Embargoed for U.S. public release until January 29th at 10:00 am EST

Safety Impacts of Using Deicing Salt

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Executive Summary

Significant research efforts have been devoted to quantifying the safety and mobility impacts of winter weather and developing cost-effective snow and ice control strategies and methods. However, most of these efforts have not reached to the level of understanding that is required to support decision-making at both operational and strategic levels. The goal of this research is to conduct a systematic investigation aimed at addressing this knowledge gap.

This report summarizes the results of an analysis performed on a set of collision data over six winter seasons (2000-2006) from 31 sections of highways in the province of Ontario. Several statistical models were developed to evaluate the association between road safety and winter road maintenance treatments and other factors. The main findings from the models and case studies are summarized as follows.

Factors Affecting Winter Road Safety

- Most results obtained from this research with respect to winter road safety are consistent with those reported in the literature, with a few exceptions. The severer the storm conditions are, as indicated by temperature, visibility, wind speed and precipitation, the higher is the expected number of collisions.

- The most interesting result is that the road surface condition index (RSI) was found to be a statistically significant factor influencing road safety across all sites, models and functional forms. It is the most influential risk factor with a 10% improvement in road surface conditions could lead to 20% reduction in mean number of collisions. RSI is a surrogate measure of road surface conditions and can thus be used to capture the effects of winter road maintenance operations, making it feasible to quantify the safety benefit of alternative maintenance policies and methods.

- Visibility and precipitation were found to be the next most prominent factors influencing road safety under adverse weather conditions. A 10% reduction in visibility or increase in precipitation rate could result in almost 5% and 0.2% increase in the mean number of collisions, respectively. Wind speed and temperature were also found to be statistically significant collision risk factors; however, the magnitude of their effects was much less as compared to other factors.

Benefits of Salting

- The collision models developed in this research provide a new way of quantifying the safety effect of winter road maintenance operations such as salting and plowing. By controlling for the external factors such as weather, road geometry and traffic, their potential confounding effects on the benefit estimates could be minimized. The modeling results has provided clear evidence on the safety benefit of salt application, reducing collisions from 20% to as high as over 85%, depending on the base conditions when salt is applied and the improved conditions due to the deicing effect of salt.

- Two case studies were conducted to illustrate the application of the developed models for evaluating the safety benefit of maintenance operations at an operational level involving a particular section of highway and snowstorm event. It is also shown that, instead of relative reduction, the absolute benefit could also be determined using the developed models, which is a function of the type of highway being considered (e.g., traffic volume) as well as other weather variables such as precipitation, visibility, wind speed and temperature.

- An analysis similar to the Marquette study was also performed using the Ontario data. Two different types of events were extracted from the main database– events where either salting was the sole operation or events where salting was applied in conjunction with plowing. The former allows us to gauge the sole effects of salting operations on winter road safety. An overall reduction of 51% was observed in the collision rate before and after salt application while a total of 65% reduction was associated with the combo operations of plowing and salting. While these benefit estimates are lower than those obtained by the Marquette study (which showed over 78% reduction in collisions on freeways and 87% reduction on two-lane highways), this analysis has nevertheless confirmed the overall findings of the Marquette study.

1. INTRODUCTION

Winter storms have a significant impact on the safety and mobility of highways. Past research indicates that highway collision rates during a snowstorm increase considerably as compared to a non-winter storm season (Andrey and Knapper 2003). Slippery road conditions and poor visibility during a winter storm also create unbearable travel environments for travelers and cause substantial delay due to reduced traffic speed and road capability and increased collisions.

To reduce the impacts of winter storms, transportation agencies spend significant resources every year to keep roads and highways clear of snow and ice for safe and smooth travel conditions. For example, Canada expends $1 billion each year on winter road maintenance, which includes the application of five million tons of salts (Transport Association of Canada, 2003). In the US, the total cost of winter road maintenance is approximately $2 billion per year. Salt use has recently raised significant concerns due to their potential damages to the environment, the road side infrastructure, and the vehicles.

While it is commonly agreed that winter road maintenance (salt) is beneficial to both safety and mobility of highways, it is however unclear about the magnitude of this benefit and the factors that influence this benefit. This knowledge gap makes it difficult to address the question of what should be the optimal amount of maintenance work (or salt) being applied for a given highway or jurisdiction under particular winter conditions.

Many attempts have been made in the past to address this knowledge gap. Most of those studies have however focused on the general impacts of winter storms on road safety and mobility. For example, Knapp et al. (2000) investigated the effects of winter storms on mobility and safety using data from a freeway section in Iowa. Their study found that the average collision rate increased by several orders of magnitude during storm events and the degree of impacts depended on storm duration, snowfall intensity and wind speed. Recently, Andrey and Knapper (2003) investigated the effects of weather on the transportation system at a national level. Note that these studies did not look into the particular issue of how winter road maintenance work affects road safety and therefore may underestimate the true effect of winter storms.

As synthesized by Wallman et al. (1997), most past studies on the effect of winter road maintenance have shown significant benefits in reducing collision rate and severity. For example, an extensive study in Germany (Hanke and Levin, 1989) showed the average collision rate dropped by 73% within two hours of salt applications. Hanbali and Kuemmel (1993) conducted a similar analysis on traffic crash rates before and after salt application on two types of highway, namely, two-lane two-way highways and freeways in several US states. They found an average of 85% reduction in traffic crashes and an 88.3% reduction in injury-causing collisions just within a few short hours of applying salt. Similar findings were observed in several Swedish and Nordic investigations (Wallman et al. 1997).

A scientific approach to achieving optimal balance of keeping road safe and environmental effect minimal requires a better understanding of the relationship between highway performance, such as collision rates and traffic delay, and maintenance operations under a variety of storm and road surface conditions. The primary goal of this research is to quantify the safety benefit of winter road maintenance operations such as salting in the Canadian environment with field data from Ontario, Canada. To ensure the validity of the results, the research will attempt to account for other confounding factors such as storm characteristics (e.g., temperature, precipitation, and wind speed) and road and traffic characteristics (e.g. classification, speed, volume), in addition to maintenance operations. The research includes the following three main objectives:

1) Conduct a thorough and critical review of past studies on the effects of winter road maintenance on road safety;
2) Investigate the collision frequency and severity patterns before and after various specific maintenance operations, such as plowing and salting, during individual winter snow storms;
3) Develop statistical models for quantifying the safety benefit of winter road maintenance and identifying the major factors that influence this benefit;

2. LITERATURE REVIEW

Significant past efforts have been directed towards road safety problems in general and winter road safety in particular. This section provides a review of studies that focused specifically on the effect of winter road maintenance on road safety. For other general winter road safety issues and research, readers are referred to Andrey et al. (2001), Shankar et al. (1995), Hermans et al. (2006), Nixon and Qiu (2008), and Qin et al. (2007) etc.

