Transportation Association of Canada

Development of Winter Severity Indicator Models for Canadian Winter Road Maintenance

October 2007

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Development of Winter Severity Indicator Models for Canadian Winter Road Maintenance

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Abstract

This report discusses the development of the TAC Winter Severity Index. A winter severity index is a measure of the relative impact of winter weather on winter road maintenance (WRM) operations using historical meteorological or Road Weather Information System (RWIS) data. It can be used to evaluate the relative harshness of a winter in comparison with a base period.

A set of models were developed using Canadian WRM, Meteorological Service of Canada (MSC) and RWIS data. WRM data were collected from across Canada from eight provincial road authorities and seven cities. Salt usage in tonnes (salt (t)/lane-km/day) was chosen as the dependent variable, standardized to account for differences in road network and the number of days in the observation period.

The first model developed based on MSC data alone achieved a goodness of fit of 0.54. Explanatory variables were based on snowfall occurrence, air temperature, freezing rain occurrence, and an east-west dummy variable to account for differences in winter road maintenance practices in different parts of Canada. A second model was developed based on MSC data together with RWIS data. This achieved a goodness of fit of 0.60, but was based on a significant smaller sample size. In this model, pavement temperature was substituted for air temperature. An Index was developed based on the predicted values using a scale between 1 and 100.

Calibration factors were developed for twenty different homogeneous groupings across Canada using the Bayesian method. Based on the calibration twelve of the twenty groups achieved a better goodness of fit compared to the national model results. The model results show a better performance in heavily populated areas and in eastern Canada. Limitations of the models and recommendations for further research are presented in the report.

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- Storm
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EXECUTIVE SUMMARY

This report discusses the development of the TAC Winter Severity Index. A winter severity index is a measure of the relative impact of winter weather on winter road maintenance (WRM) operations using historical meteorological or road weather information system (RWIS) data. It can be used to evaluate the relative harshness of a winter in comparison with a base period.

A set of models were developed using Canadian WRM, Meteorological Service of Canada (MSC) and RWIS data. WRM data were collected from across Canada from eight provincial road authorities and seven cities. Salt usage in tonnes (salt (t)/lane-km/day) was chosen as the dependent variable, standardized to account for differences in road network and the number of days in the observation period.

The first model developed based on MSC data alone achieved a goodness of fit of 0.54. Explanatory variables were based on snowfall occurrence, air temperature, freezing rain occurrence, and an east-west dummy variable to account for differences in winter road maintenance practices in different parts of Canada. A second model was developed based on MSC data together with RWIS data. This achieved a goodness of fit of 0.60, but was based on a significant smaller sample size. In this model, pavement temperature was substituted for air temperature. An Index was developed based on the predicted values using a scale between 1 and 100.

Calibration factors were developed for twenty different homogeneous groupings across Canada using the Bayesian method. Based on the calibration, twelve of the twenty groups achieved a better goodness of fit compared to the national model results. The model results show a better performance in heavily populated areas and in eastern Canada. Limitations of the models and recommendations for further research are presented in the report.

SOMMAIRE

Le présent rapport traite de l'élaboration de l'indice de mesure de la rigueur des hivers. Mis au point par l'ATC, l'indice de mesure de la rigueur des hivers se veut une évaluation des incidences relatives des conditions météorologiques hivernales sur l'entretien des routes. Cette stratégie repose sur l'utilisation de données météorologiques historiques ou de données réunies par le biais du système d'informations météo-routières (SMER). Les données accessibles dans ce contexte peuvent être utilisées pour évaluer la rigueur relative d'un hiver par rapport à une période de base.

Un certain nombre de modèles ont été élaborés en regard des pratiques hivernales d'entretien des routes au Canada, du Service météorologique du Canada et du SMER. Les données sur l'entretien hivernal des routes ont été recueillies à l'échelle du Canada, par huit administrations routières provinciales et sept villes. L'application de sel en terme de tonnes (sel (t)/kilomètre de voie par jour) a été retenue comme variable dépendante, laquelle a été normalisée aux fins de tenir compte des différences des réseaux routiers et du nombre de jours de la période d'observation.

Le premier modèle élaboré à la lumière des données du Service météorologique du Canada a permis d'en arriver à un ratio d'acceptabilité de 0,54. Les variables explicatives étaient fondées sur l'occurrence de chutes de neige, la température de l'air, l'occurrence de pluie verglaçante et une variable nominale est/ouest afin de tenir compte des différences des pratiques d'entretien hivernal des routes dans les différentes parties du Canada. Un deuxième modèle a été élaboré d'après les données du Service météorologique du Canada ainsi que les données provenant des SMER. Cette opération a permis d'en arriver à un ratio d'acceptabilité de 0,60, lequel a par ailleurs été établi à partir d'un échantillon de données beaucoup plus restreint. Dans ce modèle, la température de la chaussée a été substituée à la température de l'air. Un indice a été mis au point d'après les valeurs prévisibles, en appliquant une échelle de 1 à 100.

Des facteurs d'étalonnage ont été mis au point pour vingt groupes homogènes différents de partout au Canada, le tout en appliquant la méthode Bayesienne. Compte tenu de cette méthode d'étalonnage, il est apparu que 12 des 20 groupes avaient permis d'obtenir un meilleur ratio d'acceptabilité comparativement aux résultats des modèles d'envergure nationale. Les résultats des modèles en question ont démontré un rendement supérieur dans les régions à forte densité de population et dans l'Est du Canada. Le rapport sur le sujet rend compte des limites des modèles et propose des recommandations de futures recherches.

1 – INTRODUCTION

1.1 BACKGROUND

The Transportation Association of Canada through the Maintenance and Construction Standing Committee retained a consultant team led by Synectics Transportation Consultants to develop two winter severity indicator models that can be used by Canadian jurisdictions to evaluate the relative harshness of a winter in comparison with a base year, by using readily available meteorological data as well as road weather information systems (RWIS) data. ***A winter severity index is a measure of the relative impact of winter weather on winter road maintenance (WRM) operations using historical meteorological or RWIS data. It is a measure that simplifies one or more complex variables, or sets of information, for a particular application.***

1.2 THE NEED FOR WINTER SEVERITY INDICATORS

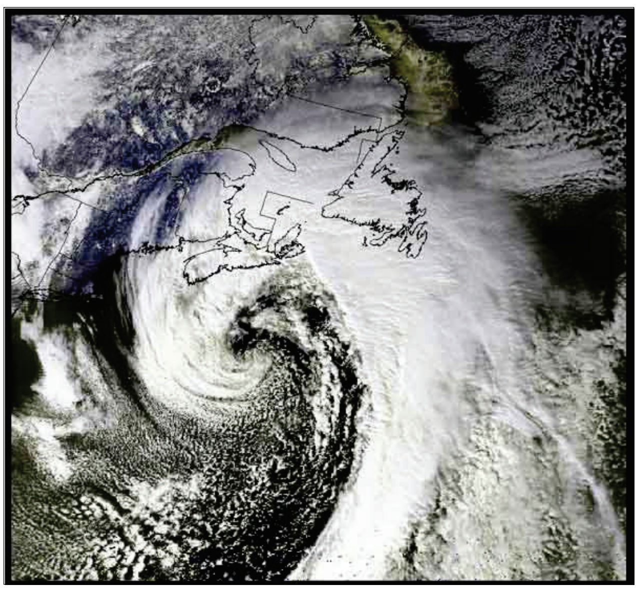

Photo Credit: Environment Canada

Winter weather has a significant impact on the safety and mobility of road transportation. Snowfall, freezing rain, strong winds and blowing snow, falling temperatures, and other elements of winter storms reduce road surface friction and impair driver visibility. Research has demonstrated that snowfall, freezing rain, and other elements of winter storms (flash freezes, blowing snow) are associated with increased numbers of property damage and injury collisions relative to dry, seasonal conditions (Andrey et al. 2001a, 2003).

In extreme cases, severe winter storms have forced the temporary closure of businesses and government services (e.g., January 1999 storms in Greater Toronto, Mills et al., 2003). Weather is thought to contribute to about one-quarter of all road delays in the U.S. (Pisano and Goodwin, n.d.)—and snow, ice, and fog were estimated to have caused 544 million vehicle-hours of delay on U.S. highways in 1999 (OFCM 2002).

While a range of responses is available to public transport agencies to mitigate these risks, including warning messages and enhanced driver training, the primary response is the prevention and clearing of snow and ice from highways through WRM (winter road maintenance). WRM programs have been established and are continuously being refined by virtually every provincial and municipal road authority in Canada. Collectively, it is estimated that about $1.3 billion and over 4.5 million tonnes of road salt are expended by these agencies each year (Jones 2003, Morin and Perchanok 2003). In addition to the considerable direct costs of WRM activities, road salts may cause damage to the environment and infrastructure.

WRM costs and the use of salt vary, both temporally and spatially. This is due to the emergence of new technologies (e.g., anti-icing, zero-velocity salt spreaders, GPS and communications improvements, plow design, fuel efficiency improvements, etc.), regional variations in maintenance practices, and growth or contraction of road networks. However, the most significant reported influence is variability in weather.

Photo Credit: Synectics

It is precisely this uncontrollable variability associated with weather that predicates the need for, and the utility of, winter severity indices. Weather variability complicates assessments of the relative efficiency and effectiveness (i.e., meeting Levels of Service standards, salt reduction and budget targets) of different road maintenance programs, technologies, policies and jurisdictions. It also must be accounted for in the performance and justification of cost-sharing adjustments with private contractors. What proportion of reported savings during a given season were due to a mild, relatively snow-free winter, compared to a portion attributable to new operational measures or a reduced road network? Were a contractor's operations inefficient or were they justifiable given the severity of a particular winter? Among other things, an index can help answer such questions by standardizing the costs, other indicators, or maintenance, in terms of winter severity.

1.3 OVERVIEW OF PROJECT

Figure 1.1 illustrates the conceptual framework for this project. The study team:

- Identified past research through a literature review, identifying relevant variables, the model's predictive ability, the model's applicability to Canada and the temporal/spatial scale of the required variables;
- Reviewed the RWIS, Environment Canada climatic data, road network and volume data, and winter road maintenance activity data, to determine its availability across Canada;
- Identified which variables should be used to develop the model(s) for the winter severity indicators;
- Selected geographic areas across Canada, considering data availability/reliability, consideration of climatic conditions, predominant winter storm types, and maintenance standards and practices.
- Inputted all identified data required to model winter road maintenance activity and for the identified geographic areas across Canada;
- Evaluated the variables in terms of their ability to predict winter road maintenance activity using multivariate regression analysis – choosing the set of variables with the best predictive ability;
- Developed a Winter Severity Index that will be directly correlated to winter road maintenance expenditures; and
- Calibrated the dependent variable in order to improve the model's predictive ability within each geographic area.

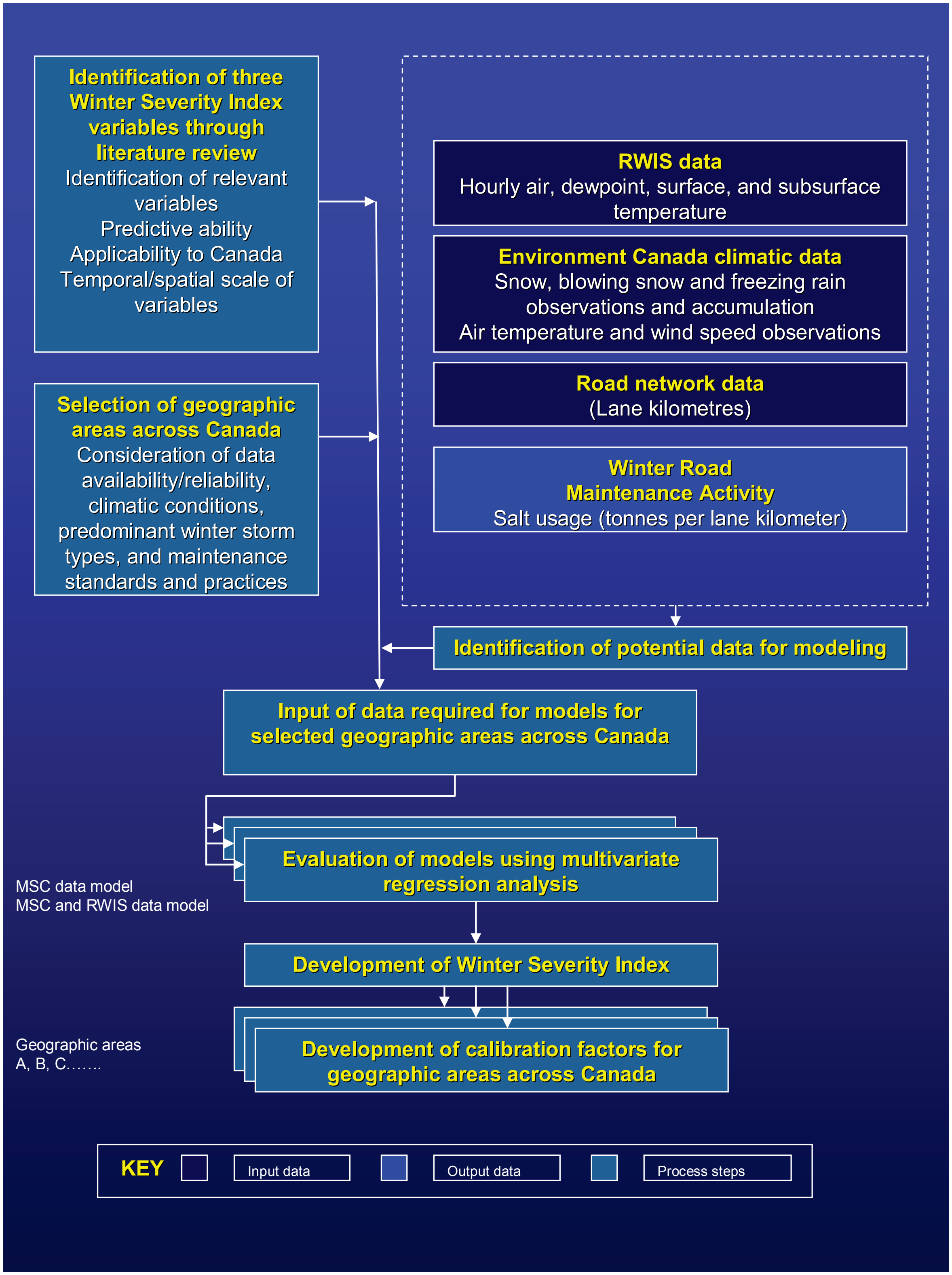

Figure 1.1 – Conceptual Framework for Project

1.4 OUTLINE OF REPORT

This report is divided into seven sections, as follows:

- **Section 1** provides background information on the project;
- **Section 2** summarizes the findings of the literature review;
- **Section 3** summarizes the availability of the winter road maintenance (WRM), road weather information system (RWIS) and meteorological data reviewed by the consultant team;
- **Section 4** summarizes the variables selected for modeling;
- **Section 5** summarizes the work done to develop the model;
- **Section 6** summarizes the local calibration of the model to individual geographic areas; and
- **Section 7** discusses the data sets required to calculate the index.

2 – PAST WORK

Work on the development of winter severity indices has been ongoing for the past twenty-five years in Canada, United States and northern European countries (United Kingdom, Finland, France, Norway, Sweden and Denmark). The key winter severity indices described in the literature, are listed in Table 2.1.

