Effectiveness of Alternative Chemicals for Snow Removal on Highways

Liping Fu, Rudolph Sooklall, and Max S. Perchanok

This paper describes an empirical study aimed at quantifying and comparing the effectiveness of several alternative chemicals for snow and ice control under specific weather, site, and traffic conditions. Data collected from a large scale field test are used in this analysis, involving measurements on snow cover, weather and pavement conditions, and treatment operations at 10-min intervals over 16 snowstorms. The paper details a case-by-case comparison of several alternative chemical treatments including dry salt and salt prewetted with different agents. Statistical models are developed and used to explain the effects on snow melting trend of various weather and treatment factors.

Maintenance of bare pavement conditions during or soon after winter storms is critical to economical flow of traffic on modern highway systems. Accumulation of winter contaminants such as frost, slush, snow, and ice reduces traffic flow and increases the risk of accidents on highways by reducing the average traction level and increasing variance of traction between vehicle tires and pavement (*1*). Contaminants are removed conventionally by plowing, followed by application of granular rock salt. By the 1970s, many highway operators recognized that the application of salt had adverse effects on highway infrastructure, vehicles, and roadside environment (*2*), and alternative application methods were developed to reduce the overall quantities needed. Principal among the methods is the use of liquid salts, either as an additive to conventional rock salt (prewetting) or applied on its own before snow accumulation (direct liquid application) (*3, 4*).

While these alternative methods have been widely implemented, assessment of their performance in comparison with conventional rock salt, and estimation of overall potential for salt reduction, is an unresolved issue. That is, their effectiveness is influenced by many uncontrolled variables during winter maintenance operations.

The primary objective of this research is to quantify and compare the effectiveness of rock salt with and without prewetting liquid, and distinguish among different chemical species of prewetting liquids. The research involves a statistical analysis of data collected by the Ministry of Transportation of Ontario (MTO) (*5*) through a large-scale field experiment called De-icing/Anti-icing Response Treatment (DART) (*6*). The paper first provides an overview of test sites and data collected from the tests. This is followed by a case-by-case comparison of several alternative maintenance treatments. A set of statistical models is developed that quantify the effects of various factors on snow removal. Finally, conclusions are summarized and future research directions are highlighted.

DESCRIPTION OF STUDY SITE AND DATA

Data in this analysis were collected at the DART field site by MTO forces in the winter season of 2002 to 2003. The test site is a 50-km maintenance route on Highway 21 in the Great Lakes–St. Lawrence climatic region of southwestern Ontario, Canada (Figure 1*a* and 1*b*). Because of its proximity to Lake Huron and Georgian Bay, the route is subject to frequent lake-effect snowfall, with normal winter snow accumulation of 2.8 m over 75 to 80 snowfall days. The mean daily temperature (MDT) at this area is below 0°C for from December through March, and the coldest month is January, with an MDT of –7°C. The topography of the route consists of rolling farmland and woodlots with a combination of open and sheltered terrain (*6*).

Highway 21 is a Service Class 2 highway with winter average daily traffic in the range 2,000 to 6,000 vehicles, which requires plowing when snow accumulation reaches 20 mm and recovery of bare pavement within 8 h after a storm (*6*). The 50-km test route was divided into eight sections, labeled sequentially from 1 to 8, with lengths varying from 2 to 5 km. Sections 1 through 7 are two-lane, two-way highways, while Section 8 is a four-lane collector with two lanes in each direction. All sections are paved with asphalt concrete.

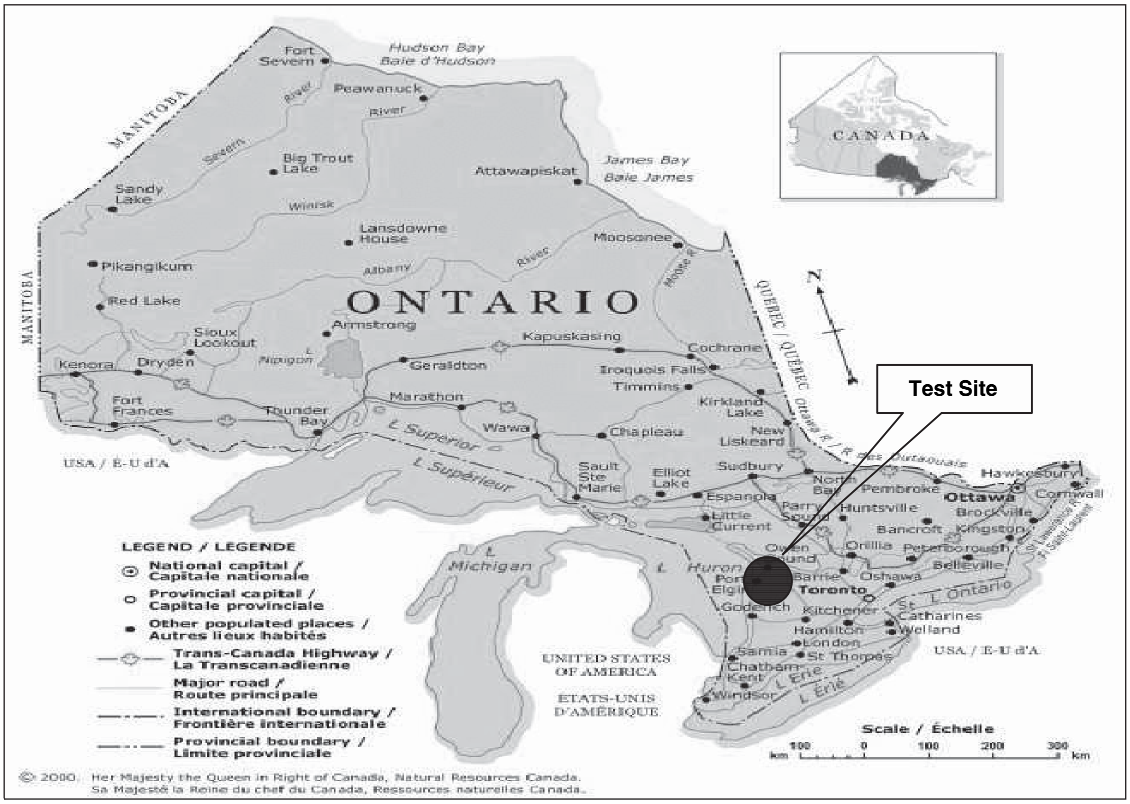
Different chemical application protocols, varying by material type, application rate, and application method, were tested. The prewetting chemicals included near-saturation solutions of NaCl (sodium chloride brine), $CaCl_2$ (calcium chloride brine with corrosion inhibiting additives marketed as Corguard), and $MgCl_2$ (magnesium chloride brine with corrosion inhibiting additives marketed as Freezeguard). All tests were conducted as part of normal winter maintenance operations while the highway was open to traffic. All test sections were plowed before chemical application, and chemicals or winter sand was reapplied if the surface was not cleared within the maintenance circuit time of approximately 1.5 h. Each pass of the plow or spreader across each test section was recorded either manually or with an automated vehicle location system, providing records of time and direction, chemical type, and application rate (*6*).