Weather has both direct and indirect impacts on highway safety. According to Ontario Road Safety Annual Report (MTO, 2002), in spite of the rare occurrence of adverse weather in daily traffic, many crashes occurred during rainfall and snowfall in Ontario (11.4 percent and 10.6 percent of total crashes, respectively). Also, crashes that occurred on wet and snowy road surface account for high proportions of total crashes (19.0 percent and 14.1 percent, respectively). This is because adverse weather reduces the friction between vehicles and the road surface and visibility, and drivers are more likely to misjudge prevailing friction conditions (Wallman et al, 1997). A similar trend was observed in the United States where over 22 percent of total crashes were weather-related, of which 49 percent and 13 percent occurred during rainfall and snowfall respectively (Goodwin, 2002).

Nilsson and Obrenovic (1998) found that drivers are twice as much likely to be involved in a collision in winter than in summer for the given distance of travel. Wallman et al. (1997) observed that more crashes tend to occur at the beginning of a winter season and when there are fewer snowy road conditions. However, some past studies have also concluded that snowfall-related crashes tend to be less severe than those under other weather conditions (Andrey et al., 2003). One possible explanation provided for this finding is that vehicles tend to travel slower under snow storm conditions than normal weather conditions (Knapp et al., 2000).

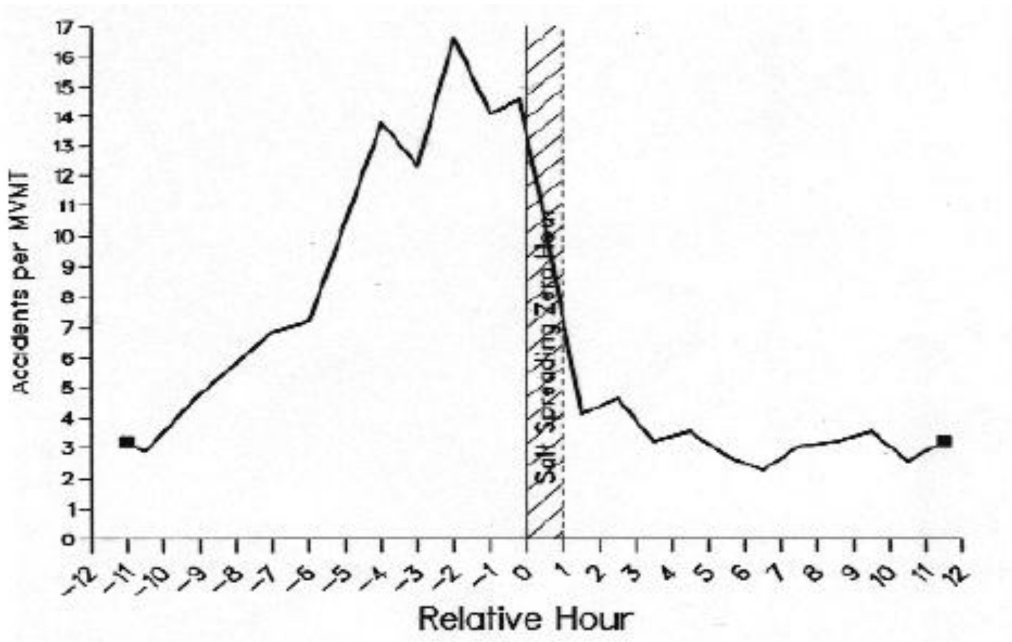
A study by Iowa State University (Knapp and Smithson, 2000) focuses on the effects of winter storms on traffic safety for a 48-km long highway section in Iowa. They concluded that crashes are more likely to occur during storm event time periods (2 crashes/event) than non-storm event time periods (0.65 crashes/event). However, this study limited the scope of winter storms to those storm events with more than 4-hour duration and more than 0.51 cm/hour snowfall intensity. Also, their analysis did not consider whether or not winter maintenance activities had been performed during or after storm events.

Khattak et al. (2000) found that there is a close relationship between crash frequency and characteristics of storm events such as snowfall intensity, snow fall duration, and maximum wind gust speed. They also considered the effect of exposure (i.e. number of vehicles during a snowfall event on a highway section under the same weather condition) and found that a snowfall event reduces traffic volume (i.e. exposure to hazardous road conditions) which results in a higher crash rate.

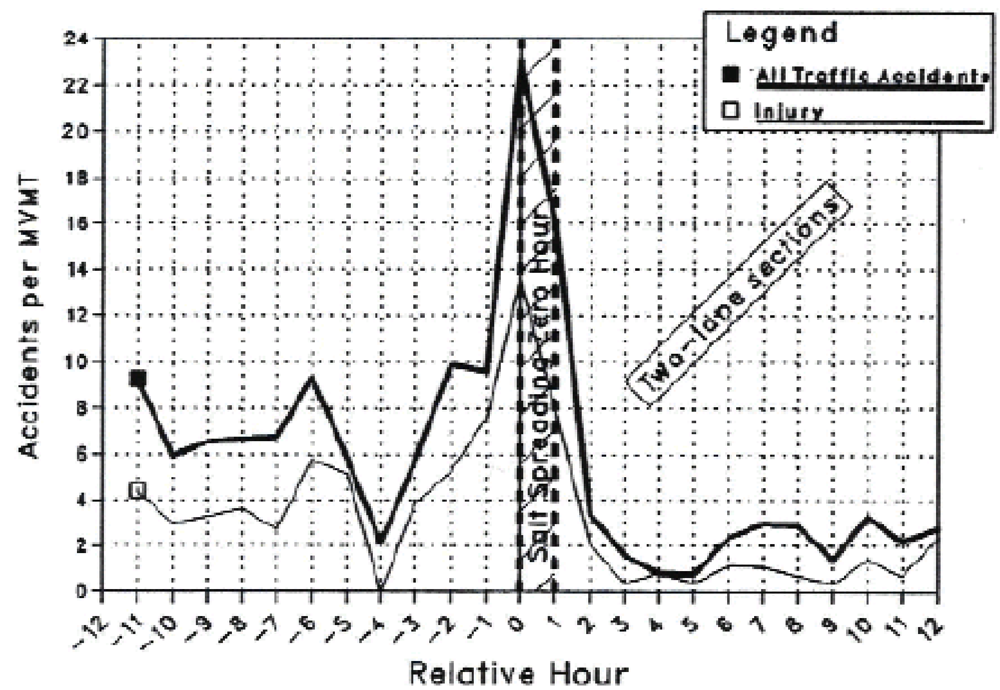
Note that these studies had mainly focused on the effects of the characteristics of storm events on crash risk and the effects of "controllable" variables such as maintenance operations on preventing or reducing crashes during winter storm events were not considered.