Table 2.1 - Winter Severity Indices Reviewed

Winter Severity Index	Reference
Cost 309 Index	Gustavsson (1996) Kirk (1996) Knudsen (1994)
Finnish Meteorological Institute Index	Venäläinen (2001) Venäläinen and Kangas (2003)
Hulme Index (Modified)	Andrey et al (2001) Cornford and Thornes (1996) Gustavsson (1996)
Indiana DOT Winter Severity Index	McCullouch et al (2004)
Iowa DOT Winter Severity Index	Carmichael et al (2004)
GAB Index	Gustavsson (1996)
MOORI Index	Johns (1996)
NORIKS Index	Mahle et al (2002)
PennDOT Winter Severity Index	Rissel and Scott (1985)
Salt Day Index	Andrey et al (2001)
Strategic Highway Research Program (SHRP) Index - (Modified)	Andrey et al (2001) Boselley et al (1993) Decker et al (2001)
Wisconsin Winter Severity Index	Adams (2001)

This section provides a synthesis of the available literature. A complete list of references is provided at the end of this report.

2.1 RATIONALE FOR STUDIES

The rationale for development and/or refinement of winter severity indices was to determine what meteorological or RWIS factors best predicted the relative severity of a winter as defined by WRM activity, whether based on expenditures, labour, and/or materials (primarily salt usage).

Most of the related research has been motivated by practical concerns and has been initiated or conducted by road authorities. For example, Rissel and Scott (1985) developed their index to learn whether winter maintenance manpower was being used effectively in different districts in the state of Pennsylvania. Decker et al (2001) wanted to develop an objective measure of winter maintenance efficiency based on labour, equipment, and material costs used in WRM, considering storm severity and duration for an established number of lane kilometers at a given service level. Mahle and Rogstad (2002) developed the NORIKS index to make it possible to adjust payments to contractors on the basis of the work that has actually been carried out (as predicted by the index). Carmichael et al (2004) wished to develop a winter severity index that would be used by IADOT staff to judge how well all maintenance personnel performed statewide during each winter season. Their index estimates expected costs and labour requirements for road treatments.

Other initiatives led by academic researchers provide comparative analyses of different approaches. Andrey et al 2001 compared the performance of three different indices (the SHRP index, Hulme index, and Salt Days) to determine which best explained salt usage and developed a modification to the SHRP Index based on Ontario climatic data. Thornes (1993) discussed how the Hulme, SHRP, and Cost 309 index could be used to evaluate the cost-effectiveness of RWIS sensors. Gustavsson (1996) compared the Hulme, COST 309 and GAB indices' ability to predict WRM activity as applied to a single RWIS sensor.

Photo Credit: MFP Associates

One theme that cut across many of the papers was the inadequacy of existing indices. Many researchers that attempted to use an existing index discovered that the variables used were not relevant to the climate in their area, were poorly correlated with WRM activity, required a shorter temporal period or a smaller spatial area to accurately capture WRM activity, or could not be calculated due to data limitations (e.g. Andrey et al 2001, Carmichael et al 2004, Johns 1996, and Adams 2001).

A second commonality among several papers was that researchers were able to reduce the number of variables used to adequately explain WRM activity and still have reasonable fit. Andrey et al. 2001 found that two variables explained as much of the variation in monthly salt use as the more complex SHRP model. Venäläinen (2001) used air temperature (monthly mean temperature) alone to explain salt use in Norway.

2.2 METHODOLOGY USED

Three broad approaches were identified. The first and most simplistic approach taken was the development of an index inclusive of a number of subjectively determined factors that were thought to influence WRM activity. The researchers then simply graphed the winter severity index against a WRM variable to determine if the two lines corresponded. If the lines did not correspond well, terms were added, subtracted, or a weighting factor was used to refine the model, until some acceptable degree of fit was achieved (McCullouch et al 2004).

The second approach involved the use of regression analysis to model the relationship between various meteorological or RWIS variables and WRM activity (e.g. Andrey et al 2001 and Johns 1996). Most often (particularly in earlier studies) linear regression was used. However, more sophisticated multiple regression modeling and different types of curve fitting procedures have been utilized in recent studies. Typically, researchers using regression modeling reported the correlation coefficient (r) or coefficient of determination (r2), the latter of which states the proportion of the total variability in WRM activity that is explained by meteorological and/or RWIS variables. Models were often rerun with weighted variable factors to achieve higher degrees of correlation.

The third and most sophisticated approach involved the use of artificial neural networks (ANN), which are computers whose architecture is modeled after the brain. They typically consist of many hundreds of simple processing units which are wired together in a complex communication network (http://www.pacontrol.com/Neural.html). Essentially, neural networks search for patterns inductively rather than beginning with a set of predefined hypotheses. However, as noted by Carmichael et al 2004, artificial neural networks are not necessarily superior to statistical approaches.

2.3 MODEL FORM

In most of the models, the explanatory terms are additive, i.e., a number of weather terms need to be added together to calculate the winter severity index (Rissel and Scott 1985, and Adams undated). This is true, even for the more complicated SHRP index (Boselly et al. 1993). This is consistent with the regression approach.

Several points were noted. Often the model form is not substantiated in any meaningful way (by means of an evaluation of the data distribution). Brief explanations were provided as to why exponential and multiplicative weights were included in the development of the model.

For some studies, authors directly use weather variables to explain some facet of WRM activities, e.g., tonnes of salt used or dollars spent. However, they stop short of developing a winter weather index per se. When an index is created, the researchers normalize the winter severity to a point scale. Adams (2001) used a 30 point scale. The SHRP Index uses a sliding point scale from -50 (most severe) to +50 (most mild). Then the index values are correlated with WRM activities.

2.4 Variables Considered

Four broad groups of variables are considered in the development of winter severity indices. Meteorological and RWIS data are the independent variables and WRM variables are the dependent variables. Road system information may be used as either an independent variable or to normalize the WRM data.

Many studies explain that the researchers had to carry out an extensive amount of data manipulation to extract the variables they required to develop their models. Rissel and Scott (1985) mention the design of several different computer modules specifically developed to refine the weather and WRM data collected from the various weather stations and districts. Recent investments in improved information management systems in many road authorities have made data extraction and manipulation much more straightforward – unless the data is in hard copy only. The digital and on-line nature of data from Environment Canada could be useful to this project.

Many of the researchers developing their own models spent a considerable amount of time speaking with local stakeholders directly involved in WRM, to determine which meteorological or RWIS variables were most likely to explain WRM activity variation (e.g Rissel and Scott 1985). In some cases, special committees were formed to guide variable selection and index development (Adams undated) while in other cases researchers worked alongside winter maintenance staff (Mahle and Rogstad 1996) or simply sought the opinions of field operations staff to identify variables that would affect WRM activity (Indiana, McCullough et al 2004).

2.4.1 Meteorological Variables Used

The two main groups of meteorological variables considered were precipitation and temperature.

Two aspects of precipitation were included in several models: snowfall and freezing rain. These forms of precipitation were expressed in various ways – from a simple yes-no (yes when this form of precipitation was observed during a specified period, no otherwise) to frequency of occurrence, frequency of occurrence of a threshold amount, amount, intensity, or duration.

Temperature variables from previous models include minimum, maximum, and mean air temperatures. These were measured over a wide variety of time periods ranging from daily values up to monthly values. Temperature range was also mentioned; it was used as a proxy for freeze/thaw cycles. Temperature variables were often considered to be proxies for frost and ice formation on roadways. Dewpoint temperature in relation to ambient temperature was used by some for frost hazard evaluation. Venäläinen (2001) used a single variable (temperature) to explain salt usage in Finland.

Drifting snow was also identified as an important variable by Mahle and Rogstad (2002) and by McCullough et al. 2004. This was collected by proxy, such as instances where snow had fallen, air temperature was below zero and wind speed exceeded a certain threshold.

2.4.2 RWIS Variables Used

Few of the studies used RWIS variables and most that did were conducted in Europe. Knudsen (1994) used RWIS variables, primarily temperature but also snowfall of a specific amount and snow drifting, in the COST 309 index. Mahle and Rogstad (2002) used air temperature, precipitation and a combination of precipitation, temperature and wind speed as a proxy for drifting snow. Gustavasson (1996) evaluated the applicability of using the Hulme, COST 309, and GAB index to predict winter maintenance activity based on RWIS sensor data.

Mahle and Rogstad (2002) identified some problems with using strictly RWIS sensor-based data in a winter severity index. Several different types of RWIS sensors have been employed in Norway which limits comparability of the data. As well, the RWIS stations are often sited in problem areas for icing (i.e., bridges or hollow/low lying areas) and may not be representative of the entire network. Together with the absence of road pavement condition information, such factors may explain the weaker performance of their model.

2.4.3 Other Independent Variables Considered

Adams (2001) used WRM incidents (i.e. drifting, clean up, and frost runs) as an additional independent variable in the Wisconsin Severity Index. Cornford and Thornes (1996) also used elevation data to refine their estimates of temperature in their winter severity index model.

2.4.4 WRM Variables Used

Many of the researchers used cost variables (i.e. total WRM expenditures) as the dependent WRM variable. In some cases WRM costs were estimated. For instance, Carmichael et al (2004) used biweekly hours, labour, equipment, and materials to estimate WRM expenditures. However, they did not specify how each type of cost was derived. Knudsen (1994) found that cost variables had the poorest correlation to the COST 309 Index in Denmark (compared to WRM activity and salt usage) and cited different contractual arrangements as being a contributing factor.

Some of the researchers (Rissel and Scott 1985 and Adams 2001) raised concerns over the accuracy of the data, particularly the WRM variables. Problems cited were:

- Missing data; and
- Inconsistencies in the way in which events were defined.

One concern with modeling WRM costs is that some of the expenditures are likely fixed every season and not related to the severity of a particular winter. Only a portion of WRM costs are likely weather-sensitive. Labour (e.g. plowing and spreading hours) and material variables (e.g salt usage), would be less likely to be affected by extraneous factors such as contractual arrangements, variable pricing, inflation rates, etc. Several researchers used WRM labour or materials variables, such as Knudsen (1994), Andrey et al (2001) and Venäläinen (2001).

Almost all of the researchers stressed the need to normalize the WRM variables. Whether collected at a provincial/state, district/regional or plow route/garage/beat level, all WRM data needs to be normalized to reflect differences in the length and extent of treatable roads at the very least. Some researchers also considered the Level of Service, the number of lane kilometres, traffic flow or population density as a further refinement (i.e., Boselly et al 1993 and Cornford and Thornes 1996). Research that accounted for this tended to have a better model performance (i.e. a higher degree of correlation).

2.5 ADEQUACY OF FIT

The correlation between winter severity indices and WRM variables varied considerably. In many cases, less than half of the total variability in WRM was explained by weather. Other times, the fit was considerably better (e.g. some of the models in Andrey et al 2001, Venäläinen 2001 and Mahle and Rogstad 2002).

While operations staff were often consulted in the identification of important variables, no mention was made in any of the literature as to whether or not the researchers questioned the operations staff on the level of confidence they wished to see in the model or what was required to support various types of decisions and applications. None of the papers indicate a level of confidence associated with the findings.

In terms of patterns, it is important to note that model performance was affected by the unit of analysis. In some cases, the focus was on a single region and thus the analysis was based on temporal variations only. In these cases, the model was calibrated to local conditions, and this typically resulted in higher correlations between weather and WRM activity (e.g. Figure 6 in Thornes 1993; last set of analyses in Andrey et al 2001). In other cases, the focus was on spatial variations only (e.g. Figure 8 in Thornes 1993), and correlations tended to be high—possibly because the analysis was based on seasonal data or multi-year averages. However, in most cases, including the current project, the focus is on explaining temporal-spatial differences so that the model can be used flexibly to compare WRM activity patterns over time and/or space. The significant challenge of this task is reflected in the modest correlations achieved in previous studies. However, as elaborated below, some of the variation in fit can be explained by differences in the spatial and temporal scale of variables.

2.6 SPATIAL SCALE OF VARIABLES

The spatial scale of the variables used to develop the various winter severity indicators dictated the functionality of each model. Analyses based on large geographic areas as opposed to smaller areas (districts or individual plow routes) tended to result in higher correlations.

Adams (2001) collected data at the county level in the state of Wisconsin so that inter-county comparisons could be made. Knudsen (1994) had the same intent in his comparison of different counties across Denmark. Carmichael et al (2004) obtained data for each individual state DOT WRM garage in the state of Iowa that allowed them to identify particular regions or even garages that were particularly efficient or perhaps could benefit from additional training (in WRM operations). Those garages that performed well (in terms of actual costs compared to expected costs) could be highlighted and their practices used as a guide for training others.

A particular challenge in determining the spatial scale of the variable is in matching meteorological and RWIS data (representing single fixed points) to WRM data (representing a larger area). The simplest method of matching meteorological and RWIS data to WRM data involves averaging all meteorological and RWIS data available at stations within a geographic area (i.e. a province, region/district) and assigning the same value to all roads therein, such as in Rissel and Scott 1985, Andrey et al 2001, and McCullouch et al 2004. Other studies such as Carmichael et al 2004 were able to access hundreds of meteorological stations to match to the various garages across the state of Iowa.
Cornford and Thornes 1996 used three different approaches to interpolate data from weather stations into adjoining roadways using a modified Hulme index. The approaches were:

- the traditional approach of taking the mean of all stations within a district and assigning the values to the roads in the district;
- the Thiessen weighted regional method – each station was assigned a domain of influence by partitioning space into Thiessen polygons; and
- the variables of interest from the weather stations are mapped onto a 10 km grid using kriging to interpolate the variables.

Of the three methods, the last method (using kriging) provided the best degree of correlation. However, it was data intensive and would require the use of a geographic information system and development of a digital model. Venäläinen (2001) also used kriging to interpolate monthly mean air temperature from various stations in Finland to corresponding roads within a 10 km x 10 km grid.

Another spatial theme developed in several of the papers, is the problem of climatic variation when considering larger geographic areas. Andrey et al 2001 found that their modeling of salt usage performed less adequately in northern portions of the province of Ontario, likely due to colder temperature experienced there and the associated impact on the effectiveness and thus use of salt in WRM. This led to a lower overall correlation coefficient in their overall provincial model.

2.7 TEMPORAL SCALE OF VARIABLES

WRM data is generally only available at coarser scales than meteorological or RWIS data. Most of the researchers used months as their temporal unit, but in most instances had aggregated the meteorological or RWIS data from daily values (i.e. Boselly et al 1993 and Andrey et al 2001). Due to the dominance of this temporal scale, there is insufficient basis to comment in detail on the effect of temporal scale on model performance.

A few researchers used shorter temporal units. Carmichael et al (2004) examined biweekly WRM data matched to daily climatological variables. Decker et al (2001) used the SHRP index variables on a daily basis to assess the level of efficiency among three different service areas in Utah. Knudsen (1996) also used daily occurrences of weather and RWIS variables. Gustavasson (1996) examined hourly temperature and precipitation readings at a single RWIS stations and evaluated their ability to predict WRM events.

2.8 POTENTIAL APPLICABILITY OF RESEARCH TO CANADA

Photo Credit: JLM Studios

The literature review represented the first step in the Development of Winter Severity Indicator Models for Canadian Winter Road Maintenance. Based on the review of the various winter severity indices and their potential applicability to Canada, the following key points summarize potential challenges:

- Some past models appear to have poor transferability;
- Some past models failed to adequately control for non-weather related WRM costs;
- Some past models lack information on how they were developed or are to be applied;
- Some of the models require an extensive amount of data extraction and manipulation.

Despite these challenges, the following key points summarize potential opportunities:

- There were high quality digital dataset available for use; and
- There are lessons that can be learned from the results of the past research.