A video surveillance camera was installed near the center of each test section to record pavement snow coverage at a pavement marking grid that divided the pavement into three consecutive 1.3-m squares across each lane. Snow cover fraction, defined as the fraction of area covered by snow (0.0 to 1.0), was estimated visually from the recorded video and tabulated for each square at a 10-min interval over the duration of a storm event.

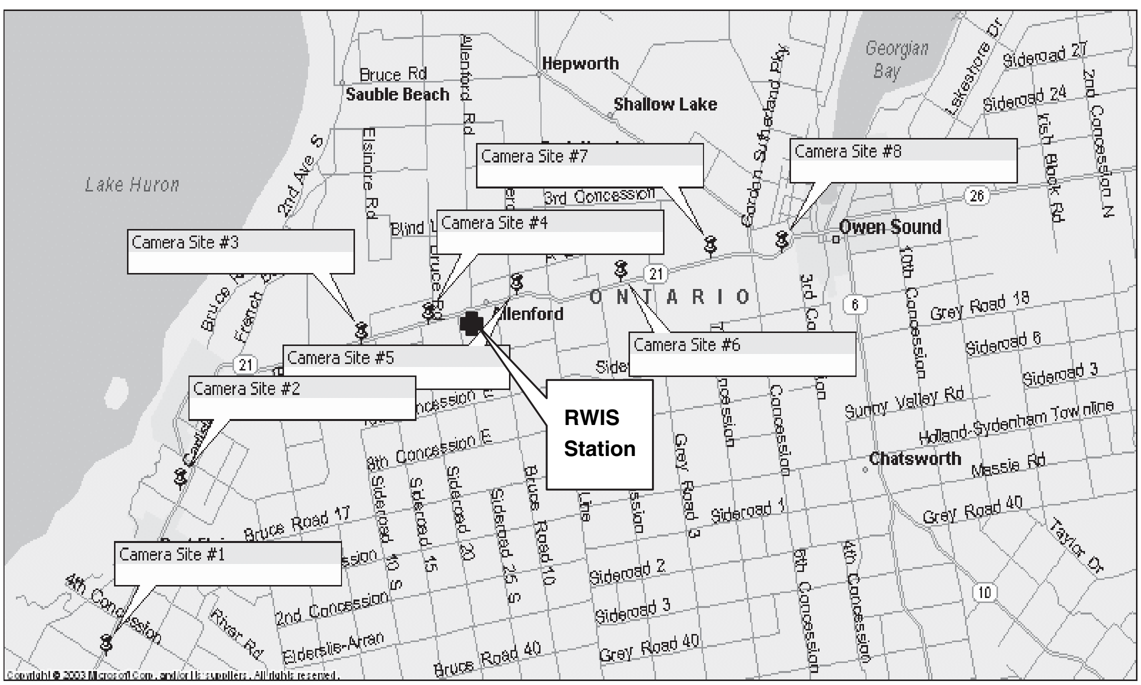
Air and pavement temperature, wind speed, and precipitation were obtained from a roadway weather information system (RWIS)

L. Fu and R. Sooklall, Department of Civil Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada. M. S. Perchanok, Construction and Operations Branch, Ontario Ministry of Transportation, 301 St. Paul Street, St. Catharines, Ontario L2R 7R4, Canada.

Transportation Research Record: Journal of the Transportation Research Board, No. 1948, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 125–134.



(a)



(b)

FIGURE 1 Study site: (*a*) Great Lakes–St. Lawrence climatic region and (*b*) test sections and roadway weather information system station.

station located at Allenford (Figure 1*b*). Data on daily snowfall were obtained from the nearest Environment Canada observing stations and were used to estimate snowfall rate during each storm (total snowfall divided by storm duration). Storm duration was defined as the time from onset of snow accumulation until restoration of bare pavement (≤5% snow cover).

Data from test Sections 6, 7, and 8, with similar weather and exposure conditions, were used in this study. Each direction of a highway section is considered a separate analysis unit. Note that snow cover measurements at all test sections were postprocessed to determine the average snow cover in each direction. Preliminary analysis showed that snow cover in the right wheel track of both Sections 6 and 7 was several times higher than in the left wheel track and lane center, while no across-pavement trend was seen in Section 8. To avoid bias due to across-lane variance in snow cover, lane center snow cover in Sections 6 and 7 was compared with mean snow cover in each direction of Section 8.

A total of 16 storms were recorded during the winter season of 2002 to 2003, with average snowfall rate in the range of 0.01 to 3.13 cm per h. Different chemical protocols were used, with dry rock salt and fine gradation salt applied at rates varying from 50 to 85 kg per lane km. Granular rates for prewetted salt ranged from 37 to 90 kg per lane km. The prewetting agents ($CaCl_2$, $MgCl_2$, and NaCl) were applied at 7% or 15% of the granular mass.

The rock salt used conformed to MTO standard specification (OPSS 2502, December 1990) (*7*), which specifies at least 96% by mass sodium chloride, 100% smaller than 9.5-mm sieve, and maximum 65% passing the 2.36-mm sieve. The gradation is similar to that of coarse sand. Fine salt consisted of 100% grains smaller than 4.75 mm and at least 35% smaller than 1.18 mm. Winter sand was applied to provide immediate traction when snow could not be removed by plowing or salting. It was premixed with granular salt at a rate of 5% by mass to prevent stockpile freezing and is referred to as dry sand to distinguish it from sand that was prewetted with chemical agents in some tests.

The spreaders discharged material from the left side of the hopper between the front and rear wheels. Spreading speeds are specified by Maintenance Best Practice 702 as 32 to 48 kmh, and during operations, speed was adjusted to maintain a constant centerline windrow pattern (*8*).