There are abundant empirical evidences showing that winter road maintenance significantly improves road safety. Quantitative investigations on this subject were however scarce. One of the first documented studies in the literature on the effect of winter road maintenance on road safety was performed by the Technical University of Darmstadt in Germany (Hanke and Levin, 1989). The study involved a statistical analysis of collisions before and after salt applications on 650 kilometres of roads in suburban and rural areas. The main finding of this research is reflected in the well cited illustration shown in **Figure 2-1**.

Hanbali and Kuemmel (1992) from Marquette University conducted a similar study applying the same methodology as the German study (Hanke and Levin, 1989) using collision data from 570 miles of divided and undivided roads from New York, Minnesota, and Wisconsin. Their analysis corroborated the German study and concluded that significant reductions in collisions were observed after salting operations. The average reduction in collision rates was 87% and 78% for two-lane undivided highways and freeways, respectively. It should be noted that the before-after analysis approach taken by these two studies did not take into account the confounding effects of many important factors, such as precipitation, temperature, and visibility, which vary over events and before and after salt applications. As a result, they may over or under estimate the benefit of winter maintenance operations (including salting), which is expected to vary by external conditions such as highway features, storm characteristics and maintenance treatments.



(a) German Study



(b) Marquette University Study

Figure 2-1: Traffic Collision Rates Before and After Salt Spreading (Source: Salt Institute)

Norrman et al. (2000) conducted a more elaborated study to quantify the relationship between road safety and road surface conditions. In their study, they classified road surface conditions into ten different types based on slipperiness, and then compared the crash rates associated with the different road surface types. They defined collision risk for a specific road surface condition type, as the ratio of the collision rate under a road surface condition to the expected number of collisions. The collision risk computed was then compared to the percentage of maintenance activities performed. They concluded that, in general, increased maintenance was associated with decreased number of collisions. However, their approach has several limitations. Firstly, it is an aggregate analysis in nature, considering roads of all classes and locations together. This approach may mask some important factors that affect road safety, such as road class and geometrical features, traffic, and local weather conditions. Secondly, the simple categorical method of determining crash rates may introduce significant biases if confounding factors exist, which is likely to be the case for a system as complex as highway traffic. Furthermore, the procedure cannot be used to quantify the safety effects of different maintenance operations.

Fu et al. (2006) investigated the relationship between road safety and various weather and maintenance factors, including air temperature, total precipitation, and type and amount of maintenance operations. Two sections of Highway 401 were considered. They used the generalized linear regression model (Poisson distribution) to analyze the effects of different factors on safety. They concluded that anti-icing, pre-wet salting with plowing and sanding have statistically significant effects on reducing the number of collisions. Both temperature and precipitation were found to have a significant effect on the number of crashes. Their study also presents several limitations. First, the data used in their study were aggregated on a daily basis, assuming uniform road weather conditions over entire day for each day (record). Secondly, their study did not account for some important factors due to data problems, such as traffic exposure and road surface conditions. Furthermore, the data available for their analysis covered only nine winter months and thus the power of the resulting model needs to be further validated. One of the implications of these limitations is that their results may not be directly applicable for quantifying the safety benefit of winter road maintenance of other highways or maintenance routes.

The Swedish Road and Traffic Road Institute (VTI) had investigated the relationship between winter road safety and road maintenance for many years with most of the findings summarized in a reviewing report completed by Wallman et al. (1997). Many original research reports cited by Wallman et al. (1997) were written in Swedish and could not be included for a detailed discussion in this literature review. The following summarizes the findings from several major studies documented by Wallman et al. (1997):

- The collision rate reached its maximum one hour before the maintenance action and the collision rate was reduced by 50 percent a half-hour after the action. The number of collisions was reduced to 1/6 6-12 hours after winter maintenance was implemented. They also cited that the numbers of collisions were reduced to 1/5~1/14 and 1/8 after maintenance was carried out in Germany and U.S., respectively. These findings demonstrate that winter road maintenance does improve road conditions and lower crash risk.
- Some before-after studies and parallel comparisons of similar roads with different maintenance intensities indicated that the effects of road salt with regard to road safety could not be statistically confirmed. It had been reported that reduction in crash frequency was not in proportion to the improvement in road conditions. Many studies attributed these counter-intuitive results to the road user's risk compensation behavior, that is, road users utilize the increase in road friction (e.g. due to salting) by increasing their speed.
- It has been observed that preventive salting (anti-icing) was more effective in reducing the crash rate than conventional salting.

In summary, a number of past studies have been dedicated to the issue of winter road safety. However, most of these studies have focused either on the effect of weather only or suffered some methodological issues, with the following specific limitations:

- Most research relied on data that were either incomplete or aggregated. For example, many studies have used aggregated seasonal and yearly average for weather and traffic conditions because daily and hourly weather and traffic counts were not available. Also, road condition data and collision reports obtained from different organizations were not consistent with each other.
- Most investigations cover large regions with large spatial (e.g. cities, provinces) and temporal (e.g. daily, seasonal, annual) analysis units. Such macro-level analysis cannot take into account local variations in weather and road conditions, traffic and maintenance operations.
- Very little empirical evidence exists in literature regarding the effects of winter road maintenance treatments on road safety, mostly, due to the fact that detailed maintenance records were not available.
- Most findings and results reported in literature were obtained directly from observations with naive before-after analysis with few resulting from systematic statistical analysis.

To cope with these problems, this research proposed a disaggregate methodology to investigate the relationship between winter road safety and winter road maintenance activities. Patrol route (road section maintained by a single contractor for maintenance purpose) is used as the spatial level of analysis and snow storm event or hourly observations (within the snow storm event) as the temporal unit of analysis. The following section provides a detailed description of the methodology adopted and the data used.

3. METHODOLOGY AND DATA

3.1 OVERVIEW OF METHODOLOGY

A statistical modeling approach is proposed to investigate the relationship between winter road safety and various influencing factors, including maintenance operations (e.g., salting). **Figure 3-1** shows the steps being followed in the development of these statistical models, including:

1) Selection of Study Sites: this is done on the basis of the availability of weather & road surface, traffic and collision data.
2) Data Processing and Integration: data from the different sources are compiled and subsequently integrated into a single cross-sectional, hourly-based dataset using location and time as the references.
3) Exploratory Data Analysis and Model Development: an exploratory data analysis is first performed for understanding the data and identifying the qualitative patterns. Statistical models are then developed for quantitative relationship between the road safety indicators (e.g., expected collision frequency) and various external factors.
4) Model Application: the developed models are lastly applied for assessing the effects of salting or generally winter road maintenance operations on road safety.

