Unit



c) Harriston Pre-Treat Salt Combination Unit

Figure 2 – Pre-Treat Salt Combination Unit for Different Test Areas

- Material application rates used in the trials are shown in Table 3. Road salt was not successful in all storms under very low temperature or drifting conditions and winter sand was applied when needed to improve traction under those conditions. Sand was applied at the recommended rate of 570 kg/2-lane km. Sand application is not shown in Table 2 but was recorded and considered in the analyses. Winter sand normally included 3 to 5% by mass of rock salt. Liquid was not added to winter sand. Normal plowing practices were also used during all storms and the frequency of plowing was identical or similar in adjacent test sections.

Table 3 – Summary of the Applied Treatments at Different Test Areas

Test Area	Dry Salt (130 kg/2ln km)	Pre-Wet			Pre-Treat			
		120 (kg/2ln.km)	100-105 (kg/2ln.km)	85-90 (kg/2ln.km)	90-95 (kg/2ln.km)	100-105 (kg/2ln.km)	120 (kg/2ln.km)	130 (kg/2ln.km)
Harriston	✓	✓	✓	✓		✓	✓	✓
Huntsville	✓							✓
Morrisburg	✓	✓	✓			✓	✓	✓
Verner	✓				✓	✓	✓	

2.2 Maintenance Performance Data

Mobile Data Collection Unit (MDCU)

The MDCU provides measurements of road condition at regular, frequent intervals along the test section and through the duration of the winter event. The MDCU is a half-ton pick-up truck that has been outfitted with the following equipment:

- Halliday RT3 trailer, which measures Road Grip (similar to friction) at one second frequency (Figure 3-a);
- Teconer spectral camera, which estimates surface temperature, road cover type (snow, slush, ice, water) and depth, and friction (Figure 3-b);
- AVL-Genius windshield camera, which takes images of the roadway every 100m and estimates roadway snow cover friction using image analysis algorithms, to provide measurement of snow covered areas on the roadway, (Figure 3-c); and
- AMDCS, which provides GPS location and time.

The MDCU was deployed in the Harriston and Verner test areas.

a) RT3 Friction Trailer

b) Teconer Spectral Camera

c) AVL Genius Windshield Camera and MDCU Operator Devices

Figure 3 – The Elements of the Mobile Data Collection Unit

Other Data

- Road and Weather Information System (RWIS): provides records of air and road temperature, wind speed and direction, and precipitation occurrence, at 20 minute intervals.
- RWIS/Roadside camera images: provide images of the roadway (for provision of estimates of roadway snow cover friction) at 20 minute intervals. One RWIS camera was in place in the pre-treat section of the Morrisburg, Huntsville, and Harriston test areas; and one in the dry salt section of the Verner test area;
- Dash camera images from MTO patrol vehicles: provide images of the roadway (for provision of estimates of roadway snow cover fraction) approximately every 0.5 to 1.0 km;
- Area Maintenance Data Collection System (AMDCS) data: provides information on material type, application rate, and plowing operation every 10 seconds;
- Winter operations records (WORs - handwritten records of plowing operations and material spreading rates each time a unit leaves the patrol yard): provide an overview of maintenance completed on each test section, for verification purposes; and
- Winter patrol records (WPRs): provide records of weather and road conditions identified visually.

2.3 Analysis Approach

Data were collected for a total of 39 snowstorm events. Depending on the data availability for different events, 3 types of analyses were conducted:

- ***Patrol Data Analysis***: Events including the operational and patrol data (e.g., the type of treatment used, application rates, and the time at which the treatment was being spread) were considered to determine event length and bare pavement regain time in the graphical analysis.
- ***Roadside Camera Data Analysis***: Snow cover area fraction was estimated at 20 minute intervals from roadside camera images and these were used to compare the rate of snow clearing during a storm.
- ***MDCU Data Analysis***: MDCU data (i.e., Halliday friction trailer, Teconer spectral camera, and AVL Genius windshield camera) were used to track changes in surface condition in adjacent road sections graphically, and to provide input to statistical analyses (10).