3 – DATA AVAILABILITY

The second task in this project was to determine data accessibility across Canada. To ensure that the Winter Severity Index would be straightforward to calculate for a typical Canadian road authority, the commonly available types of WRM and RWIS were identified. For this project, four different types of data are required to model the relationship between winter weather conditions and winter road maintenance activity. They are:

- Meteorological observations;
- RWIS observations;
- WRM activity records; and
- Road network data (for normalization of WRM activity).

Meteorological observations of weather were available through Environment Canada. The remaining three types of data were available through various transportation authorities.

3.1 DATA COLLECTION

A wide range of datasets were sought to represent different climates, storm types, and winter road maintenance practices across Canada in a variety of settings.

3.1.1 Availability of Environment Canada Data

Environment Canada data represented the primary group of input variables that will be required to model WRM activity in each jurisdiction across Canada. The chief source of information used came from the National Climate Data and Information Archive, which is operated and maintained by Environment Canada and consist of official climate and weather observations for Canada. Environment Canada data are available online. A complete list of Environment Canada variables and associated data that were considered in the analysis is provided in Table 3.1. Due to their relative abundance, stations collecting daily data (with monthly summaries) were the primary source of information.

Table 3.1 – List of Weather Variables from Environment Canada (MSC)

Variable	MSC code	Unit
Hourly Weather Observations		
Visibility	072	0.1 km
Sea Level Pressure	073	0.1 kilopascals
Dew Point Temperature	074	0.1 deg C
Wind Direction	075	10's of deg
Wind Speed	076	km/hr
Dry Bulb Temperature	078	0.1 deg C
Wet Bulb Temperature	079	0.1 deg C
Relative Humidity	080	%
Rain (R), Rain Showers (RW), Drizzle (L), Freezing Rain (ZR), Freezing Drizzle (ZL), Snow (S), Snow Grains (SG), Ice Crystals (IC), Ice Pellets (IP), Ice Pellet Showers (IPW), Snow Showers (SW), Snow Pellets (SP)	086-097	1-3 (intensity)
Fog (F), Ice Fog (IF)	099-100	1
Blowing Snow (BS)	103	1
Daily Climatological Variables		
Daily Maximum, Minimum, and Mean Temperature	001-003	0.1 deg C
6 hrly. Precipitation ending 1200, 1800, 0000 and 0600 GMT	006-009	0.1mm
Total Rainfall	010	0.1mm
Total Snowfall	011	0.1cm
Total Precipitation	012	0.1mm
Snow on the Ground	013	whole cm

3.1.2 Availability of RWIS Data

RWIS data was identified as being a secondary group of input variables to be used in one of the winter severity index models. To that end, only RWIS data that geographically matched locations of WRM data was employed.

Canada currently has approximately two hundred RWIS sites across the country, with many new sites proposed to expand the network into every province. RWIS sites provide valuable data on the timing of key events, such as the reaching of critical temperature thresholds and the onset of precipitation, subsequently affecting road conditions in turn impacting winter maintenance activities. Detailed information on instrumentation, site characteristics, and quality assurance/quality control of the data was examined to interpret the results (e.g. a change in sensor location, pavement rehabilitation/maintenance will affect the data, how data is aggregated to longer temporal intervals, etc.).

Most of the jurisdictions indicated that they owned, maintained or had access to RWIS data. However, many of the jurisdictions had difficulty obtaining or extracting the information.

3.1.3 Availability of WRM Data

Eighteen potential participants provided WRM activity data. The majority of the data provided was in a digital format. The following commonalities and differences were identified:

- Sand usage data was provided by more than half of the jurisdictions - expressed in either tonnes, hours, or as a cost;
- Salt usage data was provided by all participants that provided data – expressed in either tonnes, kilograms, litres, hours, or as a cost;
- Combined salt and sand usage data was provided by two jurisdictions; and
- A few jurisdictions provided data pertaining to equipment, labour, and plowing activity;
- All of the jurisdictions were able to provide their data at the district or city level;
- Only seven jurisdictions were able to provide their data at the daily level, with the remaining providing the data at coarser levels of aggregation (weekly, biweekly, monthly, yearly or seasonal); and
- All participating jurisdictions were able to provide data spanning at least two years.

The WRM data was normalized using the number of lane kilometres in each jurisdiction's road network.

Other information included:

- Maps showing the location of plow routes and individual districts;
- Level of Service standards; and
- Supplementary materials/past client research.

3.2 DATASET SELECTION

The following was reviewed:

- Geographic representativeness;
- Level of spatial and temporal aggregation;
- Ease of data extraction and manipulation;
- Robustness of data;
- Accuracy of data;
- Availability of corresponding RWIS data;
- Availability of road network data.

3.2.1 Geographic Representativeness

A primary consideration was to have datasets that represented varying climatic regions across Canada, varying synoptic weather influences, and different winter road maintenance practices. Ideally, the desired dataset would be from a road authority representing the following Canadian climate regions delineated in Figure 3.1 (being areas with significant winter road maintenance activity):

- Atlantic Canada;
- Great Lakes/St. Lawrence;
- Northeastern Forest;
- Northwestern Forest;
- Prairies;
- Southern British Columbia Mountains; and
- Pacific Coast.

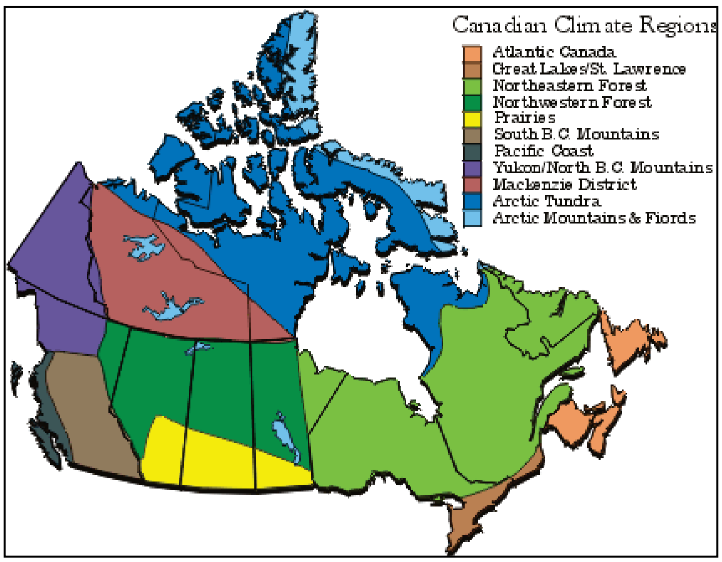

Photo Credit: Environment Canada

Figure 3.1 – Canadian Climate Regions

A secondary consideration was to have a dataset that represented both a rural highway road network as well as an urban road network for each of the above areas, if possible.

3.2.2 Level of Spatial and Temporal Aggregation

Another important consideration in evaluating the datasets was the level of spatial and temporal aggregation available to the consultant team with respect to the WRM data.

In terms of spatial aggregation, the preferred data would be available at a district (with respect to provincial road authorities) or citywide level (with respect to urban road authorities) in terms of spatial aggregation. This would allow the data to be matched to individual weather stations or RWIS stations.

In terms of temporal aggregation, the initial request was for data available at a daily level. This would provide the flexibility of aggregating up to a monthly level. However, some jurisdictions only have data available at the biweekly levels. Therefore winter road maintenance datasets that would be disaggregated to a district/city-wide-biweekly-monthly level were used. This excluded one dataset (Region of York) which only had data available at the seasonal level.

3.2.3 Ease of Data Extraction and Manipulation

For some of the road authorities, the data was stored in a digital format that lent itself to being easily extracted. In other instances, the data was stored on a system that prevented the data from being extracted in a straightforward manner – or data was not collected in a consistent manner within the jurisdiction, meaning that only a subset of the data could be used. This incompatibility among different reporting systems made data extraction difficult.

For this project, salt usage was identified as being a primary dependent variable for use in the development of the Winter Severity Index, stipulating that the data be straightforward to extract and expressed in a standard reporting unit.

3.2.4 Robustness of Data

In order to develop a model that is robust, data was needed that represented a wide variety of storm types. This can be accomplished in two different ways. Data representative of a single geographic area spanning a multi-year period or data representative of a number of individual districts within a single provincial road authority over a single year may be utilized (in the case of a larger province). Either condition (multiple years of data or multiple districts for a single year) will allow the effect of different storm types to be observed within the model and will potentially increase the ability to detect associations between different weather and RWIS variables, and WRM activity. It was noted that some of the datasets were only available for a single winter season – or for a single homogenous area. These will be of limited value for modeling.

3.2.5 Quality of Data

The outcome of the model depends on the accuracy of the data collected. In order to understand the equality of the data, a road authority may be of assistance in order to identify potential sources of error in the way the data is collected and reported, or in the way the data may be interpreted. Examples of anomalies identified were:

- Differences in the way data is collected and stored:
  - Among different pieces of equipment;
  - Among different locations within the road authority; and
  - From year to year.
- Varying definitions of 'day' in records of WRM (i.e. shift-based and not necessarily midnight to midnight); and
- Terms unique to each road authority.

3.2.6 Availability of Corresponding RWIS Data

Road authorities provided RWIS data that was geographically matched to the WRM data. In order to interpret the results, detailed information on instrumentation, site characteristics, and quality assurance/quality control of the data was needed (e.g., a change in sensor location, pavement rehabilitation/maintenance will affect the data, how data is aggregated to longer temporal intervals, etc.).

3.2.7 Availability of Road Network Information

The final evaluation criterion was the availability of road network information. Road network information (i.e. lane kilometres) will be required for normalization of the data. Other essential information relating to the road network was:

- Significant changes to the road network over time (in terms of Level of Service standards or the length of roads maintained); and
- Maps showing how the road network is divided into reporting districts (to allow the project team to determine which RWIS sensor or meteorological station should be assigned to which district).

3.3 SUMMARY

In summary, desirable datasets would:

- be unique in terms of its climatic zone;
- have data available at a district-city-wide/bi-weekly-monthly spatial-temporal aggregation;
- have salt usage data available in a standard reporting unit (i.e. tonnes/kilograms) that would be straightforward to extract/manipulate;
- span multiple years of data and/or multiple districts to capture different weather conditions;
- be consistently reported over time and in different areas within the road authority;
- have accompanying RWIS data (for the MSC-RWIS model only); and
- have information on lane kilometres and the location of the reporting districts (as well as any RWIS sensors).

4 – VARIABLE SELECTION

4.1 THE DEPENDENT VARIABLE

Photo Credit: Nova Scotia DOT

Salt usage was selected as the dependent variable. However, the manner in which salt usage is measured and documented differs in each jurisdiction. This required the input of road authorities in order to ensure that the data were being interpreted correctly. Four issues emerged through this work that had to be addressed for the analysis to proceed:

- Conversion into a common mass or volumetric reporting unit;
- Standardization of reporting periods;
- Standardization by treated network length; and
- Combined reporting of salt and sand.

4.1.1 Conversion into a Common Mass or Volumetric Reporting Unit

The salt usage data needed to be converted into a common reporting unit. The majority of jurisdictions reported salt use in metric tonnes which was therefore chosen as the desired unit. Other jurisdictions report salt usage in kilograms, cubic metres (m^3) or litres (L - when used in a brine). Kilograms were straightforward to convert to tonnes, while the volumetric units required an understanding of the standard density of salt, either as a solid or dissolved in a liquid. This information was requested from those jurisdictions that reported in cubic metres or litres.

4.1.2 Standardization of Reporting Units

The selection of an appropriate analysis period is partly a function of the available data and the type of model being developed. A sufficient number of data points are required to capture both the variability in salt use and in weather variables, in order to find a relationship between the two. Most jurisdictions collected and provided salt usage data for bi-weekly or monthly periods. Others provided daily, weekly or seasonal data. In order to compare, analyze and model the information, all variables had to be standardized by number of days. It was important to know exactly how many days were represented in the salt usage totals so that the amount of salt used per day could be calculated. (e.g., February 2005 has only 28 days compared to March 2005 having 31 days).

Due to the wide variation in temporal scale, bi-weekly or monthly intervals were used as the base temporal unit. Where necessary, salt usage totals were aggregated to bi-weekly and monthly intervals to allow their comparison to other jurisdictions. Seasonal totals were set aside, as mentioned in Section 3.0, because they could not be divided into bi-weekly or monthly intervals.

4.1.3 Standardization by Treated Network Length

In addition to reporting periods, the salt usage data will need to be standardized in terms of the length of the road network that is treated. In several jurisdictions, this variable changes each season as new roads are constructed or responsibilities are reassigned to other jurisdictions (e.g. province to a municipality). Lane kilometres were most often used in past studies and will be the standard in this investigation.

Due to the fact that the information was not available for all jurisdictions, salt usage could not be normalized using the number of lane kilometres that are salted.

4.1.4 Combined Reporting of Salt and Sand

Some of the jurisdictions report salt usage in combination with sand usage. In order to calculate the amount of salt used, the proportion of salt and salt within a sand mixture, needs to be determined. Salt and sand ratios could vary by road class and time of year as well, requiring additional calculations. For the model preparation, all salt usage, whether on its own, or in combination with sand was included. Sand usage is not being considered as a dependent variable.

The results of the above efforts are salt usage data expressed in tonnes, and standardized by day and lane kilometres. The dependent variable to be used in the model is **salt tonnes per lane kilometre per day**, hereafter referred to as salt (t)/lane-km/day.

4.2 POSSIBLE INDEPENDENT VARIABLES

For the modeling of the relationship between winter severity and winter road maintenance operations, a number of independent variables that would explain the variability in salt (t)/lane-km/day, were taken into account.

Based on the findings of the literature review, the review of data available among the jurisdictions contacted, the following variable groupings were identified:

- Precipitation variables;
- Temperature variables;
- Drifting variables;
- Winter road maintenance practice variables; and
- Roadway characteristics variables.

The relative importance of each of these groupings of variables is discussed.

4.2.1 Precipitation Variables

Precipitation data is available from Environment Canada at various levels of temporal aggregation (hourly, daily and monthly). Key variables that affect winter maintenance activities include:

- Number of days of snowfall accumulation above a particular threshold;
- Snowfall accumulation; and
- Number of days in which a particular precipitation type were observed.

4.2.2 Temperature Variables

Temperature data is also readily available from Environment Canada at various levels of temperature aggregation (hourly, daily and monthly). Temperature data will also be critical to the model as it will dictate when salt is applied to a road. Based on winter road maintenance practices documentation and discussions with maintenance managers, warm and cold temperatures (+5 C and < - 15 C) will result in only minimal or no application of salt. Types of variables considered were air, dewpoint and pavement surface temperature. Subsurface temperature is also collected by RWIS sensors in some locations, but is likely of limited applicability to this project. Dewpoint and pavement surface temperature are considered important in determining the occurrence of frost.

4.2.3 Drifting Variables

In the absence of snowfall, drifting snow may also affect salt usage. Environment Canada data is available in the form of hourly observations of blowing snow or number of days in which blowing snow was observed, but is not uniformly available at all meteorological stations across Canada or at all times. Alternatively, a hybrid variable could be considered using a threshold wind speed, snowfall, snow on the ground, and temperature data provided by either Environment Canada or RWIS sensors.

4.2.4 Winter Road Maintenance Practice Variables

Winter road maintenance practices were considered to be a variable of secondary importance to the model, but worth consideration. There is a wide variation in the way in which salt is applied across Canada. Salt may be applied:

- On its own;
- In conjunction with sand (in varying ratios);
- As a brine; and
- As a pre-wetted mixture.