A detailed discuss on these individual steps is provided in the following sections.

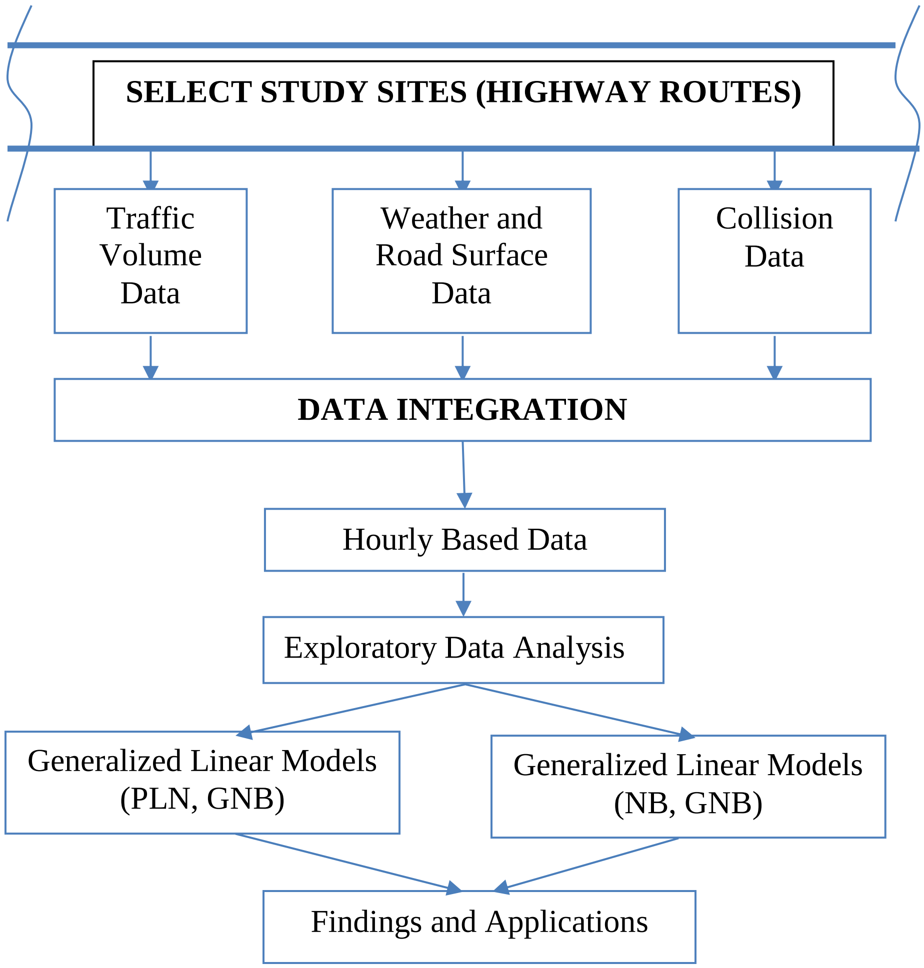


Figure 3-1: Methodology

3.2 STATISTICAL MODELS

In road safety literature, the most commonly employed approach for quantifying the effects of different factors on road safety is the generalized linear regression analysis. Specifically, the negative binomial (NB) model and its extensions have been widely used for modeling road collisions (Hauer 1997; Miranda-Moreno 2006). In this research, we have adopted the same modeling approach. Specifically, two alternative models are considered, including multilevel Poisson lognormal model (PLN) and generalized negative binomial (GNB) model (Miaou and Lord 2003; Miranda-Moreno et al 2005; Miranda-Moreno 2006). These models allow more flexibility than the basic NB model in dealing with the well-known over-dispersion problem and unobserved heterogeneities in collision data.

The PLN model differs from NB model in the sense that a lognormal distributed error term (instead of gamma distribution) is added to the Poisson model to capture the unobserved heterogeneity. This model also has the advantage that can be easily extended to deal with data of multi-level nature, which is the case with the data we have. As detailed in the following section, the hourly collision data over individual snow storms is longitudinal in nature with the hourly records within each storm forming a set of repeated measurements over time, and the number of time periods being constant for each observation site (route). The potential within-storm correlation issue can be addressed by this model structure (Usman et al 2012; Miranda-Moreno 2006; Miranda-Moreno and Fu 2006). Moreover, the lognormal tails are known to be asymptotically heavier than those of the Gamma distribution (Kim et al 2002). This can be the case when working with dataset in the presence of outliers (Winkelmann 2003).

In a multilevel setting, a PLN model for the hourly observations at the event level can be represented by **Equation 3 – 1** and **3 – 2**.

$$Y_{im} \sim \text{Poisson}\ (\theta_{im}), \text{ with } \ln(\theta_{im}) = \mu_{im} + \gamma_m + \varepsilon_{im} \qquad \textbf{(3 – 1)}$$

Where, θ_{im} and μ_{im} are defined as the number and mean number of collisions in hour i belonging or nested in the storm *m*. In addition, γ_m is a patrol route-level random effect, following a Normal distribution, i.e., $\gamma_m \sim N(0, \tau_2)$ and ε_{im} is the model error - also normal distributed, $\varepsilon_{im} \sim N(0, \zeta)$. Note that ε_{im} represents all the unobserved heterogeneities or random variations that are not captured by γ_m; while, γ_m represents event-level unobserved factors controlling for the potential within-event correlation. In this case, the equation for the mean collision frequency has the following functional form:

$$\mu_{im} = (Exposure_m)^{\beta_1} \exp(\beta_0 + \beta_2 x_{i1m} + \beta_3 x_{i2m} + \cdots + \beta_k x_{ikm}) \qquad \textbf{(3 – 2)}$$

These models are then calibrated using the data set in the following section.

3.2 DATA SOURCES AND DATA INTEGRATION

There are a large number of factors that influence the safety of a highway under winter conditions (Andrew and Bared 1998; Miaou et al 2003). The major factors affecting winter road safety can be grouped into three categories, namely, weather characteristics, traffic, and maintenance operations, as schematically illustrated in **Figure 3-2** (Usman et al 2010).