2.4 Data Preparation

Data were filtered, integrated and aggregated prior to analysis using the following criteria:

- **Data filtering:**

Data were filtered to remove errors and inconsistencies:

- outside logical range (e.g., friction measurements should vary between 0 and 1);
- Outside measurement tolerance (e.g., friction measurements associated with steering greater than +10 degrees and lower than -10 degrees);
- Inconsistent distance measurements (e.g., the cumulative traversal of the MDCU on each section should be consistent with the length of the section);

- **Data Integration**:

Measurements from different data sources were integrated in a single dataset based on their corresponding temporal and spatial information. In other words, for each measurement of friction (collected at 1 Hz), the following data are integrated into the dataset: (i) nearest snow cover estimate from the windshield camera collected at100 meter interavl; (ii) closest prior occurrence of maintenance at the location; (iii) AMDCS air and surface temperatures; (iv) spectral camera snow cover depth; (v) spectral camera friction; (vi) spectral camera air and surface temperatures; and (vii) nearest weather station information including wind speed, surface temperature, air temperature, and humidity.

- **Data Aggregation:**

Most of the data collected by the MDCU are spot measurements and are subject to high local variations due to naturally occurring conditions on the road (10,11). MDCU spot measurements were averaged over 500 meters sections of the roadway to provide a better characterization of conditions through the test section.

3 Methodology & Results

Analysis of the effectiveness of the de-icing materials (i.e., dry salt, pre-wet salt, and pre-treated salt) was made through both graphical and statistical analyses.

3.1 Graphical Analysis

The graphical analysis involved preliminary observations from winter events to identify trends in the measures of effectiveness and causative factors. The performance of various de-icing materials were compared considering a range of performance measures which are indicative of the ability of treatments to meet prescribed standards of road surface condition appropriate to highway classification. Bare pavement regain time (BPRT), which is one of the widely utilized measures in the literature, is considered as the target performance measure for the graphical analysis of this paper.

Bare Pavement Regain Time (BPRT)

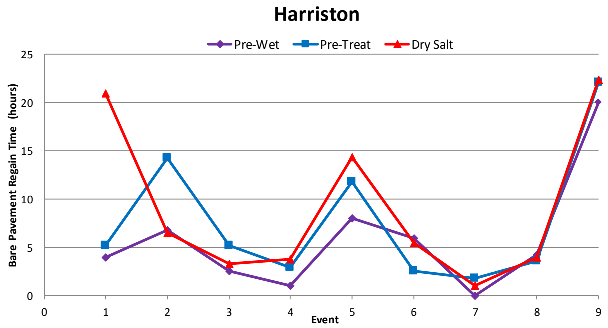
BPRT is the time interval between cessation of snow or freezing rain until restoration of essentially bare pavement. The BPRT value for each snowstorm event was calculated using the available winter patrol records (WPRs). BPRT is recorded as zero when maintenance operations are initiated pro-actively and the road does not become snow covered i.e. bare pavement is not lost. BPRT for each test section and monitored winter event is shown Figure 4, along with the air temperature and the material application rates. Harriston and Morrisburg had relatively warmer temperature conditions, and Verner and Hunstville were relatively colder.

At Harriston it is observed that pre-wet salt resulted in BPRT lower or the same as dry salt in most cases, while being applied at lower rates in most cases. Pretreated salt had both higher, lower or the same BPRT as dry salt while being applied at lower rates in most cases. It may be concluded that pre-wet salt was consistently more effective than dry salt while results for pre-treated salt were mixed.

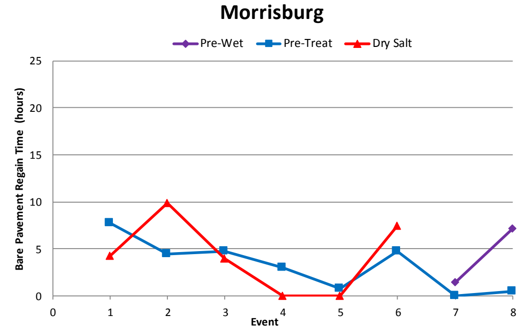
Inconsistent results were obtained at Morrisburg, showing no apparent relation between BPRT and relative application rate for pre-treated salt compared with dry salt. In two cases where pre-treated salt was compared with pre-wet salt, pre-treated salt was more effective when applied at higher rates.