One variable considered accounted for varying winter road maintenance practices, such as basic salt, pre-wetted salt, salt with sand, and brine. However, this data is not consistently collected by the various jurisdictions.

4.2.5 Roadway Characteristics Variables

The final set of variables considered in the modeling was the roadway characteristics. A basic variable considered in the modeling was whether the jurisdiction in question was primarily rural or urban, given that roads in rural areas are likely treated differently than urban areas, due to differing traffic volumes and traffic control measures.

Another consideration was the road class or priority. Roads having a higher class or priority will receive attention first during winter road maintenance operations, or will require more salt per lane kilometre, depending on the practice in each jurisdiction. Yet each jurisdiction uses its own classification system and associated level of service condition, making it difficult to develop a variable that accounts for individual road classification, yet can be used universally. Development of such a variable was abandoned, as not all jurisdictions had this information available.

4.3 VARIABLE SELECTION CRITERIA

Having identified an initial list of variables that might be considered for the model, a set of criteria was developed so that it may be used in selecting the variables. The following was taken under consideration:

- Past performance in published applications;
- Data availability;
- Expert opinion; and
- Correlation with salt use in individual study jurisdictions.

4.3.1 Performance in Published Applications

The first criterion considered was the use of the variables in past models. A literature review was conducted to determine how often certain types of variables have been used. The following winter severity indices were examined to determine the frequency with which particular meteorological variables were used:

1. Salt Days (Cohen 1981)
2. Hulme Index (Hulme 1982)
3. Venäläinen (2001)
4. Penn State Climate Office Winter Disruptiveness Index
5. Venäläinen and Kangas (2003)
6. Morin and Perchanok (1998)
7. Nixon and Qiu (2005)
8. COST 309 (Thornes 1993)
9. GAB (Gustavsson 1996)
10. MOORI (Johns 1996)
11. Wisconsin (Adams 2001)

12. NORIKS (Mahle and Rogstad 2002)
13. SHRP (Boselly et al. 1993; Decker et al. 2001)
14. Indiana WSI (McCullouch et al. 2004)
15. Carmichael et al. (2004)
16. Andrey et al. (2001)
17. Penn State DOT (Rissel and Scott 1986)

Four of the seventeen studies are italicized as they were not included in the literature review since the reference did not include a formal quantified validation against winter road maintenance data. However, they were developed for this purpose and were either constructed or qualitatively verified based on input from winter maintenance experts.

As shown in Table 4.1, most indices included terms or calculations derived from air temperature, precipitation and frost-specific criteria and/or observations. Therefore, variables appearing most often in previous literature would be considered in the model.

Table 4.1 – Variable Used in Past Research

Variable	Use (absolute)	Use (%)
Air temperature	13	76
Snowfall occurrence (above threshold x)	12	71
Snowfall amount	11	65
Frost	10	59
Freezing rain/drizzle occurrence	10	59
Drifting	5	29
Rainfall occurrence	4	24
Snow cover (snow lying, on-ground, depth)	4	24
Pavement temperature	4	24
Temperature change (rise or fall)	3	18
Dewpoint temperature	2	12
Temperature range	2	12
Precipitation occurrence/amount	2	12
Storm duration	1	6
Visibility	1	6
Air pressure	1	6
Rainfall amount	1	6
Sunshine hours	1	6

4.3.2 Data Availability

The second criterion considered was the availability of the data represented by the variable. Some of the data is unique to a particular jurisdiction and would not be available elsewhere in Canada.

One exception pertaining to availability was the choice of variables based on RWIS data, which was difficult to collect and work with for one or more of the following reasons:

- It is not available in some jurisdictions;
- It is only available for one or two seasons where RWIS sensors have only recently been installed;
- Data management systems not set up to systematically archive historic observations in a format suitable for analysis (significant manipulation and manual extraction required);
- Gaps in the data; and
- Limited choice of variables.

As more RWIS stations come ‘on-line’ across Canada, it is hoped that the model incorporating RWIS variables will become more widely used.

4.3.3 Expert Opinion

The opinions of technical experts involved in the study were considered.

4.3.4 Correlation with Salt Use in Individual Study Jurisdictions

The final criterion considered was the ‘scatterplot performance’. This is a one-variable correlation analysis of the variable in question with the dependent variable (salt (t)/lane-km/day). This required temporally matching potential variables based on MSC and RWIS station data to the salt usage data for each of the district/urban areas.

5 – MODEL DEVELOPMENT

A dataset was prepared containing data from eight provincial road authorities and six urban road authorities, representing:

- The provinces of Newfoundland, Nova Scotia, New Brunswick, Quebec, Ontario, Manitoba, Saskatchewan and Alberta; and
- The cities of Halifax, Ottawa, Toronto, Winnipeg, Calgary, and Edmonton.

5.1 THE DEPENDENT VARIABLE

The dependent variable is salt tonnes per lane kilometre per day (salt (t)/lane-km/day). A total of 1,276 individual periods of observations of the dependent variable were included in the data set. These represented bi-weekly or monthly periods of salt usage. Salt usage data is predominantly from provincial road authorities, representing 1,124 (89 percent) of the observations. The remaining 152 (11 percent) were from an urban road authority. Among the provincial road authorities, Quebec has the largest sample, followed by Nova Scotia. Edmonton and Winnipeg are the largest urban contributors. Tables 5.1 and 5.2 summarize the data collected from the urban and provincial road authorities.

Table 5.3 shows the average salt (t)/lane km/day within each road authority and district. The exhibit shows a distinct split in salt usage between Eastern and Western Canada. Eastern Canada (areas east of the Manitoba-Ontario border) generally uses between 0.01 – 0.10 tonnes of salt per lane km/day on average. Western Canada (areas west of the Manitoba-Ontario border) generally uses significantly less salt on a per lane km per day basis, less than 0.02 tonnes of salt per lane km/day. It should however be noted that some of the areas, particularly the cities of Ottawa, London, and Toronto and Ontario Ministry of Transportation data represent a single winter season. Salt usage may not be reflective of a typical winter season.

Table 5.1 – Number of Periods of Observation Extracted from Urban Road Authority Data Matched with MSC Data

Road Authority	Number	Percentage
City of Calgary	28	**18.4%**
City of Edmonton	41	**27.0%**
City of Halifax	7	**4.6%**
City of London	6	**3.9%**
City of Ottawa	16	**10.5%**
City of Winnipeg	43	**28.3%**
City of Toronto	11	**7.2%**
Grand Total	**152**	**100.0%**

Table 5.2 – Number of Periods of Observation Extracted from Provincial Road Authority Data Matched with MSC Data

Road Authority	Area	Number	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	2.5%
	Southern Alberta - near Calgary	70	6.2%
Subtotal		**98**	**8.7%**
Province of Manitoba	Brandon	20	1.8%
	Carberry	18	1.6%
Subtotal		**38**	**3.4%**
Province of New Brunswick	Fredericton	29	2.6%
	Moncton	29	2.6%
	Saint John	29	2.6%
Subtotal		**87**	**7.7%**
Province of Newfoundland	Avalon	35	3.1%
	Central	35	3.1%
	Eastern	35	3.1%
	Western	35	3.1%
Subtotal		**140**	**12.5%**
Province of Nova Scotia	Central	52	4.6%
	Eastern	61	5.4%
	Northern	53	4.7%
	Western	67	6.0%
Subtotal		**233**	**20.7%**
Province of Ontario	London Area	5	0.4%
	New Liskeard Area	96	8.5%
	Ottawa Area	5	0.4%
Subtotal		**106**	**9.4%**
Province of Quebec	Chicoutimi	56	5.0%
	Gaspe	65	5.8%
	Hull	41	3.6%
	Montreal	52	4.6%
	Quebec	61	5.4%
	Rouyn-Noranda	42	3.7%
	Sept Iles	29	2.6%
	Sherbrooke	40	3.6%
Subtotal		**386**	**34.3%**
Province of Saskatchewan	Findlater	18	1.6%
	Regina	18	1.6%
Subtotal		**36**	**3.2%**
Grand Total		**1124**	**100.0%**

Table 5.3 – Average Salt (t)/lane km/day (the dependent variable)

Road Authority	Area	Average Salt (t)/lane km/day
Province of Alberta	Northern Alberta - Hangingstone	0.0182
	Southern Alberta - near Calgary	0.0045
Province of Manitoba	Brandon	0.0067
	Carberry	0.0033
Province of New Brunswick	Fredericton	0.0257
	Moncton	0.0354
	Saint John	0.0378
Province of Newfoundland	Avalon	0.0548
	Central	0.0420
	Eastern	0.0615
	Western	0.0674
Province of Nova Scotia	Central	0.0705
	Eastern	0.0797
	Northern	0.0850
	Western	0.0651
Province of Ontario	London Area	0.1046
	New Liskeard Area	0.0598
	Ottawa Area	0.1251
Province of Quebec	Chicoutimi	0.0642
	Gaspe	0.0463
	Hull	0.0301
	Montreal	0.0877
	Quebec	0.0471
	Rouyn-Noranda	0.0048
	Sept Iles	0.0344
	Sherbrooke	0.0671
Province of Saskatchewan	Findlater	0.0135
	Regina	0.0100
City of Calgary		0.0129
City of Edmonton		0.0177
City of Halifax		0.0518
City of London		0.0318
City of Ottawa		0.1242
City of Winnipeg		0.0087
City of Toronto		0.0601
Average (All)		0.0473

5.2 EXTRACTION OF INDEPENDENT VARIABLES

The two primary groups of independent variables required for the modeling are meteorological variables extracted/derived from MSC data and RWIS variables extracted/derived from the various road authorities. Each of these are discussed in the following section.

5.2.1 MSC Data Extraction/preparation

MSC data were relatively straightforward to extract. The following variables were extracted/derived:

- Air temperature in Celsius (averaged over the entire period);
- Absolute difference between air temperature (averaged over the entire period) and a selected temperature between -12 Celsius and 0 Celsius;
- Temperature range (between daily minimum and maximum air temperature) in Celsius;
- Average daily snow accumulation in cm (snow accumulation);
- Average daily snow accumulation in cm including trace snow (snow accumulation with trace);
- Average daily occurrence of snow per period (snow occurrence);
- Average daily occurrence of freezing rain/drizzle per period (freezing rain occurrence);
- Average daily rainfall accumulation in cm (rain accumulation);
- Average daily occurrence of rainfall per period (rain occurrence);
- Average daily occurrence of blowing snow per period (blowing snow occurrence); and
- Average daily occurrence of snowfall (above 1 cm) per period (threshold snow occurrence).

Photo Credit: MFP Associates

Although values were complete for all periods in all areas, the reporting of blowing snow per period was somewhat lower than the other variables. Therefore, it was of limited use for the modeling. Appendix A shows the completeness of the MSC data.

5.2.2 RWIS Data Extraction/preparation

RWIS data sets corresponding to different locations across Canada were made available. Typically, RWIS data sets report observations every 10 – 20 minutes; therefore the filtering reduces the size of the data sets substantially.

Generally speaking, the RWIS data was only available for a limited time period and for a limited number of variables. The only variable available for all RWIS datasets is pavement temperature, which is also known as surface temperature.

RWIS data were not recorded in a standard format, and quality varied from location to locatiton. Two of the data sets initially considered were discarded due to quality issues. In other instances, the data set was kept, but certain time periods were discarded due to quality issues.

In order to identify which data sets and time periods within the data sets could be kept, the following steps can be undertaken:

- Examining gaps in the temporal coverage – any gap greater than 12 hours was discarded;
- Identifying erroneous values (either a value repeated over a successive number of observations, or a default value); and
- Comparing the pavement temperature value to the corresponding air temperature value.

Appendix B shows the completeness of the RWIS data.

Once the above screening was accomplished, there was a total of 169 potential periods with usable RWIS data that could be matched to the corresponding dependent variable. This represented 13 percent of the original data set but is representative of a variety of locations across Canada, both within provincial road authorities and in urban areas. Table 5.4 shows the number of periods extracted in each road authority/district.

Table 5.4 – Total Observation Periods that Included RWIS Data

Road Authority	Area	Total Observation Periods	RWIS Observation Periods	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	0	0.0%
	Southern Alberta - near Calgary	70	18	25.7%
Province of Manitoba	Brandon	20	0	0.0%
	Carberry	18	0	0.0%
Province of New Brunswick	Fredericton	29	0	0.0%
	Moncton	29	0	0.0%
	Saint John	29	0	0.0%
Province of Newfoundland	Avalon	35	8	22.9%
	Central	35	0	0.0%
	Eastern	35	8	22.9%
	Western	35	0	0.0%
Province of Nova Scotia	Central	52	7	13.5%
	Eastern	61	0	0.0%
	Northern	53	2	3.8%
	Western	67	15	22.4%
Province of Ontario	London Area	5	0	0.0%
	New Liskeard Area	96	27	28.1%
	Ottawa Area	5	5	100.0%
Province of Quebec	Chicoutimi	56	0	0.0%
	Gaspe	65	0	0.0%
	Hull	41	0	0.0%
	Montreal	52	10	19.2%
	Quebec	61	14	23.0%
	Rouyn-Noranda	42	0	0.0%
	Sept Iles	29	0	0.0%
	Sherbrooke	40	5	12.5%
Province of Saskatchewan	Findlater	18	8	44.4%
	Regina	18	8	44.4%
City of Calgary		28	18	64.3%
City of Edmonton		41	0	0.0%
City of Halifax		7	3	42.9%
City of London		6	0	0.0%
City of Ottawa		16	13	81.3%
City of Winnipeg		43	0	0.0%
City of Toronto		11	0	0.0%
Total Percentage		**1276**	**169**	**13.2%**

5.2.3 Additional Variables

The following additional variables were considered:

- **Geographic grouping** – All road authorities in eastern Canada (within the provinces of Ontario, Quebec, Nova Scotia, New Brunswick and Newfoundland) were assigned the value 1, reflecting the additional salt used in these provinces, while the remaining road authorities were assigned the value 0. This reflects the division in salt usage quantities observed earlier;
- **Urban and rural grouping** – The road authorities were divided into urban (cities) and provincial (rural) groups; and
- **Year** – This variable was considered for the modeling in order to account for a downward trend in salt usage over time due to salt management

Variables considered and rejected were road class and winter road maintenance practices (several road authorities did not provide a breakdown by road class and many of the road authorities did not provide data on how the salt was applied).

5.3 MODEL OPTIONS CONSIDERED

Two separate models were developed that used **salt (t)/lane km/days** as the dependent variable. The first of the two models would use MSC data as the independent variable(s). The second of the two models would use MSC supplemented with RWIS data as the independent variable(s). Other non-weather variables were considered in the model as well.

In the model development, the following three approaches were considered:

- Individual variable modeling (MSC only and MSC-RWIS);
- Composite variable modeling (MSC only and MSC-RWIS); and
- Creation of an index based on composite variables weighted according to expert opinion (MSC only and MSC-RWIS).

Individual variable modeling involved developing a relatively simple model using daily meteorological data (MSC) on its own or in combination with RWIS data, in order to identify a statistical relationship between the dependent variable, salt (t)/lane-km/day and weather conditions. Individual variable modeling of daily MSC data is straightforward to use. Future users would rely on MSC data that is available from the Environment Canada website. Nationally, this model achieved a modest goodness of fit.