COMPARATIVE ANALYSIS

Discussed here are results of a comparative analysis on the effectiveness of different chemical application protocols on snow removal, through data obtained at the three test sections mentioned. Performance of a treatment is measured by the fraction of pavement covered by snow (snow cover). Two measures of effectiveness were used: change in snow cover over time and average snow cover.

Change in snow cover was evaluated visually by graphing snow cover against time. Average snow cover is used as a surrogate for level of service (LOS) by each particular chemical application protocol. It is calculated as average of all snow covers measured over the snowstorm, from the first chemical application to the end of the storm (or end of observation period). A lower value of average snow cover can be translated as a higher LOS experienced by drivers.

To ensure validity of the comparative analysis, each comparison is formed with cases that had similar storm characteristics, location, and traffic. For example, if one compares the effectiveness of prewetted salt and dry salt, cases should be selected in which the two types of materials are applied with similar amounts (dry rates) to similar highway sections (e.g., geographical features) under similar weather conditions. Where there were differences, detailed descriptions of the differences are provided.

On the basis of chemical application protocols tested at the three highway sections, two pair-wise comparisons—prewetted versus dry salt, and prewetted salt with different prewetting chemicals—are performed as explained in the following section.

Effectiveness of Prewetted Salt

Prewetting salt has been widely accepted as an effective technique for improving the deicing capability of salt. That is because it accelerates the start of the melting process by directly providing the necessary initial moisture; it also assists salt particles in adhering to pavement. However, it is largely unknown how much more effective prewetted salt is over regular dry salt. This analysis attempts to address this question through data from the DART test.

Seven cases identified from the DART tests can be used for comparison, as shown in Table 1. The temporal variation of snow cover for two example cases is shown in Figure 2. From results shown in Table 1 and Figure 2, one can see that in five of seven cases, prewetted salt outperformed dry salt in reducing snow cover, with relative improvement ranging from 17.9% to 40.0%. For example, in the snow event of January 25, 2003 (Figure 2*a*), the same amount of dry salt (70 kg/lane km) was used for both prewetted salt applications and dry salt applications; however, the average snow cover for the section applied with prewetted salt was 40% lower than the section with dry salt. Also, in the case of January 27, 2003 (Figure 2*b*), prewetted fine salt (with 7% $CaCl_2$) was found to be 19% more effective than dry fine gradation salt even though the latter (dry fine salt) was applied twice more than prewetted salt. These results further confirm the benefit of the prewetting strategy and are consistent with findings in the literature [e.g., (*9, 10*)].

Dry salt outperformed prewetted salt in reducing average snow cover for Cases 4 and 7. Case 4 occurred on January 25, 2003, which experienced heavy snowfall; salt was applied during the first half of the storm duration and sand in the latter stage. The site treated with prewetted salt outperformed the site treated with dry salt for the storm's first half, which is consistent with the majority of the cases. However, both sites then experienced an increase in snow cover in the latter part of the storm before achieving bare pavement, with the prewetted site having a larger increase in snow cover. The greater increase at the prewetted site resulted in a higher average snow cover, thus showing that dry salt outperformed prewetted salt over the storm's duration. Possible causes for the rapid increase in snow cover at the prewetted site include blowing snow due to fairly high winds and a lower residual effect due to prewetted salt going into solution faster combined with heavy snowfall. It was difficult to pinpoint why dry salt outperformed prewetted salt for Case 7.

Effectiveness of Alternative Prewetting Agents

This section investigates the relative effectiveness of alternative chemicals used for prewetting dry salt: $CaCl_2$, $MgCl_2$, and NaCl. A total of 13 cases are identified from the DART test database: 11 cases related to $CaCl_2$ and $MgCl_2$ and the remaining 2 for comparing $CaCl_2$

TABLE 1 Summary of Treatment Cases and Effectiveness of Prewetted Salt Versus Dry Salt

Case	Date of Event	Weather and Surface Conditions[a]	Chemicals Used[b] Prewetted Salt	Chemicals Used[b] Dry Salt	LOS[c] Prewetted Salt	LOS[c] Dry Salt	LOS[c] Difference (%)
1	1/24/2003	1.0 cm 6.5 h –14.1 °C 0.6 km/h	8E Prewet rock salt at 15% $CaCl_2$[d] 70 kg/lane km (2/1) Dry sand 285 kg/lane km (2/0)	8W Dry rock salt 70 kg/lane km (2/1) Dry sand 285 kg/lane km (2/0)	0.13	0.18	27.8
2	1/25/2003	25.0 cm 8.0 h –6.1 °C 27.9 km/h	8E Prewet rock salt at 7% $CaCl_2$ 70 kg/lane km (5/3)	8W Dry rock salt 70 kg/lane km (5/3)	0.21	0.35	40.0
3	1/25/2003	25.0 cm 8.0 h –6.1 °C 27.9 km/h	7W Prewet rock salt at 7% $CaCl_2$ 70 kg/lane km (2/0)	6W Dry rock salt 70 kg/lane km (2/0)	0.23	0.33	30.3
4	1/25/2003	25.0 cm 8.0 h –6.1 °C 27.9 km/h	7E Prewet rock salt at 7% $CaCl_2$ 70 kg/lane km (2/0) Sand/salt mix (20% salt) 285 kg/lane km (1/0)	6E Dry rock salt 70 kg/lane km (2/0) Dry sand 285 kg/lane km (1/0)	0.22	0.18	–22.2
5	1/27/2003	4.5 cm 7.0 h –18.8 °C 2.8 km/h	8E Prewet fine salt at 7% $CaCl_2$ 56 kg/lane km (4/2)	8W Dry fine salt 66 kg/lane km (6/0)	0.23	0.28	17.9
6	2/14/2003	0.2 cm 8.3 h –10.0 °C 0.3 km/h	7E Prewet fine salt at 15% $CaCl_2$ 56 kg/lane km (2/0)	6E Dry fine salt 66 kg/lane km (2/0)	0.44	0.66	33.3
7	2/14/2003	0.2 cm 8.3 h –10.0 °C 0.3 km/h	7W Prewet fine salt at 15% $CaCl_2$ 56 kg/lane km (2/0)	6W Dry fine salt 66 kg/lane km (2/0)	0.62	0.57	–8.8

[a]Snowfall/storm duration/pavement temperature/wind speed; [b]site/material/granular application rate in kg/lane km (number of applications/plow only); [c]average snow cover; [d]percentage of liquid added to granular mass.

and brine, as shown in Table 2. As with the previous analysis, the average snow cover under each treatment is provided (Table 2) as well as two example charts showing snow cover variation over time for visual illustration (Figure 3). From results shown in Table 2 and Figure 3*a* and 3*b*, the following observations can be made:

- Salt prewetted with $CaCl_2$ appeared to start the melting process faster than did salt with $MgCl_2$, resulting in lower average snow cover, regardless of dry salt rate and prewetting ratio. In all except one case, $CaCl_2$ outperformed $MgCl_2$ by 9.5% to 71.4% in regard to average snow cover. It was also observed that salt prewetted with the two chemicals generally achieved bare pavement around the same time. This outcome is consistent with Minsk (*4*), who stated that $CaCl_2$ in liquid form, at about 32% concentration, is most effective in lowering the effective melting temperature, and that $MgCl_2$ and NaCl are also effective prewetting agents.
- $CaCl_2$ was also found to be more effective than salt brine in regard to snow cover reduction as shown in Cases 12 and 13. In Case 12 (February 14, 2003), the effectiveness of $CaCl_2$ was similar to that of brine, but in the case with brine, one extra salt application was made. In Case 13, salt with $CaCl_2$ resulted in an average snow cover 37.5% lower than with the brine counterpart. Nixon et al. (*11*) conducted a laboratory test of the ice melting capacity of both liquid calcium chloride and salt brine, which appeared to suggest that $CaCl_2$ performed better than NaCl.

MODELS FOR SNOW MELTING TREND

As discussed, one major challenge to quantifying the effectiveness of snow removal is the uncontrollable nature of field experiments and the multiple factors simultaneously influencing the snow melting process. A common approach to this challenge is to calibrate regression models between the response variable and influencing factors based on observational data. These models could then be used to explain the degree of effects that individual factors have on the response variable and also to predict future responses under a given condition.

The response variable in this study could be either the snow cover at a given time or snow melting rate at a given time interval during a snow event. In this study, snow melting rate was chosen as the response variable representing effectiveness of snow removal, for it better meets the requirement of independency between observations than the variable snow cover. Because snow-melting rate is a continuous variable, the researchers first attempted ordinary linear regression models as well as their variants (e.g., using nonlinear transformed functions). However, results were not satisfactory; a model

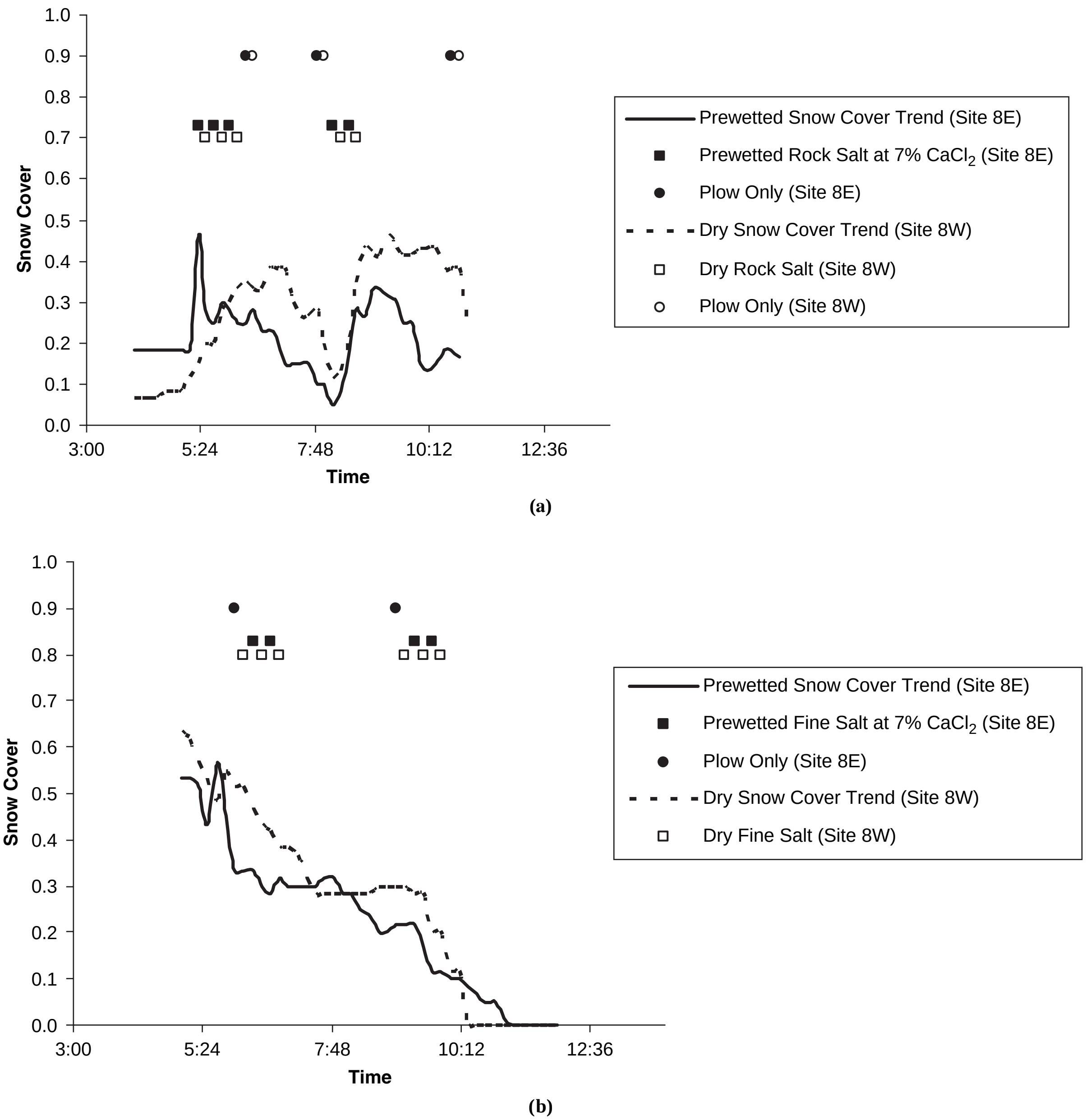


FIGURE 2 Temporal variation of snow cover with prewetted salt versus dry salt: (*a*) Case 2, January 25, 2003, and (*b*) Case 5, January 27, 2003.

with an acceptable explanatory power could not be identified as based on observations. This outcome could be attributed to the large variation in the observed snow melting rate caused by large random variations in influencing factors, such as road surface and traffic conditions, snow drifting, and even estimating snow cover. The snow-melting rates were aggregated into three categories: snow cover decreased (melting rate > 0); snow cover unchanged (melting rate = 0); and snow cover increased (melting rate < 0). Also, the researchers tried to identify factors influencing the probability of observing each outcome. Of note is that a similar approach was used by Perchanok (*6*). That author represented snow cover trend over a given period (e.g., ½ or 1 h) as a variable with two states: increased or did not increase (stayed the same or decreased) in evaluating the effectiveness of salt application in reducing snow cover.