Figure 4 illustrates very similar performance between the dry salt and pre-treated salt sections at Verner and Huntsville when application rate is not considered. At Verner it will be noted that the similar performance was obtained while using a lower application of pre-treated salt than dry salt, suggesting that pre-treated salt was more effective when application rate is considered. Most events at Huntsville used the same application rates in both sections. Where a lower application of pre-treated salt was used at Huntsville the regain time was longer. This suggests that pre-treated salt provided no advantage over dry salt at Hunstville.

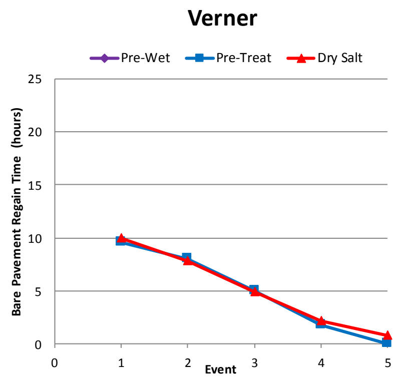
The qualitative analysis suggests that pre-wet salt may be the most effective, with pre-treated salt intermediate in effectiveness between pre-wet and dry salt. However the variance and inconsistency in results precludes any firm conclusion and indicates that a more robust analysis is needed to account for multiple factors that influence regain time.



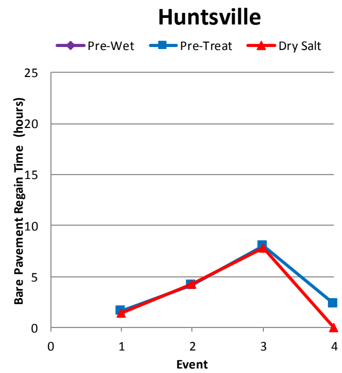
Event #	1	2	3	4	5	6	7	8	9
Temp °C	-10°C (±6)	-10°C (±5)	-14°C (±5)	-7°C (±7)	-5°C (±6)	-10°C (±10)	-9°C (±7)	-5°C (±8)	-5°C (±3)
Dry Salt	130	130	130	130	130	130	130	130	130
Pre-Treated Salt	130	120	105	105	105	105	105	120	130
Pre-Wet Salt	130	120	105	105	105	105	105	120	N/A
Date	Jan-29	Feb-1	Feb-5	Feb-7	Feb-7	Feb-18	Feb-20	Mar-02	Mar-03



Event #	1	2	3	4	5	6	7	8
Temp °C	-10°C (±5)	-5°C (±6)	-10°C (±15)	-5°C (±5)	0°C (±7)	0°C (±4)	0°C (±4)	-4°C (±5)
Dry Salt	130	130	130	130	130	130	No Dry Salt	
Pre-Treated Salt	120	105	120	120	105	130	100	105
Pre-Wet Salt	No Pre-Wet Applied for these events						85	100
Date	Feb-14	Feb-18	Feb-21	Feb-25	Mar-01	Mar-03	Mar-14	Mar-27



Event #	1	2	3	4	5
Temp °C	-5°C (±5)	0°C (±3)	0°C (±10)	0°C (±5)	0°C (±10)
Dry Salt	130	130	130	130	130
Pre-Treated Salt	90	95	105	105	120
Pre-Wet Salt	No Pre-Wet Salt Applied in Verner				
Date	Mar-03	Mar-13	Mar-21	Mar-29	Apr-01



Event #	1	2	3	4
Temp °C	-10°C (±10)	0°C (±2)	0°C (±15)	0°C (±6)
Dry Salt	130	130	130	130
Pre-Treated Salt	130	130	120	120
Pre-Wet Salt	No Pre-Wet Salt Applied in Huntsville			
Date	Feb-03	Mar-14	Mar-21	Mar-29

* Temperature data shows the average and range for each storm.

Figure 4 – Graphical Analysis - Bare Pavement Regain Time

3.2 Statistical Analysis

A multiple regression statistical approach was applied to account for the effects of external factors and for interactions between variables (11), as explained below. This approach has the advantage to quantify the effect of factors in addition to material type and application rate, each of which contributes to the clearing of the road surface during winter maintenance.