Composite variable modeling was more prescriptive; it involved the creation of four general types of potentially saltable hourly events that were modeled as a set of composite variables, to identify a statistical relationship between the dependent variable and the composite variables separately. This was attempted using MSC data only and MSC data combined with RWIS data. Modeling of composite variables at the hourly MSC level was more prescriptive by focusing in on the exact weather conditions that would likely require salting by carefully defining temperature and precipitation conditions based on expert opinion. As such, this model was less straightforward to conceptualize and would have required more data as inputs, both in the number of variables used and due to the temporal scale (hourly compared to daily). Nationally, the composite model yielded a comparable goodness of fit to the modeling of daily MSC data. Due to its complexity and results, this course of action was not carried forward.

The **creation of an index** involved using the composite variables to develop a weighted index and modeling it as a single variable, in order to identify its relationship to the dependent variable. The weightings reflect relative importance in terms of required salt usage during different weather events, being snowfall, freezing rain, drifting snow, and frost, predicated on the temperature being within a certain range. Nationally, this approach achieved a poorer goodness of fit compared to the other models. As with the composite variable modeling, the development of an index using hourly composite variables as inputs, was considered less straightforward to conceptualize and will require more data as inputs. The weighting of the different variables is also arbitrary and are not based on statistical modeling. For this reason, this model was also not carried forward.

5.4 MODEL RESULTS

A model using individual variables was developed. It was assumed that the dependent variable is normally distributed. Each of the individual MSC variables described in the previous section were modeled separately in order to identify the level of correlation (correlation coefficient) and the goodness of fit (R-squared value) of the independent variable in relationship to the dependent variable, salt (t)/lane-km/day.

Photo Credit: MFP Associates

The correlation coefficient (also known as the R-value), describes the level of correlation between the independent variable and the dependent variable and is a value between -1 and 1. Values approaching either -1 or 1 suggest a high level of correlation. The correlation coefficient may be positive or negative. A positive value indicates that the relationship between the dependent and independent variable is positive, as the dependent variable increases, so does the independent variable. Conversely, a negative value indicates that the relationship between the dependent and independent variable is negative, as the dependent variable increase, the independent variable decreases. For example, average air temperature has a correlation coefficient that is negative, meaning that as air temperature increases, salt (t)/lane-km/day decreases.

The R-squared value shows the goodness of fit between the two variables. Values approaching 1 suggest a good fit between the dependent variable and the independent variable. An R-squared value describes how much the independent variable explains the variation in the dependent variable. For example, if average threshold snow (> 1 cm) has an R-squared value of 0.30, this means that it explains 30% of the variation in salt (t)/lane-km/day.

Aside from linear modeling, different mathematical distributions of the dependent variable were examined. This included exponential and logarithmic functions. It was found that a natural log (ln) produced the best fit with the independent variables. This transformation was justified due to a better prediction performance. The function (ln) is commonly used by engineers in modeling relationships between different variables. The natural log (ln) of salt (t)/lane-km/day was used as the dependent variable for the remainder of the modeling.

5.4.1 Model Using MSC Data Alone

Table 5.5 shows the correlation coefficients and R-squared values for a selected group of non-weather variables and individual daily MSC variables, using the natural log (ln) of salt (t)/lane-km/day. The exhibit suggests that there are some variables showing a higher correlation and goodness-of-fit. Variables showing promise all relate to snowfall. The temperature and freezing rain variables had a lower degree of correlation, suggesting their potential as a secondary variable. The east-west dummy variable also showed a high degree of correlation and clearly demonstrates the difference in salt usage in western Canada versus Eastern Canada.

Table 5.5 – Correlation Coefficient and R-square Values for Selected Individual Daily MSC Variables

Variable	Correlation (R value)	Goodness of Fit (R-squared)
East-West dummy variable	0.48	0.23
Urban-Rural dummy variable	-0.18	0.03
Year	-0.02	0.00
Average air temperature (*Ta*)	-0.35	0.12
Difference between T*max* and T*min*	-0.35	0.12
Snowfall occurrence	0.58	0.34
Snowfall occurrence (including trace)	0.61	0.37
Snowfall amount	0.50	0.25
Threshold snow occurrence (>1 cm)	0.55	0.30
Freezing rain occurrence	0.34	0.12
Blowing snow occurrence	0.34	0.12

The variables described above were used in various combinations in order to identify a model that had the highest goodness of fit.

In addition, the temperature variable was modified to account for temperature range in which salt is applied (between 0 Celsius and -12 Celsius). A variable was derived from the mean air temperature by calculating the absolute difference between the mean air temperature and a temperature between 0 Celsius and -12 Celsius, accounting for the fact that salt usage should decrease as the mean air temperature range moves outside the range of temperatures at which salt is applied. The variable with the best result was the absolute difference between -6.5 Celsius and the mean air temperature (for a given time period), yielding a correlation of -0.52 or an R-squared value of 0.27.

The model with the highest correlation and goodness-of-fit is shown in Table 5.6. A total of 1,255 observation periods were used for this model (some of the periods did not have a value for the required variables). The correlation between the dependent variable (the natural log of salt(t)/lane-km/day) and the independent variables is **0.74**. The model has a goodness of fit of **0.54**, in other words, the model explains 54 percent of the variation in salt usage (expressed as a natural log).

Table 5.6 – Best MSC Model Results Incorporating Simple Meteorological Variables

Model form: ln of salt (t)/lane-km/day = -5.59431 + 2.36059 (snow) - 0.08616 (air) + 1.37785 (EW) + 0.74326 (frz)			
Observations	1255		
Correlation Coefficient (R value)	0.74		
Goodness of Fit (R squared)	0.54		
Variable Name	**Parameter Estimate**	**t-value**	**Probability>t**
1. Measurable or trace snowfall occurrence (snow)	2.36059	14.66	<0.0001
2. Absolute air temperature difference (air)	-0.08616	-10.30	<0.0001
3. East - west dummy variable (EW)	1.37785	18.20	<0.0001
4. Freezing rain occurrence (frz)	0.74326	2.07	0.039
Notes: 1. Proportion of days in which measurable or trace snowfall was reported. 2. Absolute difference between average air temperature and -6.5 Celsuis. 3. East - west dummy variable, for all road authorities east of Ontario-Manitoba border use 1, otherwise use 0. 4. Proportion of days in which freezing rain was reported.			

The parameter estimates for the measurable or trace snowfall occurrence, east-west dummy variable and freezing rain occurrence are all positive. This suggests a positive relationship with the dependent variable. The absolute air temperature difference has a negative parameter estimate, suggesting a negative relationship with salt usage. As the difference between average air temperature and -6.5 Celsius increases (in other words, it moves out of the range of temperatures at which salt is applied), the level of salt usage decreases. The first three variables are significant ($p<0.0001$), indicating that they are each contributing to the goodness of fit of the model. The freezing rain occurrence variable is showing a lesser degree of significance ($p<0.039$).

It should be noted that the weather variables (without the benefit of the east-west dummy variable) had a goodness-of-fit of **0.42**. In other words, weather is explaining 42 percent of the variation on salt usage.

Model Using MSC and RWIS Data

Average pavement temperature, being the variable most often reported within the RWIS data, was then substituted for average air temperature. As mentioned in the previous section, based on a number of quality checks, 169 observations of pavement temperature were extracted. The correlation between pavement temperature and the dependent variable was determined to be **-0.50.** In other words, as pavement temperature increases, the dependent variable tends to decrease. The goodness-of-fit was 0.25. Modeling of a variety of different combinations of variables was attempted.

As with the air temperature variable, the pavement temperature variable was modified to account for temperature range in which salt is applied (between 0 Celsius and -12 Celsius). A variable was derived from the mean pavement temperature by calculating the absolute difference between the mean air temperature and a temperature between 0 Celsius and -12 Celsius, accounting for the fact that salt usage should decrease as the mean pavement temperature range moves outside the range of temperatures at which salt is applied. The variable with the best result was the absolute difference between -4.0 Celsius and the mean air temperature (for a given time period), yielding a correlation of **-0.46** or an R-squared value of **0.21**.

The model with the highest correlation and goodness-of-fit is shown in Table 5.7. A total of 164 observations were used for this model (some of the periods of observation did not have a value for measurable or trace snowfall occurrence). Freezing rainfall occurrence, while significant in the previous model, was not significant in this model. Therefore, it was removed.

The correlation between the dependent variable and the independent variable is **0.77**. This model has a goodness of fit of **0.60.** In other words, the model explains 60 percent of the variation in salt usage. The higher correlation and goodness-of-fit is somewhat misleading given the smaller sample size.

The parameter estimates for the east-west dummy variable and the measurable or trace snowfall occurrence are positive, suggesting a positive relationship with the dependent variable. As well, the absolute air temperature difference variable has a negative parameter estimate, indicating a negative relationship with the dependent variable. All variables are highly significant (p<0.001), indicating that they are each contributing to the goodness of fit of the model.

It should be noted that the two weather variables (measurable or trace snowfall occurrence and absolute pavement temperature difference) are explaining 42 percent of the variation in salt usage without the benefit of the east-west dummy variable.

Table 5.7 – Best Model Results Incorporating Single MSC Variables in Conjunction with a Derived Pavement Temperature Variable (RWIS)

Model form: In of salt (t)/lane-km/day = -5.1447 + 3.28835 (snow) - 0.08226 (pave) + 1.36468 (EW)			
Observations	157		
Correlation Coefficient (R value)	0.77		
Goodness of Fit (R squared)	0.60		
Variable Name	Parameter Estimate	t-value	Probability>t
1. Measurable snowfall occurrence (snow)	3.41662	7.48	<0.0001
2. Absolute pavement temperature difference (pave)	-0.08532	-4.91	<0.0001
3. East - west dummy variable (EW)	1.34889	8.25	<0.0001

Notes:
1. Proportion of days in which measurable or trace snowfall was reported.
2. Absolute difference between average air temperature and -4.0 Celsius
3. East - west dummy variable, for all road authorities east of Ontario-Manitoba border use 1, otherwise use 0.

5.5 TAC WINTER SEVERITY INDEX DEVELOPMENT

An index (hereafter referred to as the TAC Winter Severity Index) uses a numerical scale between 1 and 100. It was developed based on the predicted salt usage (expressed as a natural log). First, the predicted range of salt usage determined in the national model (a total of 1255 observations) was taken as the working range of possible values. The lowest and highest predicted salt usage was used to identify the lower and upper range of values for the Index. A predicted salt usage value below the minimum predicted salt usage value in the model, would be 1. A predicted salt usage value, above the maximum predicted salt usage value in the model, would be 100. A lower and upper range of values was determined for the values 2 through 99, with the upper range for 50 being set at the median predicted value. Thus half of the predicted salt usage values in the model are between 1 and 50 and the remaining of the predicted salt usage values are between 51 and 100. The increments defining the lower and upper range of values for 2 through 50 and 51 through 100 were divided equally.

The distribution of calculated TAC Winter Severity Index values based on the 1255 observations using the MSC data in the national model is shown in Figure 5.1.

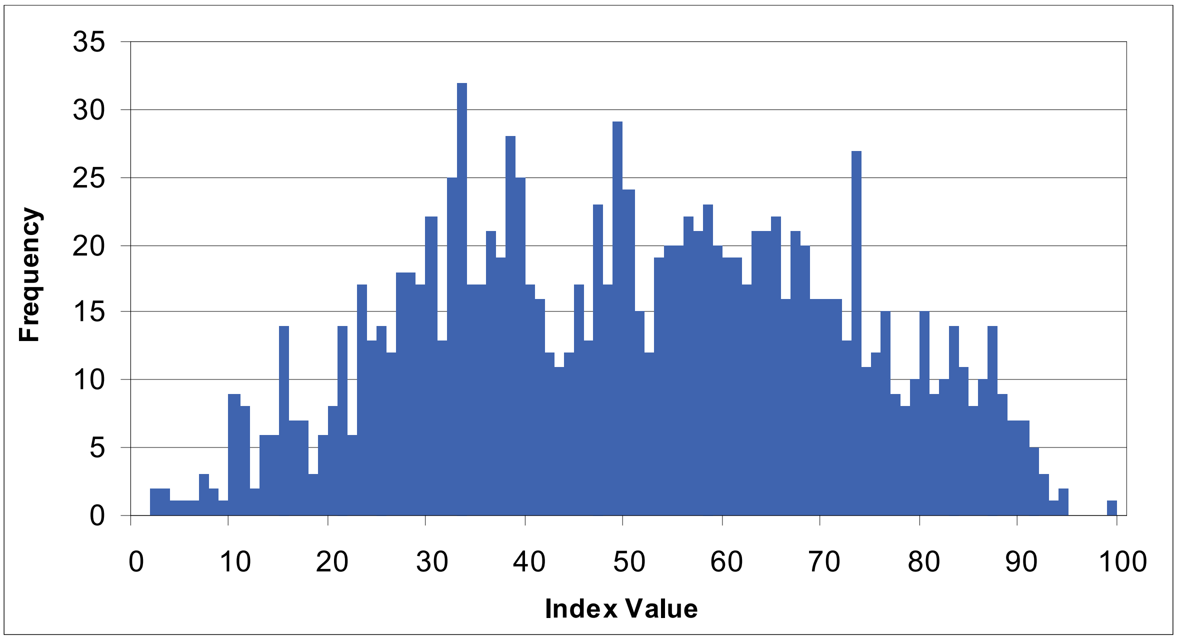

Figure 5.1 – Distribution of Calculated TAC Winter Severity Index Values

6 – LOCAL CALIBRATION

The first task involved in local calibration was grouping the various geographic areas represented in the national model into homogenous groups. Two different road authorities (or individual districts within a provincial road authority) were considered homogenous if:

- The observed salt usage (salt (t)/lane-km/days) in each was similar; and
- They were considered to be in the same climatic zone.

The observed salt usage (salt (t)/lane-km/days) of two different groups were considered to be similar if the mean and standard deviation were found to be similar using a t-test. The calculation of this t-test is shown in Appendix C. The local calibration groups are shown in Table 6.1.

Table 6.1 – Local Calibration Groups

Group	Road authorities/districts
1	Province of Newfoundland – Central District
2	Province of Newfoundland – Western District
3	Province of Newfoundland – Avalon and Eastern District
4	Province of Quebec – Montreal and Sherbrooke District
5	Province of Quebec – Gaspe and Sept Illes District
6	Province of Quebec – Chicoutimi and Quebec City District
7	Province of Quebec – Hull District
8	Province of Quebec – Rouyn District
9	City of Ottawa Province of Ontario, Ottawa District
10	Province of New Brunswick – Fredericton District
11	Province of New Brunswick – Moncton and St John District
12	Province of Nova Scotia – All Districts and City of Halifax
13	Province of Ontario – New Liskeard
14	City of London, City of Toronto, and Province of Ontario, London
15	City of Winnipeg and Province of Manitoba, Brandon District
16	Province of Manitoba, Carberry District
17	Province of Alberta, Southern Alberta District (south of Calgary)
18	Province of Alberta, Northern Alberta and Province of Saskatchewan, Regina District and Findlater
19	City of Calgary
20	City of Edmonton

6.1 CALIBRATION METHODOLOGY

Using MSC data only, the result of the national model was calibrataed to the twenty local areas identified in Table 6.1. Local calibration was not done using the MSC-RWIS model, due to the lack of representation in many areas of Canada.

Several different possible methods of calibrating the results of the national model to the local results were attempted. They were:

- Creating a single local calibration factor that would be applied to the national model results for each area;
- Calibrating the individual model parameters independent of the national results; and
- Calibrate each of the national model parameters to the local model (Bayesian method).

For all three methods of calibration, the east-west dummy variable was not used.

Creating a single calibration factor to weight the local results, involved calculating the ratio of total observed salt usage from each calibration group to the sum of the predicted salt usage using the national model for the same calibration group. Then, the calibration factor estimated for each group was multiplied by the national model in order to "transfer" the national model for application to local conditions. However, this method was not used as it did not substantially improve the goodness of fit of the model locally.