As commonly used in literature to model discrete response variables, a multinomial logit model was applied in this study to capture the propensity toward each snow melting outcome under various operating conditions. For convenience of calibration and interpretation, the researchers formulate the multinomial logit model as ratios of odds between two of the three outcomes, using the third category (snow cover increased) as the basis, that is

$$\frac{P_1}{P_0} = e^{Z_1}$$
$$\frac{P_2}{P_0} = e^{Z_2} \qquad (1)$$

TABLE 2 Summary of Treatment Cases for Comparing Prewetting Chemicals

Case	Date of Event	Weather and Pavement Conditions[a]	Prewetting Chemicals Used[b]		LOS[c]		
			$CaCl_2$	$MgCl_2$	$CaCl_2$	$MgCl_2$	Difference (%)
1	2/3/2003	0.2 cm (19.3 h) –1.4 °C (14.4 km/h)	8E Rock salt 50 kg/lane km at 15% (4/1)[d]	8W Rock salt 50 kg/lane km at 15% (4/1)	0.12	0.14	14.3
2	2/6/2003	13.0 cm (6.0 h) –5.5 °C (14.4 km/h)	8E Rock salt 56 kg/lane km at 7% (4/1)	8W Rock salt 56 kg/lane km at 7% (5/0)[e]	0.26	0.39	33.3
3	2/6/2003	13.0 cm (6.0 h) –5.5 °C (14.4 km/h)	7E Rock salt 56 kg/lane km at 7% (2/0)	6E Rock salt 56 kg/lane km at 15% (2/0)	0.27	0.31	12.9
4	2/6/2003	13.0 cm (6.0 h) –5.5 °C (14.4 km/h)	7W Rock salt 56 kg/lane km at 7% (2/0)	6W Rock salt 56 kg/lane km at 15% (2/0)	0.29	0.26	–11.5
5	3/2/2003	0.5 cm (23.8 h) –5.7 °C (20.6 km/h)	8E Rock salt 37 kg/lane km at 15% (4/0)	8W Rock salt 37 kg/lane km at 7% (4/0)	0.19	0.30	36.7
6	3/2/2003	0.5 cm (23.8 h) –5.7 °C (20.6 km/h)	7E Rock salt 50 kg/lane km at 15% (2/3) Dry sand 300 kg/lane km (3/0)	6E Rock salt 50 kg/lane km at 7% (2/3) Dry sand 300 kg/lane km (3/0)	0.10	0.21	52.4
7	3/2/2003	0.5 cm (23.8 h) –5.7 °C (20.6 km/h)	7W Rock salt 50 kg/lane km at 15% (2/5) Dry sand 300 kg/lane km (1/0)	6W Rock salt 50 kg/lane km at 7% (2/5) Dry sand 300 kg/lane km (1/0)	0.06	0.21	71.4
8	3/5/2003	16.0 cm (11.0 h) –1.8 °C (16.1 km/h)	8E Rock salt 90 kg/lane km at 7% (2/1)	8W Rock salt 90 kg/lane km at 7% (3/0)	0.67	0.74	9.5
9	3/5/2003	16.0 cm (11.0 h) –1.8 °C (16.1 km/h)	8E Rock salt 46 kg/lane km at 15% (3/0)	8W Rock salt 46 kg/lane km at 15% (3/0)	0.14	0.32	56.3
10	3/5/2003	16.0 cm (11.0 h) –1.8 °C (16.1 km/h)	7E Fine salt 46 kg/lane km at 7% (1/1)	6E Fine salt 46 kg/lane km at 7% (1/1)	0.45	0.51	11.8
11	3/5/2003	16.0 cm (11.0 h) –1.8 °C (16.1 km/h)	7W Fine salt 46 kg/lane km at 7% (1/1) Sand 285 kg/lane km at 15% (2/0)	6W Fine salt 46 kg/lane km at 7% (1/1) Sand 285 kg/lane km at 7% (2/0)	0.43	0.48	10.4
			$CaCl_2$	NaCl	$CaCl_2$	NaCl	
12	2/14/2003	0.2 cm (8.3 h) –10.0 °C (0.3 kph)	8E Rock salt 56 kg/lane km at 15% (4/1)	8W Rock salt 56 kg/lane km at 15% (5/0)	0.66	0.65	–1.5
13	2/25/2003	0.2 cm (9.0 h) –6.7 °C (12.5 kph)	8E Rock salt 46–50 kg/lane km at 7–15% (6/2)	8W Rock salt 46–50 kg/lane km at 7% (6/2)	0.05	0.08	37.5

[a]Snowfall (storm duration)/pavement temperature (wind speed); [b]site/material/granular application rate in kg/lane km (number of applications/plow only); [c]average snow cover; [d]percentage of liquid added to granular mass; [e]one of the five applications was dry rock salt.

where

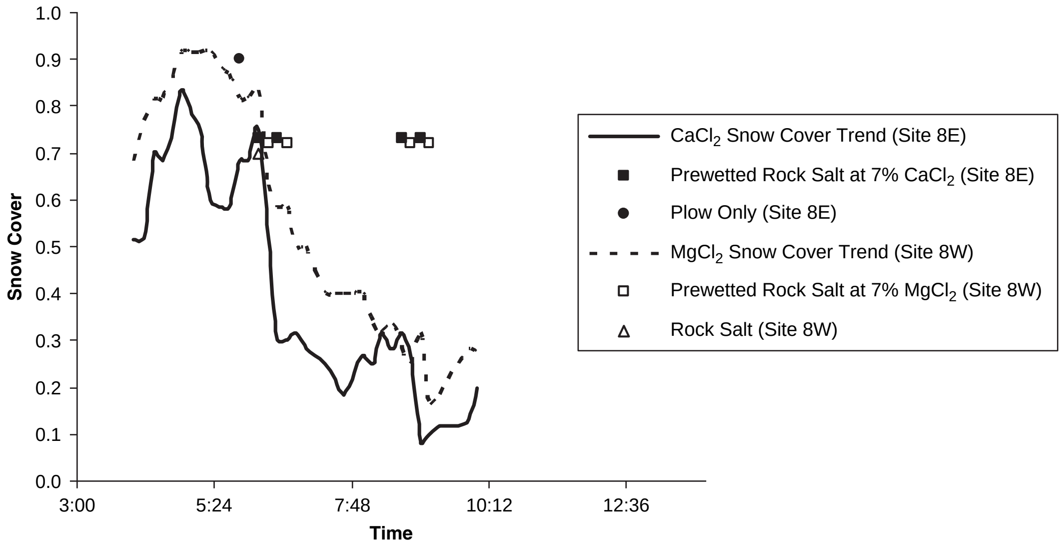
P_0, P_1, P_2 = probabilities for observing outcome 0 (snow cover increased), 1 (snow cover unchanged), and 2 (snow cover decreased), respectively,
Z_i = an intermediate variable representing the relative tendency toward the outcome of i (i = 1 or 2) compared with the outcome of the base category of snow coverage increased, and
e = the base of natural logarithms.