Measure of Effectiveness

As mentioned earlier, the snow-clearing efficiency of the applied treatments can be examined through different measures of effectiveness. For the purpose of statistical analysis, traction measured by the Halliday friction trailer was adopted as the measure of effectiveness. It is a suitable measure because it is measured frequently and objectively along the road surface to provide a reliable characterization of surface conditions during each measurement traverse.

Model Structure

To statistically compare the effectiveness of the snow removal treatments, an overall multiple regression model was developed using data from both Harriston and Verner test areas. The structure and results of this model is presented along with statistically significant variables in Table 4.

Table 4 – Final Model Structure – Overall Model

Model Structure
$Friction = \gamma_0 + \gamma_1 \cdot Temp_m^{Surface} + \gamma_2 \cdot PWet_{105} + \gamma_3 \cdot PTreat_{90} + \gamma_4 \cdot PTreat_{105} + \gamma_5 \cdot PTreat_{120^+} + \gamma_6 \cdot Sand + \gamma_7 \cdot PCI + \gamma_8 \cdot PWet_{105} \times Temp_m^{Surface} + \gamma_9 \cdot PTreat_{90} \times Temp_m^{Surface} + \gamma_{10} \cdot PTreat_{105} \times Temp_m^{Surface} + \gamma_{11} \cdot PTreat_{90} \times ElapseTime + \gamma_{12} \cdot PTreat_{105} \times ElapseTime + \gamma_{13} \cdot PTreat_{120^+} \times ElapseTime + \gamma_{14} \cdot Sand \times ElapseTime + \gamma_{15} \cdot Harriston$

The included variables in this model are defined as follows:

Friction: Average friction estimated over 500-meters spacing (Halliday friction);

$Temp_m^{Surface}$: Surface temperature recorded at the time of AMDCS maintenance (^{o}C);

$PWet_{105}$: Binary variable representing the pre-wet treatment type; 1 for 105 application rate, 0 otherwise;

$PTreat_{90}$: Binary variable representing the pre-treat treatment type; 1 for 90 application rate, 0 otherwise;

$PTreat_{105}$: Binary variable representing the pre-treat treatment type; 1 for 105 application rate, 0 otherwise;

$PTreat_{120}{}^{+}$: Binary variable representing the pre-treat treatment type; 1 for 120 and higher application rates, 0 otherwise;

$PTreat_{130}$: Binary variable representing the pre-treat treatment type; 1 for 130 application rate, 0 otherwise;

Sand: Binary variable representing the sand treatment type; 1 for sand treatment, 0 otherwise;

Elapsed Time: The time difference between the latest AMDCS maintenance and MDCU measurement (min);

PCI: Pavement condition index under summer conditions; (varies between 0 and 100);

Harriston: Binary variable representing the observations collected on Harriston test area; 1 for Harriston, 0 for Verner; and

γ_i: Model coefficients.

The model form has the following advantages in understanding the relative performance of winter materials:

- The compounding effect of main factors in association with different snow removal treatments were evaluated through the inclusion of first order interaction terms. A number of terms in addition to those listed here were examined. Among all the examined interaction terms, only the ones included in Table 4 were statistically significant.

  The term interaction, in statistics, refers to how the effect of one independent variable depends on the value of one or more other independent variables. In other words, how the effects of different variables interact (e.g. low temperature and wind may act together to cause snow drifting which results in an icy surface) to affect the dependent variable (i.e. friction).

- A variable representing dry salt treatment was not included in the final model shown in Table 3. According to this structure, the friction values resulting from the application of dry salt are the baseline to which other treatments added.

- In this modelling assignment, the effect of antecedent roadway condition was captured through the inclusion of the "elapsed time" variable. This variable is important because it surrogates the roadway snow accumulation and at the same time considers the time lag since the applied salt treatments.

- Using the proposed model structure the extra variation due to the changes in surface temperature, elapsed time between maintenance and measurement of road condition, and pavement condition index would be extracted from the data. In this way, the remaining variation in the examined response variable (i.e., friction) would be hypothesized to be the result of different treatments. Following this procedure, if the variables (main effects and/or interactions) representing treatments become statistically significant, it can be concluded that the change in treatments results in different friction values along the study corridor.