Photo Credit: MFP Associates

The second method considered was calibrating the individual model parameters independent of the national results. This method did improve the goodness of fit in some of the jurisdictions, but some of the parameter estimates changed substantially, producing results that were counterintuitive due to lack of representative data (i.e. a negative parameter estimate for snow occurrence, meaning that snowfall had a negative relationship with salt usage in the model). This was the reason this method was not employed.

The third method involved the use of the Bayesian method. The Bayesian method combines the information from the national model with the information obtained from local calibration, in order to achieve more accurate updated information. The Bayesian approach provides an opportunity to solve the problem encountered in the second method. The results generated using the Bayesian method improved on the national results but did not produce any counterintuitive results. Further description of the Bayesian method is presented in Appendix C.

Therefore, the Bayesian method was used to calibrate the results of the national model to the local results. For this method, the east-west dummy variable was not included in the calibration, since the data came from the local jurisdictional level.

6.2 RESULTS OF LOCAL CALIBRATION

The results of the local calibration using the Bayesian method are shown in Figure 6.1 along with the comparable national model result that did not include the east-west dummy variable (0.42).

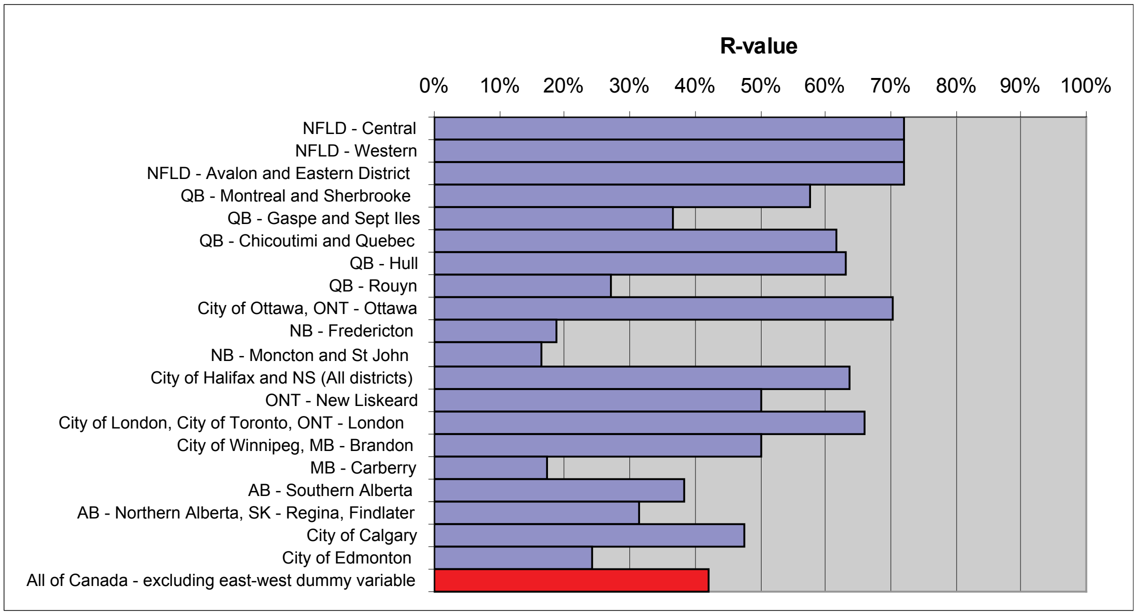

Figure 6.1 – R-values for Each Local Calibration District

The results of the local calibration suggest a wide variation in the goodness of fit across Canada. The local calibration was able to improve upon the national model in twelve out of twenty of the groups. A higher goodness of fit was realized in all districts of Newfoundland, Nova Scotia, Quebec (with the exception of Rouyn District and Gaspe and Sept Iles), Ontario, and Manitoba (Brandon only), and all of the Cities (except Edmonton). These areas achieved a goodness of fit of 42 percent or greater.

All of New Brunswick, the two areas (Rouyn, Gaspe and Sept Illes) within Quebec, the district of Carberry in Manitoba, districts within the provinces of Alberta and Saskatchewan, and the City of Edmonton all achieved a somewhat lower goodness of fit than the national model results. There are several possible reasons for this.

First, road authorities in these areas of Canada do not respond to weather conditions in a similar manner to the rest of the jurisdictions in terms of their salt usage. Generally speaking, with the exception of the districts in Quebec and New Brunswick, it was noted that the areas with a poorer fit were in western Canada. Western Canada was noted to use less salt than eastern Canada. It is speculated that some of these jurisdictions either use sand as an alternative, plow, or may only use a small amount of salt mixed in with sand during weather conditions, where another road authority would chose to use salt.

Second, the districts that had poorer results were rural areas, with a low population density (such as Rouyn District in Quebec and Carberry District in Manitoba). These areas likely include lower priority roads which may not require immediate attention (in terms of salting) or these roads may not be salted at all.

Table 6.2 shows the detailed results of the local calibration for each district.

Table 6.2 – Results of Local Calibration

District	Observation Periods	Intercept	East-west dummy	Parameter Estimates			Correlation (R value)	Goodness of fit (R-squared)
				Snow	Temp	Frz		
NFLD - Central	35	-5.52	1.00	2.29	-0.09	0.76	0.85	0.72
NFLD - Western	35	-5.43	1.00	2.30	-0.07	0.77	0.85	0.72
NFLD - Avalon and Eastern District	70	-5.48	1.00	2.33	-0.09	0.77	0.85	0.72
QB - Montreal and Sherbrooke	91	-5.55	1.00	2.41	-0.09	0.71	0.76	0.58
QB - Gaspe and Sept Iles	94	-5.59	1.00	2.40	-0.08	0.77	0.60	0.37
QB - Chicoutimi and Quebec	115	-5.36	1.00	2.38	-0.09	0.73	0.78	0.62
QB - Hull	41	-5.59	1.00	2.36	-0.08	0.87	0.79	0.63
QB - Rouyn	42	-5.65	1.00	2.39	-0.08	0.74	0.52	0.27
City of Ottawa, ONT - Ottawa	21	-5.54	1.00	2.39	-0.09	0.73	0.84	0.70
NB - Fredericton	28	-5.57	1.00	2.36	-0.08	0.79	0.43	0.19
NB - Moncton and St John	56	-5.34	1.00	2.19	-0.08	0.69	0.41	0.17
City of Halifax and NS (All districts)	237	-4.99	1.00	2.08	-0.09	1.10	0.80	0.64
ONT - New Liskeard	85	-5.52	1.00	2.45	-0.09	0.81	0.71	0.50
City of London, City of Toronto, ONT - London	22	-5.59	1.00	2.37	-0.09	0.76	0.81	0.66
City of Winnipeg, MB - Brandon	62	-5.56	0.00	2.36	-0.09	0.72	0.71	0.50
MB - Carberry	18	-5.62	0.00	2.36	-0.09	0.79	0.41	0.17
AB - Southern Alberta	70	-5.61	0.00	2.34	-0.09	0.79	0.62	0.38
AB - Northern Alberta, SK - Regina, Findlater	64	-5.61	0.00	2.37	-0.08	0.84	0.56	0.32
City of Calgary	28	-5.52	0.00	2.34	-0.08	0.77	0.69	0.48
City of Edmonton	41	-5.60	0.00	2.37	-0.09	0.77	0.49	0.24
All of Canada*	1255	-4.87	N/A	2.83	-0.08	1.62	0.65	0.42

Notes:
Snow - Proportion of days of reported measurable or trace snow during period.
Temp - Absolute difference between average air temperature (Celsius) and -6.5 Celsius.
Frz - Proportion of days of reported freezing rain or drizzle during period.
*Results of Canada wide modelling - excluding the east-west dummy variable.

7 -- FUTURE DATA REQUIREMENTS

An Excel spreadsheet (The TAC Winter Severity Index Calculator Spreadsheet) was developed to allow road authorities to calculate their own Index values for a given time period by means of a set of inputs based on the independent variables identified in the two models. This spreadsheet is located on the CD attached to the front cover of this report. An example is shown in Figure 7.1.

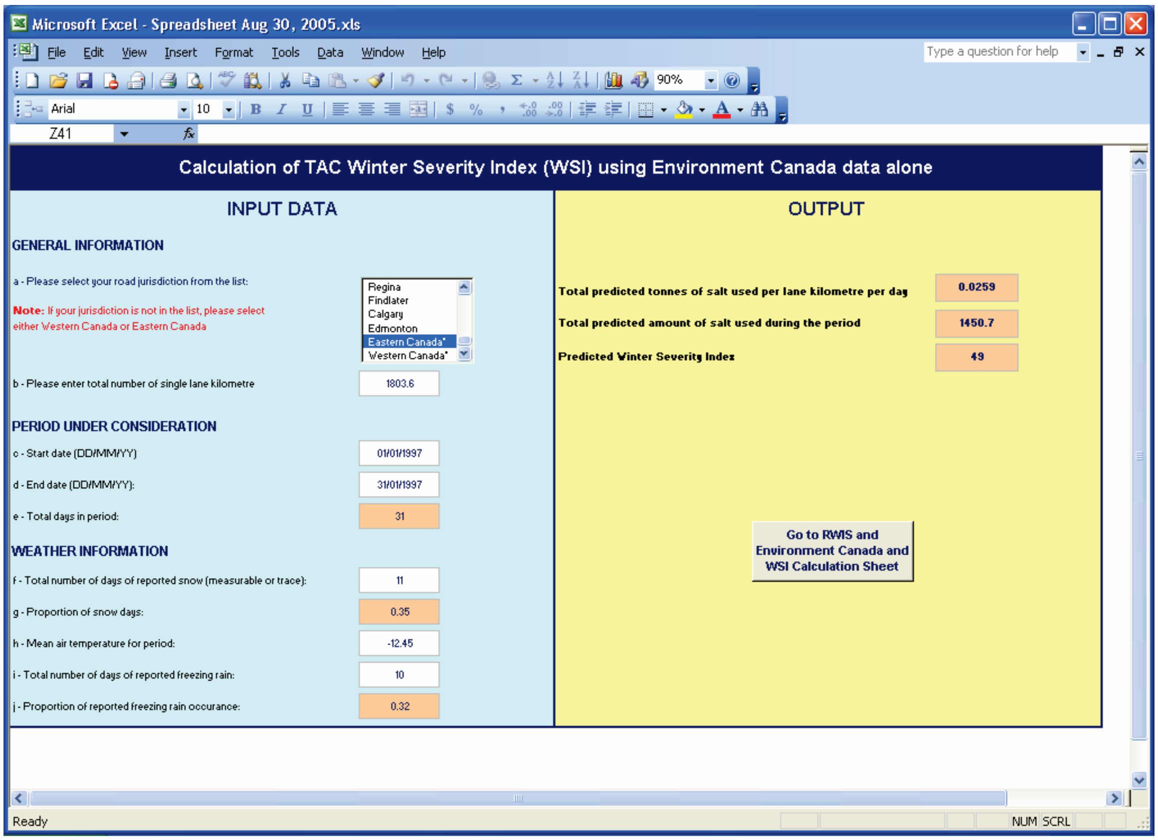

Figure 7.1 – TAC Winter Severity Index Calculator Spreadsheet

The spreadsheet allows for the selection of any one of twenty different calibrations (based on the twenty different calibrated areas across the country). This will allow road authorities to calculate the Index based on either MSC data or a combination of MSC and RWIS data. The spreadsheet also indicates the predicted salt usage based on the model. This will allow each road authority to assess the relative severity of a given winter compared to past winters in terms of salt usage.

Users wishing to calculate their own Index using MSC data and calculate the predicted salt usage require six pieces of information, as follows:

- Their geographic area
- The time period under consideration;
- The number of days in which measurable or trace snowfall occurred;

- The average air temperature;
- The number of days in which freezing rain occurred; and
- The length of the road network in single lane kilometres (in order to calculate the predicted salt usage).

7.1 SELECTION OF GEOGRAPHIC AREA

Road authorities who contributed data to the development of the national model need only to select their area from the drop down menu shown on the spreadsheet. For all other road authorities wishing to use the model, it is recommended that they choose either Eastern or Western Canada, depending on whether they are east or west of the Manitoba-Ontario border, in keeping with the east-west dummy variable. It is not recommended that road authorities in British Columbia use the spreadsheet, as none of their data was included in the modeling.

7.2 SELECTION OF TIME PERIOD UNDER CONSIDERATION

In the spreadsheet, users are required to select the beginning and end date of the period under consideration. The spreadsheet automatically calculates the length of the period using the two dates. Users may select a period of any length from two weeks (the smallest temporal unit used in the national model) up to an entire winter season. To ensure the greatest accuracy when selecting an entire winter season, users should include all dates in which salt was used to allow for a valid comparison between the observed and predicted salt usage, as described later in this section.

7.3 SELECTION OF MSC STATION

The following should be considered in selecting a MSC station for calculating the TAC Winter Severity Index. In choosing an MSC station, observations may be missing for certain periods of time. When this occurs, the user may either choose the next closest MSC station or exclude those time periods when calculating the Index. While the MSC or RWIS station may currently be in operation, it may close at a future point in time, so the user will need to substitute another station further away when calculating the Index in the future.

Meteorological data required for the model may be downloaded from the Environment Canada website at http://www.climate.weatheroffice.ec.gc.ca. Table 7.1 shows the MSC stations used to derive the MSC data for each road authority. For other road authorities, it is recommended that the user select an MSC station that is located either within the road authority or nearby.

Table 7.1 – MSC Stations used for Each Road Authority/district

WRM district	Weather station
Newfoundland	
Avalon	St. John's Airport (MSC 8403506)
Eastern	St. John's Airport (MSC 8403506)
Central	Gander Airport (MSC 8401700)
Western	Stephenville Airport (MSC 8403800)
New Brunswick	
Moncton	Moncton Airport (MSC 8103200)
Saint John	Saint John Airport (MSC 8104900)
Fredericton	Fredericton Airport (MSC 8101500)
Nova Scotia	
RM of Halifax	Shearwater (MSC 8205090)
Central	Halifax Airport (MSC 8202250)
Western	Greenwood Airport (MSC 8202000)
Northern	Halifax Airport (MSC 8202250)
Eastern	Sydney Airport (MSC 8205700)
Alberta	
City of Calgary	Calgary Airport (MSC 3031093)
Southern Alberta	Calgary Airport (MSC 3031093)
Northern Alberta	Fort McMurray Airport (MSC 3062693) *freezing rain derived from hourly observations
City of Edmonton	Edmonton City Centre Airport (MSC 3012208) Freezing rain supplement: Edmonton Int'l Airport (MSC 3012205)
Saskatchewan	
Regina	Regina Airport (MSC 4016560)
Findlater	Regina Airport (MSC 4016560)
Manitoba	
City of Winnipeg	Winnipeg Airport (MSC 5023222) supplement for snowdepth: MSC 502M001
Brandon	Brandon Airport (MSC 5010480)
Carberry	Brandon Airport (MSC 5010480)
Ontario	
City of Toronto (Scarborough)	Toronto Buttonville Airport (MSC 615HMAK)
City of London	London Airport (MSC 6144475) Supplemented for several variables: London CS (MSC 6144478)
City of Ottawa	Ottawa MacDonald-Cartier Airport (MSC 6106000)
MTO Ottawa	Ottawa MacDonald-Cartier Airport (MSC 6106000)
MTO London	London Airport (MSC 6144475) Supplemented for several variables: London CS (MSC 6144478)
MTO New Liskeard	Earlton Airport (MSC 6072225)
Quebec	
Montréal Chicoutimi	Montreal Pierre Elliott Trudeau Airport (MSC 7025250) Freezing rain supplement: St Genevieve (MSC 7027280) Bagottville (MSC 7060400)
Québec City	Beausejour (MSC 7020657)
Sherbrooke	Magog (MSC 7024440)
Gaspé	Gaspé Airport (MSC 7052605)
Sept-Iles	Sept-Iles Airport (MSC 7047910)
Rouyn-Noranda	Mont Brun (MSC 7081506)

7.4 MEASURABLE OR TRACE SNOWFALL

Measurable or trace snowfall may be calculated from daily data taken from the MSC website at http://www.climate.weatheroffice.ec.gc.ca. The TAC Winter Severity Index spreadsheet requires the number of days in which measurable or trace snowfall fell at the Environment Canada station in between the selected start and end dates supplied by the user.