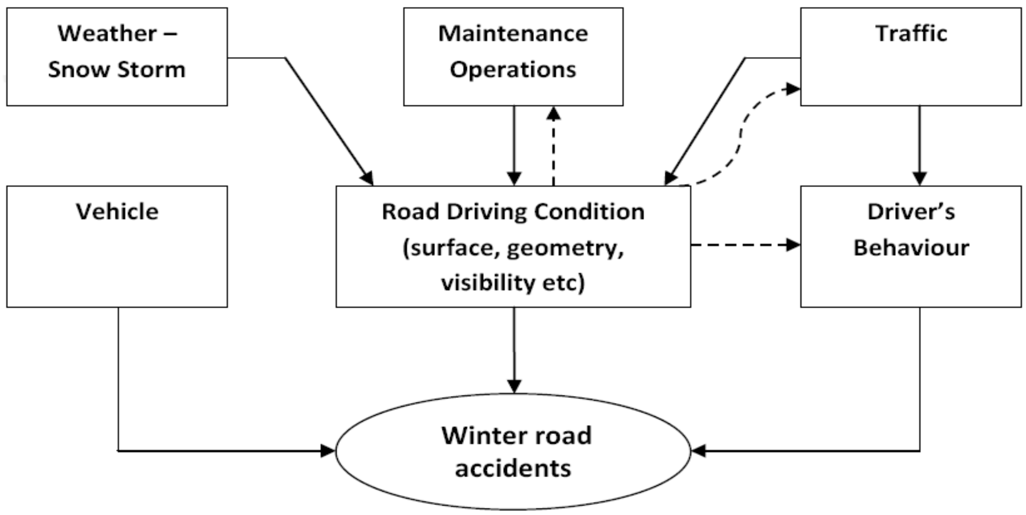


Figure 3-2: Relation between Weather, Traffic Maintenance, and Safety

Models can be developed by establishing a relationship between collision frequency and these factors. Analyses could be performed at an aggregate level, e.g., event-based analysis (Usman et al 2010) or at disaggregate level, e.g., hourly-based analysis (Usman et al 2012). This report describes the latter approach with the following five steps:

- Selection of study sites
- Data source identification (traffic, weather, maintenance and collision data)
- Data processing (hourly data and storm-event data)
- Modeling road surface conditions
- Exploratory data analysis and development of statistical models

Study Sites

MTO has divided the province of Ontario into five different regions, namely, Central (CR), Eastern (ER), South-West (SWR), North-West (NWR) and North-East (NER). These regions are further subdivided into different contract areas. Each contract area contains multiple patrols and each patrol covers different routes. A route covered by a patrol for a particular highway is known as "patrol route" for that highway. Spatially, highway sections designated by these patrol routes are selected as the basic analysis units. To fulfil the purpose of this research a temporal aggregation level of one hour is considered as the minimum analysis unit. It was found that detailed hourly traffic data is not available for all the sites/patrol routes. Accordingly sites were selected where such data was available. Based on traffic data availability, a set of 34 sites were selected which were further reduced to 31 due to data unavailability from other data sources. Details of the selected sites are given in **Table 3-1** and **Figure 3-3**.

Table 3-1: Summary of Study Sites

Highway Class	No. of Sites (Routes)	Total Length	AADT Range
Freeway	17	753.6	14,600 to 430,000
4-lane Highway	3	127.71	5,000 to 129,000
2-lane Highway	11	874.1	400 to 17,700

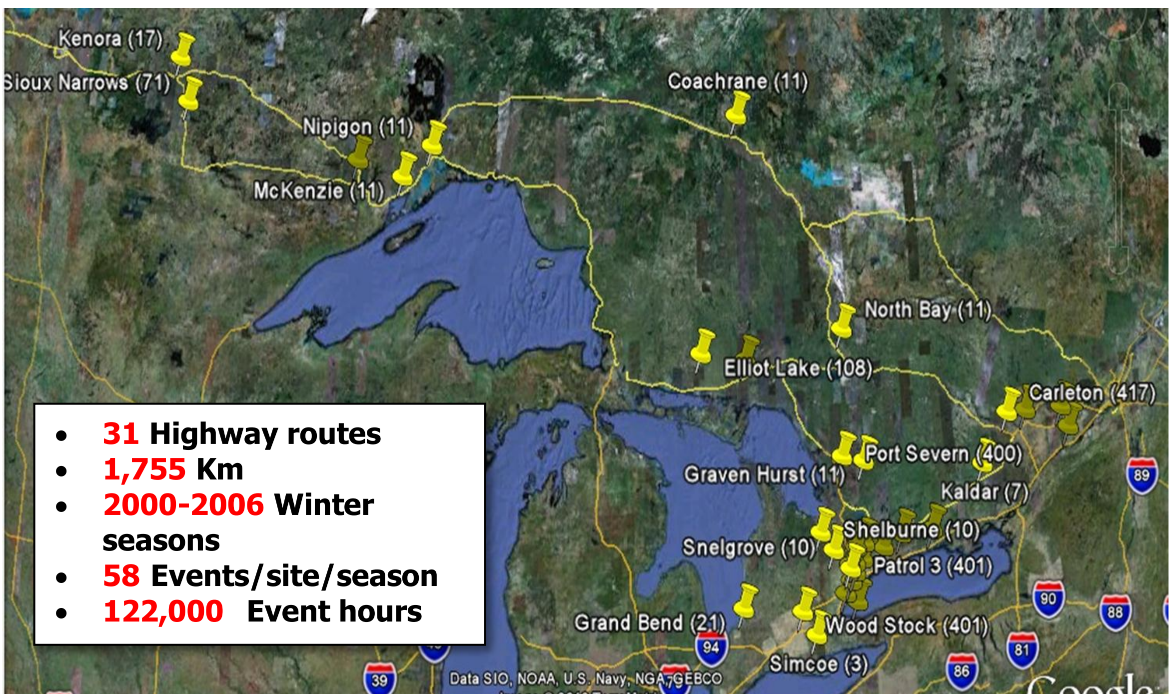


Figure 3-3: Ontario Road Network and Study Sites

After the sites were finalized, data collection was started. The time span selected for data collection was set to the period October 1999 to April 2010. However, due to unavailability of data from some sources, the final analysis period was restricted to the time frame of October 2000 to April 2006 (six winter seasons). Hourly data was obtained from each data source (details in the following section) for each site.

Data Sources

Five types of data were obtained and compiled, including weather data, traffic data, collision data, road surface condition data and winter operations data. These data were gathered from different sources and managed by different organizations. This section provides a description of these data sources.

Traffic Volume Data

Traffic volume data for each study site is obtained from two sources. The first source is traffic data from MTO's permanent data count stations (PDCS). PDCS provided traffic counts in different resolutions, including 15 minutes, 30 minutes, hourly and daily. Some of the stations also contained speed information.

The second data source is from loop detectors. This data is collected at 20 seconds interval and contains information about speed, traffic flow and density. This data was provided in an hourly format by MTO for this research. The original data is organised by individual loop detectors. These loop detectors are located on Highway 400, 401, 404, 410 and QEW. Loops belonging to a particular patrol route on the highways mentioned were identified and processed together. Both data sources were screened for any outliers caused by detector malfunction.