- The extra variation due to the difference between long-term or consistent friction trends on the examined test areas was excluded by defining a blocking variable representing the observations collected at Harriston test area. In fact, the included blocking variable absorbs the relative variation between the Verner and Harriston test areas, such that the interpretation of the model coefficients becomes easier and at the same time more accurate.

- The inclusion of the interaction terms in the models allows a graphical interpretation of the sensitivity of the response variable (friction) to the included independent variables (Figure 5).

Dataset for Statistical Modelling

The data obtained from 10 snowstorm events having suitable MDCU datasets was used for this modelling assignment (Table 5).

Table 5 – Number of observations for different Snow Removal Treatments Included in the Statistical Modelling

Test Area	Dry Salt (130 kg/2ln km)	Pre-Wet	Pre-Treat				Sand (570 kg/2ln.km)	No Treatment	All Treatments
		105 (kg/2ln.km)	90 (kg/2ln.km)	105 (kg/2ln.km)	120 (kg/2ln.km)	130 (kg/2ln.km)			
Harriston	504	191	---	618	---	187	308	---	1,808
Verner	537	---	226	135	31	7	21	---	957
Overall	1,041	191	226	753	31	194	329	---	2,765

Results

Using the available data for both Harriston and Verner an overall regression model was developed for these test areas. In this model, the effect of both main factors and their interaction terms was examined. The final regression model coefficients are provided in Table 6. The following observations can be made from this table:

- All the included variables were statistically significant at 88% significance level or higher.
- The adjusted R^2 value of 0.40 is reasonable considering the uncontrolled nature of the operational field experiment. This R^2 value in association with significant factor coefficients indicates that the selected variables influence friction, although the equation should not be used as a predictor of the overall friction value.
- The presented model was developed to estimate the relative difference in friction resulting from different salt treatments. The coefficients can be interpreted as indicators of the relative effectiveness of the different salt treatments in maintaining road surface conditions during a storm. When interaction terms are included, the coefficients of single variables that are also included as interaction variables cannot be readily interpreted. Therefore, to help explain the relative performance of different treatments, the effect of interacting factors can be graphically examined.

- Among all examined interaction terms, only the interactions between the surface temperature & treatments and the elapsed time & treatments was statistically confirmed.

The effect of interacting factors is graphically illustrated in Figure 5. In this figure, the x-axis shows the surface temperature, the y-axis represents the friction value (estimated using the developed regression model), the color-coded trend lines correspond to the examined treatments, and three different elapsed times are presented in separate diagrams.

The following observations can be made based on this figure:

- Within 30 minutes of application pre-wet salt is associated with higher friction than pre-treated salt at any application rate except at the lowest temperatures, where they are equally effective. Pre-treated salt was more effective than dry salt in the higher temperature range and less effective in the low temperature range.
- The presented results for 90 minutes elapsed time reveals that the pre-wet salt was associated with higher friction values in the high temperature range while pre-treated salt at high application rate was associated with higher friction values in the low temperature range. Dry salt was associated with higher friction values than pre-treated salt under most conditions, when lower application rates were used for pre-treated salt.
- The performance of dry salt, pre-wet salt, and pre-treated salt at 90 and 105 kg/2ln-km application rates was reduced with increasing elapsed time. In other words roadway conditions worsened with increasing time since material application. In the case of pre-treated salt at 120^{+} kg/2ln-km application rate the roadway conditions tended to improve with increasing time since application.
- Overall, the performance of all types of salt treatments was superior to that of the sand (when surface temperature varies between -10 C and 0 C).
- Both dry salt and pre-treated salt at 105 application rate were more effective than per-treated salt at 90 application rate.

Table 6 – Developed Regression Model based on Halliday Friction Trailer Measurements (Overall Model)