This variable can be expressed as a linear function of covariates representing factors that influence the snow melting trend, that is

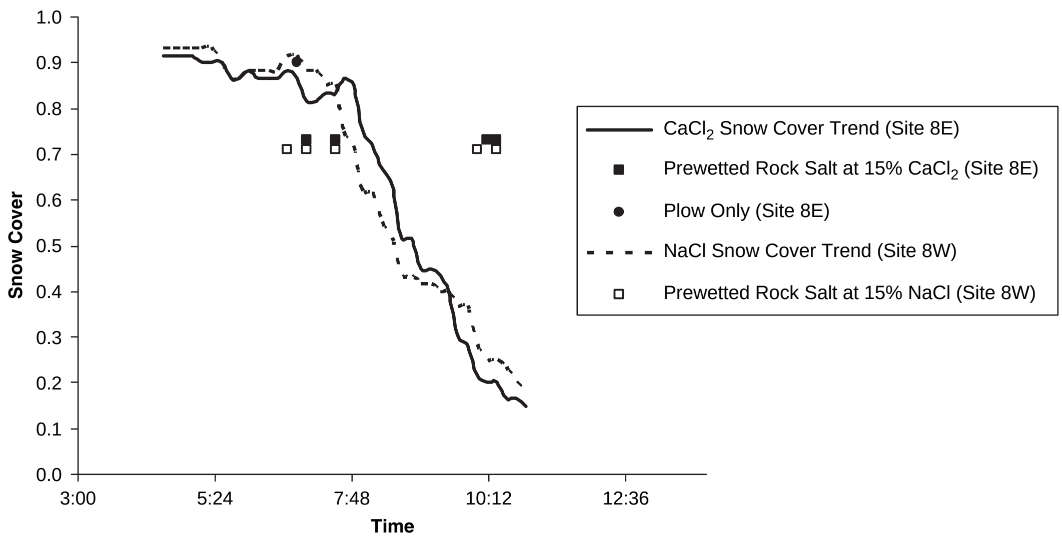
$$Z_i = \beta_{i0} + \beta_1 x_{i1} + \cdots + \beta_{ik} x_{ik} \tag{2}$$

where

$\beta_0, \beta_1, \ldots, \beta_k$ = regression parameters estimated from the data.
x = covariates, and
x_{ik} = the kth covariate for the ith outcome.



(a)



(b)

FIGURE 3 Temporal variation of snow cover—prewetting with $CaCl_2$ versus prewetting with $MgCl_2$ and prewetting with $CaCl_2$ versus prewetting with NaCl: (*a*) Case 2, February 6, 2003, and (*b*) Case 12, February 14, 2003.

In consideration of available data and anticipation of possible factors influencing the snow-melting trend, the following factors were considered independent variables in regression analysis:

- Weather conditions: snowfall rate, air temperature, and wind speed;
- Road conditions: initial snow cover (snow cover at the beginning of time interval) and pavement surface temperature; and
- Maintenance treatment: total amount of salts remaining on the road at beginning of the time interval and material type.

The total amount of salts previously applied during the storm that remain active on the pavement is an intermediate variable with no field data available; it must also be estimated. As discussed previously, data on treatment operations include only the application rate of dry salt, mixing ratio in the case of prewetted salt and brine, and time the salt was applied. Once the salts are applied, part of them will be lost over time due to the impacts of traffic and the melting process itself. It is still an open question about how the applied salt depreciates over time (*10*, *12*). In this study, the following simple empirical model is assumed to simulate the process:

$$S_t = S_0 e^{-bt} \qquad (3)$$

where

S_0 = initial amount of salts applied, expressed in dry salt kilograms per lane kilometers;
S_t = amount of salts remaining at time t, expressed in dry salt kilograms per lane kilometers; and
b = parameter to capture rate of depreciation.

A *b*-value of zero means that the salts will remain unchanged over time while a larger value of *b* indicates a faster rate of salt loss.

Because there are not direct observations on the amount of salts remaining on the road by time for calibrating the parameter of *b*, the *b*-value is chosen as part of the calibration process, discussed later. In addition to use of the foregoing variables, confounding effects of some of the influencing factors are evaluated, such as wind speed, snow cover or snowfall, pavement temperature, and amount of salts remaining; they are included as two-way interaction terms.

The statistical software package SPSS was used to obtain model coefficients and performance statistics. Each calibration started with an assumed *b*-value for calculating the residual amount of salt on road, which, combined other data items, was used to calibrate the multinomial logit model as described. After a set of *b*-values ranging from 0 to 1.0 were tried, it was found that a *b*-value ranging from 0.01 to 0.2 generally yielded the best results and the significance of variables other than salt were insensitive to the *b*-value. As a result, a common *b*-value of 0.1 was chosen for all test sections in further analysis. Tables 3 and 4 summarize the calibration results for Sections 7 and 8, respectively. (Section 6 was not included because the majority of the snow trend observed at this site was zero; that is, no change in snow cover was observed.) Separate models were calibrated for the two directions of each test section; this allowed one to capture any directional differences in response variation and to cross-validate the calibrated models.

The log likelihood values (–2 log likelihood) given in Tables 3 and 4 are used to test the significance of the multinomial logit model compared with the intercept-only model. The intercept-only model assumes that the probability of snow cover remaining the same or decreasing is not related to the proposed model variables. By comparing the likelihood ratio to the critical χ^2 value, one can test the null hypothesis, H_0, in which all coefficients except the intercepts are zeros. Statistics shown in Tables 3 and 4 indicate that all models adequately fit the data at a level of significance α, less than 0.1%.