Traffic Collision Data

The Ontario Provincial Police (OPP) maintains a database of all collisions that have occurred on Ontario highways. This is "person based" data and includes information related to individuals as well as vehicles involved in each collision. A total of 147 variables are recorded. A database including all collision records for the study routes was obtained from MTO for the ten winter seasons (1999-2009).

The database includes detailed information on each collision, including:

- Collision time
- Collision Location
- Collision type
- Impact type
- Severity level

- Vehicle information
- Driver information
- Road conditions – surface and geometry
- Weather conditions
- Speed
- Visibility

Note that the data on the collision occurrence time and location are needed for data aggregation over space (e.g., highway maintenance route) and time (e.g., by hour). The data items related to weather and road surface conditions represent only the conditions at the time and location associated with the observed collisions and therefore do not necessary represent the whole maintenance route. As a result, we did not use this data field directly and instead used it to complete any missing RSC data which was primarily sourced from MTO's road condition weather information system (RCWIS) and road weather information system (RWIS).

Road Condition Weather Information System (RCWIS) Data

This data contains information about road surface conditions, maintenance, precipitation type, accumulation, visibility and temperature. RCWIS data is collected by MTO maintenance personnel, who patrol the maintenance routes during storm events; 3 to 4 times on the average. Information from all patrol routes are conveyed to a central system six times a day. Instead of stations this data is collected for road sections. Each observation contains information regarding the section of road to which it belongs. One of the most important pieces of information in this data source is description of road surface condition, which is used in this study as a primary factor for collision modeling. A detailed description on this data field and its processing for the subsequent modeling analysis is given in later sections. This data is also used by MTO in their traveler's road information system; however, this is the first time that it has been utilized for research purposes.

Road Weather Information System (RWIS) Data

This data source contains information about temperature, precipitation type, visibility, wind speed, road surface conditions, etc., recorded by the RWIS stations near the selected maintenance routes. All data except precipitation were available on an hourly basis. Hourly precipitations from RWIS sensors were either not available or not reliable. As a result, we derive this information from the daily precipitation reported by Environment

Canada (EC). Temperature and RSC data from RWIS were used to fill in the missing data from RCWIS. For visibility and wind speed RWIS was used as the primary source. RWIS stations record data every 20 minutes.

Environment Canada (EC) data

Weather data from Environment Canada (EC) includes temperature, precipitation type and intensity, visibility and wind speed. Except precipitation related information, all data from this data source are used as a secondary source for filling in the missing data from RCWIS/RWIS. EC is the only reliable data source for precipitation type and intensity and it is therefore used as the primary source for these variables. Data is available at different time resolutions; but hourly data was selected for the purpose of this research.

Data Processing

As described previously, there are three main types of data available for each selected study site. Once these data were obtained, they were pre-processed for subsequent merging and integration. Details on the steps involved are described in the following sections:

Traffic volume data: the traffic volume data is obtained from two sources: permanent data count stations (PDCS) sites, and loop detectors. Data from both sources is in hourly format; however, some pre-processing is required. These sources are used to supplement each other when data from one of the data source is missing. In cases where data is available from multiple loop detectors and/or PDCS sites, an average is used.

Collision data: collision data is compiled as person/occupant based data (Note that person and occupant are used interchangeably in this research). Each observation in the data belongs to an individual person involved in a collision. A stepwise aggregation approach is used to compile this data into hourly records by totalling the collisions that occurred within each hour of the day. Other attributes associated with collisions are averaged for each hour. In the collision data (occupant based) each person and vehicle involved in a collision are identified uniquely. This dataset is first converted to vehicle-based data, then to collision based data, and finally to hourly based data.

Weather and road surface data: weather data are obtained from three different sources: RCWIS, RWIS and EC. Most of the weather data from MTO's RCWIS is descriptive (or categorical) in nature. The data is thus coded to fulfill the specific purpose of this research. RCWIS data, organized by patrol route, is descriptive in nature, similar to event-based records with a time stamp. As a result, two immediate issues needed to be addressed. First, the original RCWIS data classifies road surface condition into seven major classes with a total of 486 sub-classes, making it difficult to use it as a categorical factor in a statistical analysis. Secondly there was missing information - a large number of hours did not have RCWIS observations. These issues were addressed by converting RSC to a scalar variable. This is discussed in detail in the following section. RCWIS data is converted to hourly data whenever the observations are available by taking the average of the variables within that hour and counting the number of different WRM operations performed within that hour. RWIS data is recorded every 20 minutes and is converted to hourly data by averaging observations within an hour. In cases that more than one RWIS stations are available for a single site, their average value is used. Data from Environment Canada is available in five different formats:

1) Data prefixed by MIN is hourly record of data recorded each minute
2) Data prefixed by FIF is fifteen minute data
3) Data prefixed by HLY is daily record of hourly data
4) Data prefixed by DLY is monthly record of daily data
5) Data prefixed by MLY is annual record of monthly data

Hourly format is chosen as it suites our data needs. However, precipitation data is mostly available in the daily data-format, which is the water equivalent of the total precipitation amount over a day. Data was downloaded from Environment Canada website[1] for 389 stations. 217 Stations were selected based on their proximity to the sites. Out of these 217 stations were used in this research - 69 stations with hourly data and 171 stations with daily data (Precipitation data). These stations are selected using a two-step process. First, an arbitrary 60 Km buffer is assumed around each site and sites falling within that boundary are selected. In the next and final step, stations closer to patrol routes are selected as control stations. Each control station is compared with other stations lying close to the control station using a paired t-test to determine whether stations distant from the control stations have a statistically different mean for each variable compared to the control stations. This step is necessary to select only stations with weather conditions similar to the control stations, which in turn represent the conditions at the patrol route. If, for a station, a variable, e.g., visibility is showing a significant difference in its mean from the mean visibility value of the control EC station near patrol route, the variable is removed. In the case that all variables show a significant difference, the whole station is discarded. Data from multiple stations are used to ensure that there are no missing values

[1] http://www.climate.weatheroffice.gc.ca/climateData/canada_e.html

and to capture the average effects for a patrol route. Arithmetic mean is found to give better results than weighted average.

Precipitation intensity data is available only as a daily total, which is the water equivalent of the total precipitation amount over a day. Based on the data describing “precipitation type” the hours with and without snow/freezing rain precipitation are identified. The total precipitation amount of each day is then uniformly allocated to the individual hours of the day during which precipitation occurred.