For instance, if a user wished to calculate the Index for the month of January 2006 for Calgary, they would refer to the monthly meteorological summary on the MSC website. According to the

website, at Calgary airport in January 2006, there were four days in which measurable snow was reported and six days in which trace snow (indicated by the letter "T") was reported. Therefore, there were ten days of measurable or trace snowfall.

The TAC Winter Severity Index spreadsheet automatically calculates the proportion of days in which measurable or trace snowfall fell, considering the beginning and end dates supplied by the user.

7.5 AVERAGE AIR TEMPERATURE

The next information required for the TAC Winter Severity Index spreadsheet is the average (mean) air temperature. For this information, the user may refer again to the Environment Canada website. If they are calculating the Index for a single month, this information is found at the bottom of each monthly meteorological summary. For example, the average air temperature (shown as the mean) was -1.5 Celsius in Calgary during January 2006.

In instances where the user is calculating the average air temperature for a biweekly period or an entire winter season, the user may download the daily data for the desired time period. Daily Environment Canada meteorological data representing an entire month may be downloaded as a CSV file and opened in MS-Excel.

The TAC Winter Severity Index spreadsheet automatically calculates the absolute difference between the inputted value and -6.5 Celsius, as required for the model.

7.6 FREEZING RAIN OCCURRENCE

The last meteorological variable required is the occurrence of freezing rain. Hourly observations of freezing rain (or freezing drizzle) are noted in the daily meteorological summaries at Environment Canada stations at all major airports. To calculate freezing rain occurrence, the user may download the hourly data for the desired time period. Hourly Environment Canada meteorological data representing an entire month may be downloaded as a CSV file and opened in MS-Excel.

Observations of freezing rain or drizzle appear in three columns labelled 'Weather', allowing for three different observations of weather to be reported at the top of each hour. Each day in which one or more observations of either freezing rain or drizzle are reported, the data should be counted as a day in which freezing rain occurred.

The spreadsheet automatically calculates the proportion of days in which freezing rain (or drizzle) occurred during the desired period inputted by the user.

Once the above information has been placed in the spreadsheet, the Index is automatically calculated.

7.7 SINGLE LANE KILOMETRES

Finally, the user may calculate the predicted salt usage by providing the single lane kilometres for their road network. It should be noted that the predicted salt usage is only an estimate based on the model.

7.8 PAVEMENT TEMPERATURE

Users may wish to calculate the TAC Winter Severity Index based on the MSC-RWIS model results. The MSC-RWIS model uses pavement temperature instead of air temperature. The user will need to calculate the average pavement temperature over the desired period. The quality of the data should be reviewed carefully prior to calculating average pavement temperature. The following questions relate to the quality of the data:

- Are there any significant gaps in the data over the period being considered?
- Are there any erroneous observations (repeated or default values)?
- Are there any values that seem suspicious?

If there were more than 12 consecutive observations identified as missing, erroneous, or suspicious, the data was excluded from the model. Users may wish to follow similar guidelines when reviewing their RWIS data.

The location of the data may not be representative of weather conditions in the road district it is matched to. For example, an RWIS station may be situated in a location identified as being more frost prone than the surrounding road network (on a bridge). Information regarding the representativeness of a particular RWIS sensor should involve consultation with the appropriate individual.

8 – CONCLUDING REMARKS

Through this report, an index has been developed that can be calculated from either MSC data alone or MSC data in conjunction with RWIS data. Key variables identified as predictors of salt usage are the occurrence of measurable or trace snowfall, air temperature (constructed as the absolute difference between the average air temperature and a selected value chosen as a representative midpoint in the saltable temperature range) and the occurrence of freezing rain. In the MSC-RWIS model, pavement temperature was substituted for air temperature. Each of these variables identified make intuitive sense and are contributing to the model in a significant and meaningful way.

The models presented in this report also show clear evidence that geographic variation is a significant factor in modeling salt usage in Canada. The east-west dummy variable was a significant variable in both models – reflecting the fact that there is a significant difference in WRM practices in western Canada compared to eastern Canada that cannot be explained by weather variables alone. It is likely that there are other geographic variations that relate to the unique climate of different regions of Canada and differing WRM practices at the local level.

8.1 GOODNESS OF FIT

The goodness of fit in the MSC model was **0.54.** In other words, the variables explain 54 percent of the variation in the dependent variable (salt usage). In the MSC-RWIS model, the goodness-of-fit was **0.60.** However, the sample size was significantly smaller and did not include significant portions of the country.

With respect to the goodness of fit of the models presented in this report, it should be noted that past literature indicates the correlation between winter severity indices and WRM variables does vary considerably. In many cases, less than half of the total variability in WRM is explained by weather. Past models that had a better goodness-of-fit were those that focused either on a single region (the model was calibrated to local conditions and needed to only account for temporal variations), or those that examined a larger unit of analysis (typically a whole winter season). In contrast, the focus of the modeling discussed in this paper has been to explain variations both temporally and spatially at the city/district level for individual biweekly or monthly periods, across an entire country with differing winter road maintenance practices and climatic regions. As such the models developed for the TAC Winter Severity Index involved a significantly more ambitious undertaking than past efforts.

Generally speaking the Index will be more representative of salt usage in eastern Canada compared to western Canada. Populated areas fared better when compared to rural areas with a low population density. The Index will work best in areas where salt is the primary material used for conducting winter road maintenance. The Index should perform better in densely populated areas due to the higher Level of Service required on these roads.

Figure 8.1 shows the monthly observed salt usage and the calculated Index in the Province of Newfoundland in Central District, based on the calibrated factors for the model using MSC data alone for the winter seasons 1999/2000 to 2003/2004. As shown, the Index is correlating well with the observed salt usage and would be an effective tool for the province in evaluating salt usage on a monthly basis and making comparisons over different successive monthly periods.

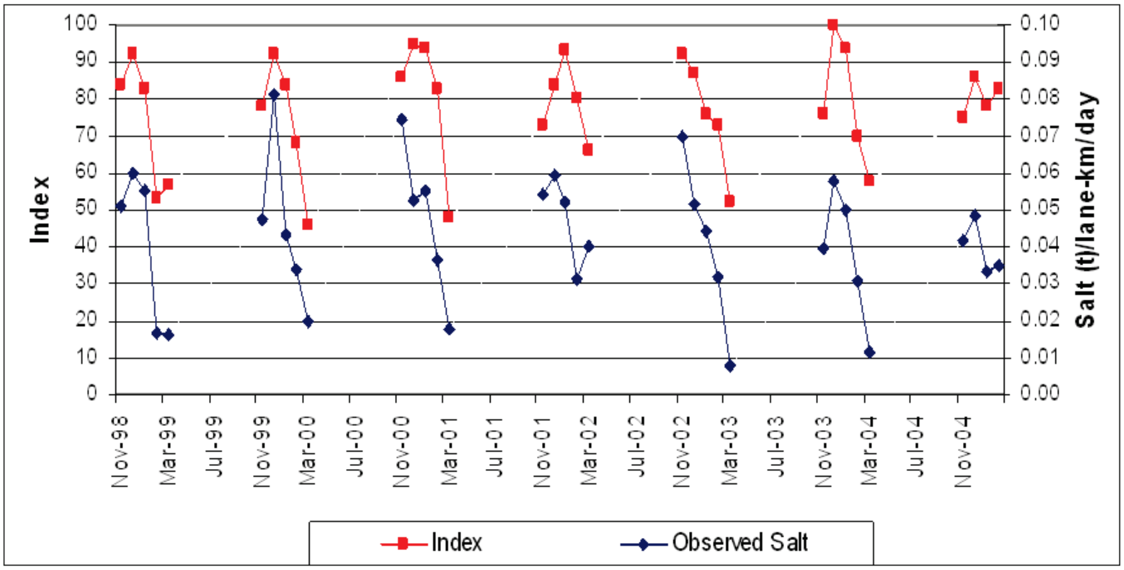

Figure 8.1 – Comparison of Calculated Index Values (based on predicted salt and observed salt (t)/lane-km/day) Central District of Newfoundland: (November 1999 - March 2004)

In other areas of Canada where the local calibration did not achieve as high of a goodness of fit (less than 0.42), the TAC Winter Severity Index is of limited value for short time periods (biweekly or monthly). It is recommended that users of the Index use the spreadsheet to examine and compare the actual and predicted salt usage over a successive number of winter seasons to evaluate the goodness of fit. A better goodness of fit should be realized at the seasonal level.

8.2 INDEX LIMITATIONS

Several limitations of the Index should be noted. Weather plays a key role in the variability of salt usage. However, apart from the east-west dummy variable, non-weather related variables such as winter road maintenance practices and varying standards of service across the country have not been considered in the model due to a lack of data. Therefore, the predicted salt usage developed in the model may be lower or higher than actual salt usage in a particular jurisdiction due to these local variations. The predicted salt usage and index is not intended to be used as a comparison among different road authorities. Rather, the predicted salt usage and index may be used to make internal comparisons -- between a given winter and past winters, and for assessments regarding the reasonableness of salt usage for a given period of time.

If the road authority does not have calibrated results, they can use the applicable national model values (either eastern of western Canada).

The model cannot be used in British Columbia due to the absence of any WRM from that area.

8.3 – FUTURE RESEARCH

Several findings for future research emerged from this work. It may be useful to develop a winter severity index model for sand usage or equipment hours. Sand is more heavily used in western Canada. It is believed that a better fit could be developed in western Canada using sand as the dependent variable. Alternatively, equipment hours could be a potentially useful variable in that it predicts winter road maintenance activity independent of the choice of materials. It is widely known that labour costs (as indicated by equipment hours) contribute to the largest portion of a WRM budget.

It may be helpful if a winter road maintenance authority standardized their reporting of materials (into a common reporting unit, such as tonnes). This will better facilitate any future modeling. Information on road class (as expressed in lane kilometres) would also likely strengthen any future model predicting WRM activity based on weather.

As RWIS data becomes more widely available, another national model should be developed using MSC data supplemented by RWIS data. The results shown in this report are promising but have limited value based on the relatively small number of observations.

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APPENDIX A: MSC DATA

Road Authority	Area	Total	Air	SnowAm	SnowOc	SnowTrOc	FreezOc	RainAm	RainOcc	Blowing	Threshold	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	28	28	28	28	28	28	28	0	28	88.9%
	Southern Alberta - near Calgary	70	70	70	70	70	70	70	70	70	70	100.0%
Province of Manitoba	Brandon	20	20	20	20	20	20	20	20	18	20	98.9%
	Carberry	18	18	18	18	18	18	18	18	16	18	98.8%
Province of New Brunswick	Fredericton	29	29	28	28	28	29	29	29	29	28	98.5%
	Moncton	29	29	29	29	29	29	29	29	29	29	100.0%
	Saint John	29	29	27	27	27	29	29	29	29	27	96.9%
Province of Newfoundland	Avalon	35	35	35	35	35	35	35	35	5	35	90.5%
	Central	35	35	35	35	35	35	35	35	5	35	90.5%
	Eastern	35	35	35	35	35	35	35	35	5	35	90.5%
	Western	35	35	35	35	35	35	35	35	5	35	90.5%
Province of Nova Scotia	Central	52	51	52	52	52	52	52	52	44	52	98.1%
	Eastern	61	61	61	61	61	61	61	61	52	61	98.4%
	Northern	53	52	53	53	53	53	53	53	45	53	98.1%
	Western	67	66	66	66	66	67	67	67	67	66	99.2%
Province of Ontario	London Area	5	5	5	5	5	5	5	5	0	5	88.9%
	New Liskeard Area	96	89	85	85	85	85	85	85	85	85	89.0%
	Ottawa Area	5	5	5	5	5	5	5	5	5	5	100.0%
Province of Quebec	Chicoutimi	56	56	56	56	56	56	56	56	39	56	96.6%
	Gaspe	65	65	65	65	65	65	65	65	24	65	93.0%
	Hull	41	41	41	41	41	41	41	41	41	41	100.0%
	Montreal	52	52	52	52	52	52	52	52	0	52	88.9%
	Quebec	61	61	61	61	61	59	61	61	0	61	88.5%
	Rouyn-Noranda	42	42	42	42	42	42	42	42	0	42	88.9%
	Sept Iles	29	29	29	29	29	29	29	29	18	29	95.8%
	Sherbrooke	40	40	39	39	39	40	40	40	0	39	87.8%
Province of Saskatchewan	Findlater	18	18	18	18	18	18	18	18	0	18	88.9%
	Regina	18	18	18	18	18	18	18	18	0	18	88.9%
City of Calgary		28	28	28	28	28	28	28	28	27	28	99.6%
City of Edmonton		41	41	41	41	41	41	41	41	0	41	88.9%
City of Halifax		7	7	7	7	7	7	7	7	5	7	96.8%
City of London		6	6	6	6	6	6	6	6	0	6	88.9%
City of Ottawa		16	16	16	16	16	16	16	16	16	16	100.0%
City of Winnipeg		43	43	43	43	43	42	43	43	0	43	88.6%
City of Toronto		11	11	11	11	11	11	11	11	11	11	100.0%
Total		1276	1266	1260	1260	1260	1262	1265	1265	690	1260	93.9%
Total Percentage		**100%**	**99%**	**99%**	**99%**	**99%**	**99%**	**99%**	**99%**	**54%**	**99%**	

Key:

Total - Total Observations
Air - Air Temperature
SnowAm - Snow Accumulation
SnowOc - Snowfall Occurrence
SnowTrOc - Snowfall occurrence (including trace snow)
FreezOc - Freezing Rain/Drizzle Occurrence
RainAm - Rainfall Accumulation
RainOcc - Rainfall Occurrence
Blowing - Blowing Snow Occurrence
Threshold - Threshold Snow Occurrence

APPENDIX B: RWIS DATA

Road Authority	Area	Total Observation Periods	RWIS Observation Periods	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	0	0.0%
	Southern Alberta - near Calgary	70	18	25.7%
Province of Manitoba	Brandon	20	0	0.0%
	Carberry	18	0	0.0%
Province of New Brunswick	Fredericton	29	0	0.0%
	Moncton	29	0	0.0%
	Saint John	29	0	0.0%
Province of Newfoundland	Avalon	35	8	22.9%
	Central	35	0	0.0%
	Eastern	35	8	22.9%
	Western	35	0	0.0%
Province of Nova Scotia	Central	52	7	13.5%
	Eastern	61	0	0.0%
	Northern	53	2	3.8%
	Western	67	15	22.4%
Province of Ontario	London Area	5	0	0.0%
	New Liskeard Area	96	27	28.1%
	Ottawa Area	5	5	100.0%
Province of Quebec	Chicoutimi	56	0	0.0%
	Gaspe	65	0	0.0%
	Hull	41	0	0.0%
	Montreal	52	10	19.2%
	Quebec	61	14	23.0%
	Rouyn-Noranda	42	0	0.0%
	Sept Iles	29	0	0.0%
	Sherbrooke	40	5	12.5%
Province of Saskatchewan	Findlater	18	8	44.4%
	Regina	18	8	44.4%
City of Calgary		28	18	64.3%
City of Edmonton		41	0	0.0%
City of Halifax		7	3	42.9%
City of London		6	0	0.0%
City of Ottawa		16	13	81.3%
City of Winnipeg		43	0	0.0%
City of Toronto		11	0	0.0%
Total Percentage		**1276**	**169**	**13.2%**

APPENDIX C: STATISTICAL METHODOLOGY

LOCAL CALIBRATION

The national model was calibrated to local geographic areas within Canada. This was done for the model shown in Table 5.6 in the report, using MSC data only, as there was insufficient data to conduct the calibration for the second model using both MSC and RWIS data.