The pseudo R^2 provided in Tables 3 and 4 is a statistic similar to the R^2 used in ordinary linear regression, for measuring explanatory power of the estimated multinomial logit models. The benchmark pseudo R^2 value for multinomial logit models is usually much lower than the R^2-value acceptable for ordinary linear regression, with a value as low as 0.15 considered reasonable. On the basis of this statistic, all the models could be considered as statistically reliable with an acceptable explanatory power.

Columns headed "*B*" in Tables 3 and 4 provide coefficients of the calibrated models, with their corresponding level of significance listed in columns headed "Sig." In this analysis, a level of significance of 20% or less is considered acceptable in further interpretation.

A comparison between models for different sections and directions indicates that most of the calibrated models are comparable in regard to magnitude and sign of the coefficients, providing further evidence of their validity. From results, the following observations are made:

- The effect of wind speed on snow cover was statistically significant and consistent across all locations. At both sites, wind speed alone was associated with increase in snow cover (negative coefficients). Furthermore, the two-way interaction term, initial snow cover and wind speed, was found to have a significant effect on snow accumulation. This result statistically confirms the expected effect of blowing snow. Also, based on the magnitude of the coef-

TABLE 3 Model Estimation Results: Parameter Values and Significance Tests for Test Section 7

Factor		Site 7 Eastbound					Site 7 Westbound				
		B	Std. Error	Wald (*t*)	Sig.	Exp(*B*)	*B*	Std. Error	Wald (*t*)	Sig.	Exp(*B*)
1	Intercept	2.042	.739	7.642	.006		1.281	.671	3.643	.056	
	Snowfall rate (cm/h)	–.284	.334	.727	.394	.752	–1.350	.326	17.138	.000	.259
	Wind speed (km/h)	–.098	.049	4.079	.043	.906	–.014	.027	.271	.603	.986
	Surface temperature (°C)	–.055	.030	3.316	.069	.947	–.075	.037	4.257	.039	.927
	Initial snow cover (fraction)	–.335	1.135	.087	.768	.715	.651	.893	.531	.466	1.917
	Snowfall rate * Wind speed	.010	.014	.529	.467	1.010	.040	.014	7.730	.005	1.041
	Initial snow cover * Wind speed	–.076	.058	1.737	.188	.926	–.074	.046	2.586	.108	.929
	Applied salt (kg/lane km)	–.012	.009	2.050	.152	.988	.016	.009	3.381	.066	1.016
	Applied sand (kg/lane km)	.005	.002	10.884	.001	1.005	.001	.001	5.363	.021	1.001
2	Intercept	1.663	.818	4.131	.042		1.290	.756	2.911	.088	
	Snowfall rate (cm/h)	–.434	.373	1.354	.245	.648	–.740	.364	4.118	.042	.477
	Wind speed (km/h)	–.044	.053	.687	.407	.957	–.040	.031	1.600	.206	.961
	Surface temperature (°C)	–.072	.035	4.219	.040	.931	.018	.042	.180	.672	1.018
	Initial snow cover (fraction)	–.815	1.256	.421	.517	.443	.219	.996	.048	.826	1.245
	Snowfall rate * Wind speed	.024	.016	2.281	.131	1.024	.031	.016	3.546	.060	1.031
	Initial snow cover * Wind speed	–.041	.065	.405	.525	.959	–.078	.055	1.978	.160	.925
	Applied salt (kg/lane km)	–.009	.009	.842	.359	.991	.002	.010	.024	.878	1.002
	Applied sand (kg/lane km)	.002	.002	1.040	.308	1.002	.001	.001	3.238	.072	1.001
–2 log likelihood (Intercept)/ –2 log likelihood (model)				992.62/925.27					992.6/931.2		
Chi-square/significance				67.3/0.000					61.4/0.000		
Pseudo R^2				0.142					0.178		

NOTE: The reference category is: –1. Wald (*t*) is a statistic used to test the statistical significance of each coefficient (*B*) and it is the ratio of the coefficient to its standard error, squared. Exp(*B*) is a notation for e^B and it is the odds of observing an outcome to the reference outcome.

TABLE 4 Model Estimation Results of Parameter Values and Significance Tests for Test Section 8

Factor		Site 8 Eastbound					Site 8 Westbound				
		B	Std. Error	Wald (t)	Sig.	Exp(B)	B	Std. Error	Wald (t)	Sig.	Exp(B)
1	Intercept	1.228	.419	8.591	.003		1.000	.484	4.264	.039	
	Snowfall rate (cm/h)	–.065	.291	.050	.824	.937	–.054	.346	.024	.876	.947
	Wind speed (km/h)	–.016	.024	.457	.499	.984	–.020	.028	.505	.477	.980
	Surface temperature (°C)	.032	.020	2.539	.111	1.032	.059	.025	5.429	.020	1.061
	Initial snow cover (fraction)	–.100	.728	.019	.890	.905	1.059	.935	1.282	.257	2.883
	Snowfall rate * Wind speed	.000	.013	.000	.997	1.000	–.016	.015	1.213	.271	.984
	Initial snow cover * Wind speed	–.247	.054	20.547	.000	.781	–.244	.064	14.285	.000	.784
	Applied salt (kg/lane km)	.001	.001	.229	.632	1.001	.003	.001	5.972	.015	1.003
	Applied sand (kg/lane km)	.000	.001	.655	.418	1.000	.000	.001	.162	.687	1.000
2	Intercept	–.682	.503	1.840	.175		–1.522	.583	6.812	.009	
	Snowfall rate (cm/h)	.080	.281	.080	.777	1.083	.001	.371	.000	.998	1.001
	Wind speed (km/h)	–.063	.027	5.559	.018	.939	–.080	.031	6.716	.010	.923
	Surface temperature (°C)	.004	.023	.035	.853	1.004	.048	.029	2.793	.095	1.049
	Initial snow cover (fraction)	1.310	.734	3.187	.074	3.705	2.776	.984	7.963	.005	16.059
	Snowfall rate * Wind speed	.003	.013	.068	.795	1.003	–.016	.016	.990	.320	.985
	Initial snow cover * Wind speed	–.094	.045	4.371	.037	.911	–.150	.067	4.946	.026	.861
	Applied salt (kg/lane km)	.004	.001	8.589	.003	1.004	.006	.001	23.717	.000	1.006
	Applied sand (kg/lane km)	.000	.001	.005	.942	1.000	.000	.001	.202	.653	1.000
–2 log likelihood (Intercept)/ –2 log likelihood (model)				1531.6/1368.3					1348.0/1209.7		
Chi-square/significance				163.3/0.001					138.3/0.001		
Pseudo R^2				0.220					0.200		

NOTE: The reference category is: –1.

ficients, the effect of blowing snow at Section 8 appeared larger than the effect at Section 7 (0.094~0.247 for Section 8 versus 0.041~0.078 for Section 7). However, analysis rejected the possible effect of combined snowfall and wind speed; it might make sense, in that wind moves the snow around, though it does not increase snowfalls.