Once all the data’s are converted into an hourly format, they are then fused into a single dataset on the basis of date (day), time (hour) and location (patrol route). Some of the variables in this dataset are duplicated as these variables are present in different data sources. In these cases priority is given to RCWIS data then RWIS data and then EC data because the former data sources are collected nearer the study sites and are therefore considered to be more representative. Similarly in case of any missing data for temperature, precipitation or wind in RCWIS, data from RWIS or EC data is used. Missing RSC data from RCWIS are retrieved from collision data or RWIS data. It is also assumed that the RSC for the hour directly following maintenance activities could be considered as at least partially snow covered. This data field is then subsequently linearly interpolated for hourly conditions, as discussed in the following section. This gives us values for road surface condition for all hours over individual storms. Once the three sources of data are finalized, a single dataset is formed by combining all datasets on the basis of date (day), time (hour) and location (patrol route). This process resulted in an hourly-based dataset.

Modeling of Road Surface Conditions

MTO reports RSC using qualitative descriptions, i.e., a categorical measure (with 7 major categories and 486 subcategories). These categories have intrinsic ordering in terms of severity, which means that a more sensible measure would be an ordinal one. While binary variables could be used to code ordinal data, it would mean loss of information on the ordering. We therefore decided to use an interval variable to map the RSC categories and at the same time make sure that the new variable would have physical interpretations. Road surface condition index (RSI), a surrogate measure of the commonly used friction level, was therefore introduced to represent different RSC classes described in RCWIS. The reason that we used a friction surrogate is that there have been a number of field studies available on the relationship between descriptive road surface conditions and friction, which provided the basis for us to determine boundary friction values for each category. To map the categorical RSC into RSI, the following procedure was used

(Usman et al 2010):

1. The major classes of road surface conditions, defined in RCWIS, were first arranged according to their severity in an ascending order as follows:
   Bare and Dry < Bare and Wet < Slushy < Partly snow covered < Snow Covered < Snow Packed < Icy. This order was also followed when sorting individual sub categories in a major class.

2. Road surface condition index (RSI) was defined for each major class of road surface state defined in the previous step as a range of values based on the literature in road surface condition discrimination using friction measurements (Wallman et al 1997; Wallman and Astrom 2001; Transportation Association of Canada 2008; Feng et al 2010). For convenience of interpretation, RSI is assumed to be similar to road surface friction values and thus varies from 0.05 (poorest, e.g., ice covered) to 1.0 (best, e.g., bare and dry).

3. Each category in the major classes is assigned a specific RSI value. For this purpose, sub categories in each major category were sorted as per step 1 above. Linear interpolation was used to assign RSI values to the sub categories.

RSI values for major road surface classes are given below:

Road Surface Condition major Classes	**RSI Range**
Bare and dry	0.9~1.0
Bare and wet	0.8 ~ 0.9
Slushy	0.7 ~ 0.8
Partly snow covered	0.5 ~ 0.7
Snow covered	0.30 ~ 0.5
Snow packed	0.2 ~ 0.3
Icy	0.05 ~ 0.2

Database Integration and Pre-processing

The data obtained from all the data sources were subsequently pre-processed and merged to form a data set of hourly records on weather, traffic, and collisions. Snow storm events are then identified based on weather conditions and road surface conditions, as shown in **Figure 3-4**. The following assumptions were considered in the event identification process:

Each event is defined with the following constraints:

- An event starts at the time when snow/freezing rain is observed;
- An event ends when snow/freezing rain stops and a certain predefined road surface condition is achieved after that time.
- Precipitation must be greater than zero (0 cm/hr)
- Air temperature must be less than 5 ^{o}C
- Road surface conditions index value must not be equal to bare dry conditions

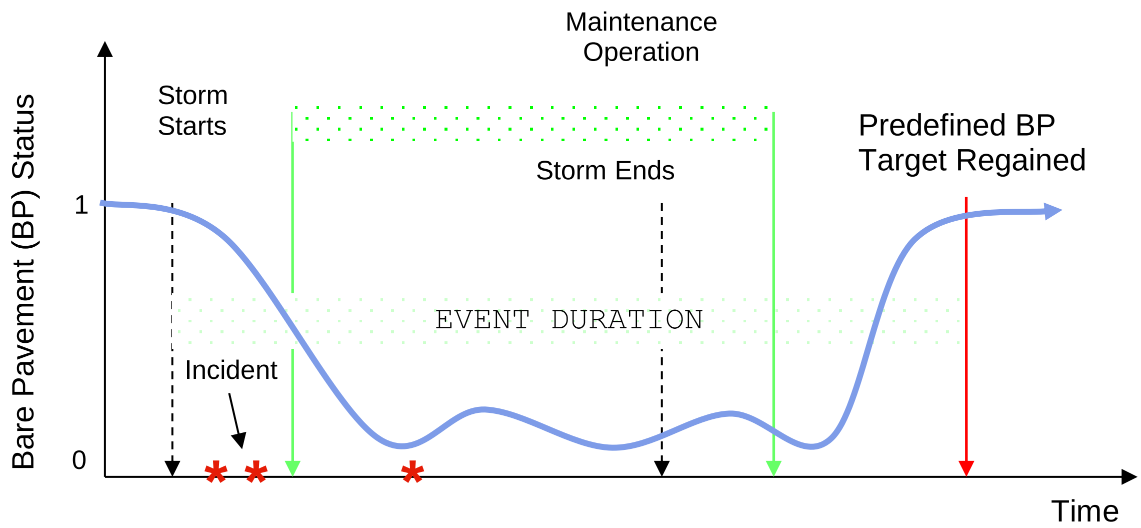


Figure 3-4: Road Surface Conditions over a Snow Storm Event

A total of 10932 route-events are extracted based on the event definition and restriction defined above. A total of 3035 collisions were observed over these events.

4. DATA ANALYSIS AND MODEL CALIBRATION

4.1 EXPLORATORY DATA ANALYSIS

A total of 32 datasets (31 individual sites and one combined set) were formed for the 31 sites selected. Inconsistencies were verified through exploratory analysis. Descriptive statistics were computed. The combined data set has a total of 122,059 observations recorded over 10,932 snow events. All the data sets were checked for any outliers using box plots of individual data fields in the database.