Parameter	Description	Coefficient	P-Value
Υ_0	Intercept	0.5572	0.00
Υ_1	Surface Temperature (°C)	0.0122	0.00
Υ_2	Pre-Wet $_{105}$	0.2250	0.00
Υ_3	Pre-Treat $_{90}$	0.0491	0.05
Υ_4	Pre-Treat $_{105}$	0.0898	0.00
Υ_5	Pre-Treat $_{120^+}$	-0.2408	0.00
Υ_6	Sand	-0.2110	0.00
Υ_7	PCI	0.0009	0.00
Υ_8	Pre-Wet$_{105}$ × Surface Temperature	0.0350	0.00
Υ_9	Pre-Treat$_{90}$ × Surface Temperature	0.0131	0.00
Υ_{10}	Pre-Treat$_{105}$ × Surface Temperature	0.0186	0.00
Υ_{11}	Pre-Treat$_{90}$ × Elapsed Time	-0.0007	0.05
Υ_{12}	Pre-Treat$_{105}$ × Elapsed Time	-0.0002	0.12
Υ_{13}	Pre-Treat$_{120^+}$ × Elapsed Time	0.0033	0.00
Υ_{14}	Sand × Elapsed Time	0.0004	0.03
Υ_{15}	Harriston	0.0987	0.00
No. of Observations		2,765	
Adjusted R^2		0.40	

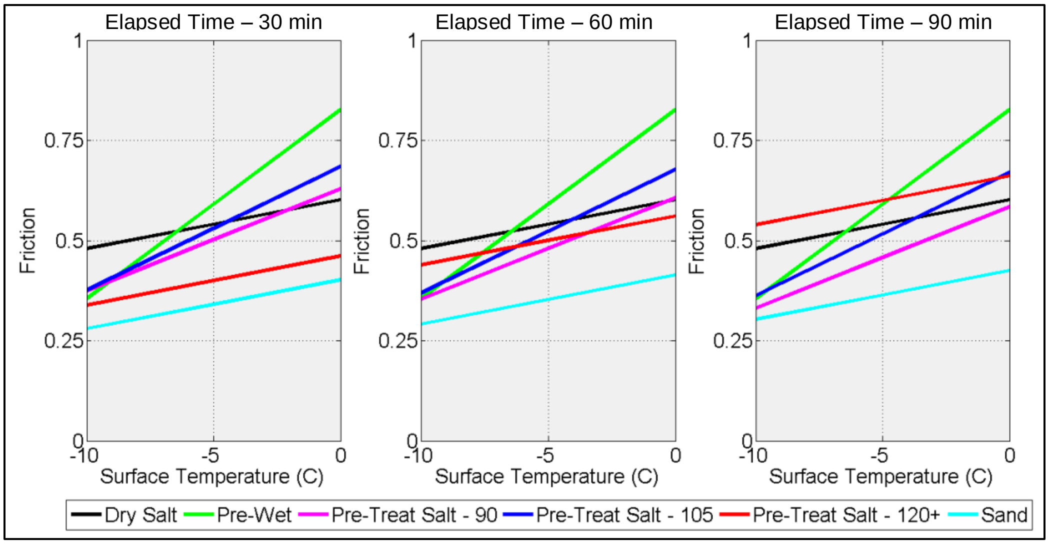


Figure 5 – Performance of the Snow Removal Treatments under Different Factor Levels (Overall Model)

4 Summary, Conclusions and Further Work

The De-Icing Material Trials took place on four test areas. On these test areas, three test treatments were applied with various application rates, including: dry salt, pre-wet salt and pre-treated salt. Winter sand was also applied in some storms, at a fixed application rate.

Analysis of the effectiveness of the four different materials (dry salt, pre-wet salt, pre-treated salt, and sand) was made quantitatively, through graphical and statistical analyses.

- This study developed several advanced methods for investigation of the performance of alternative winter maintenance practices, including:
  - Integration of maintenance operations and performance data to discrete road segments and time periods using GPS tags;
  - Application of objective and automated road condition measurements such as friction and snow cover fraction to characterize winter maintenance performance on a storm event basis.; and
  - Further development of multiple regression statistical models with interaction terms to isolate the impact of temperature, material types and application rates on road surface conditions.
- This preliminary study showed that the performance of the pre-wet salt treatment was superior to other treatments for surface temperatures above -5 C and that pre-treated salt was sometimes intermediate between pre-wet salt and dry granular salt.. However, the adoption of reduced application rates for pre-treated salt as compared with dry salt or pre-wet salt is not justified without further investigation. The relative performance of pre-treated salt under some conditions suggests the possibility to use reduced rates

compared with dry salt, but the data available from the present study do not allow identification of equivalent application rates.

- Analysis is continuing from additional test cases obtained in 2015-16, in efforts to identify equivalent application rates between dry and pre-treated salt.

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