- The snow cover at the beginning of each observation interval was found to have a significant effect on the snow melting trend at Section 8: the higher the initial snow cover, the more frequent the snow cover had decreased. Snow cover alone (without wind), however, was not found to be a significant factor influencing the snow-melting trend at Section 7.
- Snowfall rate was found to be a significant factor only in the westbound lane of Section 7. The result, somehow unexpected, could be attributed to the fact that this variable was not measured directly but estimated on the basis of total snowfall.
- Pavement surface temperature was found to have a positive effect on snow melting at Section 8
- The total amount of salts applied was found to have a positive effect on snow removal at Section 8 in both directions. However, results at Section 7 were mixed. The researchers could not statistically confirm the effect of salts on the outcome of decreased snow cover, or they obtained conflicting results on the status of unchanged snow cover (–0.012 for eastbound versus 0.016 for westbound).
- The model coefficients associated with sand were positive for all cases, suggesting its positive effect on snow melting trend. However, the effect was confirmed statistically only for Section 7. Sand was applied mostly for increasing pavement friction instead of for deicing. The reason that sand had a positive effect on snow removal at these test sites is still unclear; further investigation is needed.

CONCLUSIONS

Quantifying the effectiveness of alternative winter maintenance treatments is a challenging and elusive goal due to large variation in observational environments such as weather, traffic, and location. This research has attempted to compare the effects of treatments involving different prewetting chemicals. A systematic statistical analysis was performed on observational data, toward identifying quantitative effects of weather and maintenance operations on snow melting trend. Results obtained from this study are based on data from one winter season, and further investigation using data from other winter seasons may be required to confirm the results. Major conclusions and findings obtained from this analysis are as follows:

- Prewetted salt outperformed dry salt in most test cases by a reduction in snow cover from 17.9% to 40.0%.
- As a prewetting agent, $CaCl_2$, was found to be much more effective than $MgCl_2$, providing higher overall LOS (or lower average snow cover), regardless of dry salt rate or prewetting ratio. $CaCl_2$ outperformed $MgCl_2$ by 9.5% to 71.4% pertaining to reduction in average snow cover. $CaCl_2$ was also found to be more effective than salt brine, NaCl.
- Statistical analysis of the snow-melting trend indicated that snow removal was not successful under high wind speeds due to the

expected effect of blowing snow. The cumulative amount of salt and sand–salt mix applied also had a positive effect on snow removal.

- This research introduced a multinomial logit model framework for capturing the relationship between time-varying, random snow melting trend and various influencing factors. Resulting models were found to make intuitive sense, signifying its potential as an appropriate tool for analyzing the effectiveness of alternative winter maintenance methods and relative importance of various environmental factors.

ACKNOWLEDGMENTS

This research was supported by the Ontario Ministry of Transportation under the Highway Infrastructure Innovation Funding Program. The authors acknowledge the Aurora Partnership, and the assistance of MTO staff and contractors in Owen Sound Area, Southwest Region and Head Office Maintenance. Rob McInnis coordinated field operations.

REFERENCES

1. Perchanok, M. S. Patchiness of Snow Cover and Its Relation to Quality Assurance in Winter Operations. *Proc., 11th PIARC International Winter Road Congress* (CD-ROM), Sapporo, Japan, 2002.
2. Perchanok, M. S., D. G. Manning, and J. J. Armstrong. *Highway De-Icers: Standards, Practice and Research in the Province of Ontario.* Ontario Ministry of Transportation, Research and Development Branch, Downsview, Ont., Canada, 1991.
3. Blackburn, R. R., K. M. Bauer, D. E. Amsler Sr., S. E. Boselly, and A. D. McElroy. *NCHRP Report 526: Snow and Ice Control Guidelines for Materials and Methods.* Transportation Research Board of the National Academies, Washington, D.C., 2004.
4. Minsk, L. D., *Snow and Ice Control Manual for Transportation Facilities.* McGraw-Hill Companies, New York, 1998.
5. Ministry of Transportation Ontario. *Maintenance Technology Project: Integrating Technology for Winter Road Maintenance.* www.mto.gov.on.ca/english/transtek, Accessed 2005.
6. Perchanok, M. S. *Decision Support System for Winter Maintenance: The DART Database.* AURORA Partnership. Project 1997-03. Ontario Ministry of Transportation, Downsview, Ont., Canada, 2002.
7. Chemical Specification—OPSS 2502 (Material Specification for Sodium Chloride), Ontario Provincial Standards, Highway Design Office, Ontario Ministry of Transportation, St. Catharines, Ont., Canada, Dec. 1990.
8. Maintenance Best Practice—MBP 702 (Winter Maintenance Preseason Preparation), Ontario Provincial Standards, Maintenance Office, Construction and Operations Branch, Provincial Highways Management Division, Ontario Ministry of Transportation, St. Catharines, Ont., Canada, 2001.
9. Ketcham, S. A., L. D. Minsk, R. R. Blackburn, and E. J. Fleege. *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel.* Report FHWA-RD-95-202. FHWA, U.S. Department of Transportation, 1996.
10. Fonnesbech, J. K. Ice Control Technology with 20 Percent Brine on Highways. In *Transportation Research Record: Journal of the Transportation Research Board No. 1741,* TRB, National Research Council, Washington, D.C., 2001, pp. 54–59.
11. Nixon, W. A., J. Qiu, L. Qiu, G. Kochumman, and J. Xiong. Ice Melting Performance for Ice Control Chemicals. Presented at 84th Annual Meeting of the Transportation Research Board, Washington, D.C., 2005.
12. Blomqvist, G., and M. Gustafsson. *Patterns of Residual Salt on Road Surface: Case Study.* Swedish National Road and Transport Research Institute. Presented at 6th International Symposium on Snow Removal and Ice Control Technology, Spokane, Wash., 2004.

The Winter Maintenance Committee sponsored publication of this paper.