This section provides an approach for updating the calibrated national model to local geographic areas since only limited data are available for calibrating a meaningful model for each geographic area. Generally, the updating technique is helpful in applying an estimated model in a specific region for prediction in a different one with minimum data requirements, consequently cutting the cost of data collection. Also, it seems desirable, when transferring a model, to update it by making adjustments based on locally available information.

Prior to updating the national model for each area, the various geographic areas were evaluated for their homogeneity based on their observed salt usage (salt (t)/lane-km/days) and similarity in their climatic zone. The reason for the groupings was to avoid bias that could be encountered because of the small available sample size for each area.

To accomplish this, a t-test was conducted using the mean and standard deviation of observed salt used for each two areas. In this test, the null hypothesis is that the sample means for two geographic areas are the same. It was assumed that the population variances for both samples (i.e., geographic areas) are unknown and are not equals to each other. The t-statistic can be expressed as follows:

$$t_0^* = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{S_1^2/n_1 + S_2^2/n_2}} \tag{1}$$

With degrees of freedom is given by:

$$\nu = \frac{\left(S_1^2/n_1 + S_2^2/n_2\right)^2}{\dfrac{\left(S_1^2/n_1\right)^2}{n_1 - 1} + \dfrac{\left(S_2^2/n_2\right)^2}{n_2 - 1}} \tag{2}$$

where the $\overline{X}_i$ and Si is the mean and standard deviation of the sample, respectively. If $|t_0^*| > |t_{\alpha/2,\nu}|$, then null hypothesis can be rejected.

On the basis of this process, a total of twenty calibration groups were developed representing various combinations of provincial districts and urban road authorities. The next step involved updating the national model to reflect the local geographic area under consideration.

The updating procedures examined are the Bayesian updating and updating based on recalibration factors. Moreover, the parameters of national model were used for calibrating of model for each group.

Updating Using a Calibration Factor

The updating procedure was recommended by Harwood et al. and a recent paper by Oh et al., for application in the Interactive Highway Safety Design Model (IHSDM) for transferring accident prediction models calibrated for one geographic region to apply to another region. In this procedure, a calibration factor can be obtained as the total observed salt usage of a group divided by the sum of the predicted salt usage for the group using the national model. The calibration factor can be expressed as follows:

$$Calibration\ Factor = \sum_{i=1}^{n} Y_i \Big/ \sum_{i=1}^{n} \hat{Y}_i \tag{3}$$

Y_i= Observed amount of salt usage for period of i in each group

$\hat{Y}_i$= Predicted amount of salt usage for period of i by using the national model in each group.

Then, the calibration factors estimated for each group were simply multiplied by the national model in order to update the national model for application to local conditions. However, after exploring the results obtained from this procedure, this method was not used for the updating process since the goodness of fits obtained from these models was not satisfactory.

Local Calibration of the National Model

The second method considered was calibrating the individual model parameters independent of the national results. This method did improve the goodness of fit in some of the jurisdictions, however, some of the parameter estimates changed substantially, producing results that were counterintuitive (i.e. a negative parameter estimate for snow occurrence, meaning that snowfall had a negative relationship with salt usage in the model) due to lack of representative data. For this reason, this method was rejected.

Bayesian Updating

Bayesian updating, which was introduced by Atherton and Ben-Akiva, is another approach that is adopted for updating the national model for application to local conditions for each group. This methodology combines sample information with prior information in order to achieve more accurate updated information. Atherton and Ben-Akiva assumed both prior and posterior (updated) distributions of the parameters to be normally distributed. The Bayesian method combines the information from the national model with the information obtained from calibration of local model in order to achieve more accurate updated information. The updated parameters are expressed as

$$\beta_{updated} = [(\beta_n / S_n^2) + (\beta_n / S_n^2)/[(1/S_n^2) + (1/S_l^2)] \tag{4}$$

$$S_{updated} = 1/[(1/S_n^2) + (1/S_l^2)]^{0.5} \tag{5}$$

$\beta_{updated}$ = Updated coefficient
β_n = Coefficient estimated from the national model

β_l = Coefficient estimated from calibration of local model
$S_{updated}$ = Standard deviation of updated coefficient
S_n = Standard deviation of coefficient estimated from the national model
S_l = Standard deviation of coefficient estimated from calibration of local model

The results generated using the Bayesian approach improved on the national results yet did not produce any counterintuitive results. Therefore, the Bayesian method was used to calibrate the results of the national model to the local results.

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Harwood, D. W., Council, M., Hauer, E., Hughes, W. E., and Vogt, A., *Prediction of The Expected Safety Performance of Rural Two-Lane Highways*. Report FHWA-RD-99-207, FHWA, Department of Transportation, Washington, D.C., 2003.

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APPENDIX A: MSC DATA

Road Authority	Area	Total	Air	SnowAm	SnowOc	SnowTrOc	FreezOc	RainAm	RainOcc	Blowing	Threshold	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	28	28	28	28	28	28	28	0	28	88.9%
	Southern Alberta - near Calgary	70	70	70	70	70	70	70	70	70	70	100.0%
Province of Manitoba	Brandon	20	20	20	20	20	20	20	20	18	20	98.9%
	Carberry	18	18	18	18	18	18	18	18	16	18	98.8%
Province of New Brunswick	Fredericton	29	29	28	28	28	29	29	29	29	28	98.5%
	Moncton	29	29	29	29	29	29	29	29	29	29	100.0%
	Saint John	29	29	27	27	27	29	29	29	29	27	96.9%
Province of Newfoundland	Avalon	35	35	35	35	35	35	35	35	5	35	90.5%
	Central	35	35	35	35	35	35	35	35	5	35	90.5%
	Eastern	35	35	35	35	35	35	35	35	5	35	90.5%
	Western	35	35	35	35	35	35	35	35	5	35	90.5%
Province of Nova Scotia	Central	52	51	52	52	52	52	52	52	44	52	98.1%
	Eastern	61	61	61	61	61	61	61	61	52	61	98.4%
	Northern	53	52	53	53	53	53	53	53	45	53	98.1%
	Western	67	66	66	66	66	67	67	67	67	66	99.2%
Province of Ontario	London Area	5	5	5	5	5	5	5	5	0	5	88.9%
	New Liskeard Area	96	89	85	85	85	85	85	85	85	85	89.0%
	Ottawa Area	5	5	5	5	5	5	5	5	5	5	100.0%
Province of Quebec	Chicoutimi	56	56	56	56	56	56	56	56	39	56	96.6%
	Gaspe	65	65	65	65	65	65	65	65	24	65	93.0%
	Hull	41	41	41	41	41	41	41	41	41	41	100.0%
	Montreal	52	52	52	52	52	52	52	52	0	52	88.9%
	Quebec	61	61	61	61	61	59	61	61	0	61	88.5%
	Rouyn-Noranda	42	42	42	42	42	42	42	42	0	42	88.9%
	Sept Iles	29	29	29	29	29	29	29	29	18	29	95.8%
	Sherbrooke	40	40	39	39	39	40	40	40	0	39	87.8%
Province of Saskatchewan	Findlater	18	18	18	18	18	18	18	18	0	18	88.9%
	Regina	18	18	18	18	18	18	18	18	0	18	88.9%
City of Calgary		28	28	28	28	28	28	28	28	27	28	99.6%
City of Edmonton		41	41	41	41	41	41	41	41	0	41	88.9%
City of Halifax		7	7	7	7	7	7	7	7	5	7	96.8%
City of London		6	6	6	6	6	6	6	6	0	6	88.9%
City of Ottawa		16	16	16	16	16	16	16	16	16	16	100.0%
City of Winnipeg		43	43	43	43	43	42	43	43	0	43	88.6%
City of Toronto		11	11	11	11	11	11	11	11	11	11	100.0%
Total		1276	1266	1260	1260	1260	1262	1265	1265	690	1260	93.9%
Total Percentage		**100%**	**99%**	**99%**	**99%**	**99%**	**99%**	**99%**	**99%**	**54%**	**99%**	

Key:

Total - Total Observations
Air - Air Temperature
SnowAm - Snow Accumulation
SnowOc - Snowfall Occurrence
SnowTrOc - Snowfall occurrence (including trace snow)
FreezOc - Freezing Rain/Drizzle Occurrence
RainAm - Rainfall Accumulation
RainOcc - Rainfall Occurrence
Blowing - Blowing Snow Occurrence
Threshold - Threshold Snow Occurrence

APPENDIX B: RWIS DATA

Road Authority	Area	Total Observation Periods	RWIS Observation Periods	Percentage
Province of Alberta	Northern Alberta - Hangingstone	28	0	0.0%
	Southern Alberta - near Calgary	70	18	25.7%
Province of Manitoba	Brandon	20	0	0.0%
	Carberry	18	0	0.0%
Province of New Brunswick	Fredericton	29	0	0.0%
	Moncton	29	0	0.0%
	Saint John	29	0	0.0%
Province of Newfoundland	Avalon	35	8	22.9%
	Central	35	0	0.0%
	Eastern	35	8	22.9%
	Western	35	0	0.0%
Province of Nova Scotia	Central	52	7	13.5%
	Eastern	61	0	0.0%
	Northern	53	2	3.8%
	Western	67	15	22.4%
Province of Ontario	London Area	5	0	0.0%
	New Liskeard Area	96	27	28.1%
	Ottawa Area	5	5	100.0%
Province of Quebec	Chicoutimi	56	0	0.0%
	Gaspe	65	0	0.0%
	Hull	41	0	0.0%
	Montreal	52	10	19.2%
	Quebec	61	14	23.0%
	Rouyn-Noranda	42	0	0.0%
	Sept Iles	29	0	0.0%
	Sherbrooke	40	5	12.5%
Province of Saskatchewan	Findlater	18	8	44.4%
	Regina	18	8	44.4%
City of Calgary		28	18	64.3%
City of Edmonton		41	0	0.0%
City of Halifax		7	3	42.9%
City of London		6	0	0.0%
City of Ottawa		16	13	81.3%
City of Winnipeg		43	0	0.0%
City of Toronto		11	0	0.0%
Total Percentage		**1276**	**169**	**13.2%**

APPENDIX C: STATISTICAL METHODOLOGY

LOCAL CALIBRATION

The national model was calibrated to local geographic areas within Canada. This was done for the model shown in Table 5.6 in the report, using MSC data only, as there was insufficient data to conduct the calibration for the second model using both MSC and RWIS data.

This section provides an approach for updating the calibrated national model to local geographic areas since only limited data are available for calibrating a meaningful model for each geographic area. Generally, the updating technique is helpful in applying an estimated model in a specific region for prediction in a different one with minimum data requirements, consequently cutting the cost of data collection. Also, it seems desirable, when transferring a model, to update it by making adjustments based on locally available information.

Prior to updating the national model for each area, the various geographic areas were evaluated for their homogeneity based on their observed salt usage (salt (t)/lane-km/days) and similarity in their climatic zone. The reason for the groupings was to avoid bias that could be encountered because of the small available sample size for each area.

To accomplish this, a t-test was conducted using the mean and standard deviation of observed salt used for each two areas. In this test, the null hypothesis is that the sample means for two geographic areas are the same. It was assumed that the population variances for both samples (i.e., geographic areas) are unknown and are not equals to each other. The t-statistic can be expressed as follows:

$$t_0^* = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{S_1^2/n_1 + S_2^2/n_2}} \quad (1)$$

With degrees of freedom is given by:

$$\nu = \frac{\left(S_1^2/n_1 + S_2^2/n_2 \right)^2}{\frac{\left(S_1^2/n_1 \right)^2}{n_1 - 1} + \frac{\left(S_2^2/n_2 \right)^2}{n_2 - 1}} \quad (2)$$

where the $\overline{X}_i$ and Si is the mean and standard deviation of the sample, respectively. If $|t_0^*| > |t_{\alpha/2,\nu}|$, then null hypothesis can be rejected.
On the basis of this process, a total of twenty calibration groups were developed representing various combinations of provincial districts and urban road authorities. The next step involved updating the national model to reflect the local geographic area under consideration.

The updating procedures examined are the Bayesian updating and updating based on recalibration factors. Moreover, the parameters of national model were used for calibrating of model for each group.

Updating Using a Calibration Factor

The updating procedure was recommended by Harwood et al. and a recent paper by Oh et al., for application in the Interactive Highway Safety Design Model (IHSDM) for transferring accident prediction models calibrated for one geographic region to apply to another region. In this procedure, a calibration factor can be obtained as the total observed salt usage of a group divided by the sum of the predicted salt usage for the group using the national model. The calibration factor can be expressed as follows:

$$Calibration\,Factor = \sum_{i=1}^{n} Y_i \Big/ \sum_{i=1}^{n} \hat{Y}_i \qquad (3)$$

Y_i= Observed amount of salt usage for period of i in each group

$\hat{Y}_i$= Predicted amount of salt usage for period of i by using the national model in each group.

Then, the calibration factors estimated for each group were simply multiplied by the national model in order to update the national model for application to local conditions. However, after exploring the results obtained from this procedure, this method was not used for the updating process since the goodness of fits obtained from these models was not satisfactory.

Local Calibration of the National Model

The second method considered was calibrating the individual model parameters independent of the national results. This method did improve the goodness of fit in some of the jurisdictions, however, some of the parameter estimates changed substantially, producing results that were counterintuitive (i.e. a negative parameter estimate for snow occurrence, meaning that snowfall had a negative relationship with salt usage in the model) due to lack of representative data. For this reason, this method was rejected.

Bayesian Updating

Bayesian updating, which was introduced by Atherton and Ben-Akiva, is another approach that is adopted for updating the national model for application to local conditions for each group. This methodology combines sample information with prior information in order to achieve more accurate updated information. Atherton and Ben-Akiva assumed both prior and posterior (updated) distributions of the parameters to be normally distributed. The Bayesian method combines the information from the national model with the information obtained from calibration of local model in order to achieve more accurate updated information. The updated parameters are expressed as

$$\beta_{updated} = [(\beta_n / S_n^2) + (\beta_n / S_n^2)/[(1/S_n^2) + (1/S_l^2)] \qquad (4)$$

$$S_{updated} = 1 \big/ [(1/S_n^2) + (1/S_l^2)]^{0.5} \qquad (5)$$

$\beta_{updated}$ = Updated coefficient
β_n = Coefficient estimated from the national model

β_l = Coefficient estimated from calibration of local model
$S_{updated}$ = Standard deviation of updated coefficient
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The results generated using the Bayesian approach improved on the national results yet did not produce any counterintuitive results. Therefore, the Bayesian method was used to calibrate the results of the national model to the local results.

References

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