For the purpose of the subsequent modeling analysis, the following variables were defined:

- Total number of collisions over an hour **(Y,** dependent variable**)**
- Indicator for month (**M**, including October, November, December, January, February, March, and April)
- Indicator for hour of the event (**FH**, FH = 1 if first or second hour, 0 otherwise)
- Average air temperature (**T**, C^{o})
- Average wind speed (**WS**, km/hr)
- Average visibility (**V**, km)
- Precipitation intensity - hourly precipitation (**HP**, cm)
- Average road surface index (**RSI**)
- Precipitation type (**PT**, PT = 1 for freezing rain/ snow; 0 otherwise)
- Indicator for winter road maintenance operation type (**WRM**, including sanding, salting, ploughing, and a combination of them)
- Exposure defined as the product of segment length and hourly traffic, in million vehicle kilometres traveled (**EXP**, MVKm)
- Site indicator (**S**, including all 31 sites)

Month was included as a variable to test monthly trend over a season. To test the trend within a storm, time factors were included in the analysis to check whether the start of the event is more susceptible to collisions compared to the rest of the storm. It was found that the effect of the first hour against other hours in the snow storm (FH) was significant.

Site-specific effects were included in the models to take into account the potential effects of specific unmeasured factors on road safety, such as driver population, and road geometry.

For this purpose, three different fixed effects were investigated:

- Site-specific fixed effects using a dummy variable for each site
- Region-specific effects using a dummy variable for each region
- Road-type specific effects using a dummy variable for each road type

Ontario province is divided into 5 regions given below:

- Region 1 - Central Region
- Region 2 - Eastern Region
- Region 3 - North-Eastern Region
- Region 4 - North-West Region
- Region 5 - South-Western Region

A correlation analysis was conducted for each patrol dataset and the combined dataset. It was found that precipitation type and maintenance operations were consistently correlated with RSC across all datasets (with a correlation coefficient greater than 0.60) and were therefore removed from further analysis. Descriptive statistics are given in **Table 4-1**.

Table 4-1: Descriptive Statistics of the Data

	No. of Collisions	**Temp (c^o)**	**Wind Speed (km/hr)**	**Visibility (km)**	**Hourly Ppt (cm)**	**RSI**	**Event Duration (hr)**	**Ln Exp**
	Sample Size (N) = 122,058							
Min	0	-33	0	0	0	0.05	2	3.8
Max	7	28	69	40	13.8	1	47	14.3
Mean	0.02	-5	16	11	0.24	0.75	19	8.0
St. Dev	0.18	6	10	8	0.37	0.20	11.6	1.7

4.2 MODEL CALIBRATION

After identifying the modeling approach, the next step was to fit the models to the data. Though models were calibrated for all the 32 data sets, only the combined data will be discussed here because of the relatively large sample size which makes it feasible to check the effects of different site specific factors. Results obtained with larger samples are more trustworthy (Wright 1995).

The data used in this research is a 2-level hierarchical dataset where storm hours are nested within individual storms. This type of data generally suffers from within subject correlation. Intra-class correlation (ICC) (correlation among observations within the same storm event) was computed for this correlation. ICC, denoted by ρ, has a value ranging from 0 to 1. This means that if all hourly collision count observations are independent of one another, then $\rho = 0$. On the other hand, if observations inside each cluster (in this case, storm) are exactly the same, $\rho = 1$ (Usman et al. 2012). Obviously, a $\rho \neq 0$ implies that the observations are not independent, e.g., ICC > 0 implies that the collision occurrence in the same storm is influenced by similar unobserved storm factors. ICC for this dataset comes out to be 6.05%. Though there is no set rule for the ICC value; a value close to zero suggests the presence of weak correlation. Under such circumstances the less complex single level models could also be applied to this data. In such cases the distortion effect of the correlation on the parameter estimate is expected to be minimal.

The following models were calibrated:

A. Poisson lognormal - Two Level Models
  - PLN1: A model without any spatial factors
  - PLN 2: A model with regional effects
  - PLN 3: A model with road type effects
  - PLN 4: A model with site effects

B. Generalised Negative Binomial - Single Level Models
  - GNB1: A model without any spatial factors
  - GNB2: A model with regional effects
  - GNB3: A model with road type effects
  - GNB4: A model with site effects

Site-specific variables are included in the specification of each model to capture the possible effect of other route specific factors (such as location, driver population, and road geometry, on road safety). All models were calibrated using Stata[2] (Version 11). A stepwise elimination process was followed to identify the significant factors. The best fit model was identified using likelihood ratio test and Akaike Information Criterion (AIC) (Akaike 1974). The AIC statistic is defined as -2LL+2p, where LL is the log likelihood of a fitted model and p is the number of parameters, which is included to penalize models with higher number of parameters: a model with smaller AIC value represents a better overall fit. Based on both the likelihood ratio test and AIC criterion, the GNB4 model calibrated, considering the effects of the first hour of a storm and site specific variables was found to be the best fitted model for the combined data set. **Table 4-2** shows the modeling results for GNB and PLN**.** The GNB model is given in **Equation 4-1**.

$$\mu = EXP^{0.235} e^{-1.249-0.011T+0.005WS-0.039V+0.097HP-2.594RSI+M+S+FH} \qquad \textbf{(4-1)}$$

where μ = Mean number of collisions
T = Temperature (C)
WS = Wind Speed (km/hr)
V = Visibility (km)
TP = Total Precipitation (cm)
HP = Hourly Precipitation (cm)
RSI = Road surface index representing road surface conditions
EXP = Exposure (total traffic in an hour multiplied by length of the section, MVKm)
M = Indicator for month (**Table 4-2**)
S = Indicator for site (**Table 4-2**)
FH = Dummy variable for the effect of first hour (-0.302 if first hour, 0 otherwise).

These modelling results are used for identifying the factors that have a significant effect on winter road safety and the magnitude of these effects, as discussed in the following section.

[2] http://www.stata.com/

Table 4-2: Summary Results of GNB and PLN Models for combined dataset

Variable		GNB1		PLN1		GNB2		PLN2		GNB3		PLN3		GNB4		PLN4	
		B	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	Sig	B	Sig
Constant		-8.246	0.000	-8.811	0.000	-5.729	0.000	-6.675	0.000	-3.940	0.000	-4.870	0.000	-1.249	0.006	-2.082	0.000
M	October	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
	November	-0.761	0.003	-0.772	0.004	-1.111	0.000	-1.106	0.000	-0.934	0.000	-0.863	0.001	-1.029	0.000	-1.023	0.000
	December	-0.927	0.000	-0.869	0.001	-1.331	0.000	-1.225	0.000	-1.122	0.000	-1.107	0.000	-1.262	0.000	-1.174	0.000
	January	-0.898	0.000	-0.830	0.001	-1.369	0.000	-1.261	0.000	-1.100	0.000	-1.062	0.000	-1.308	0.000	-1.238	0.000
	February	-1.217	0.000	-1.135	0.000	-1.637	0.000	-1.527	0.000	-1.382	0.000	-1.355	0.000	-1.536	0.000	-1.488	0.000
	March	-0.952	0.000	-0.958	0.000	-1.373	0.000	-1.263	0.000	-1.113	0.000	-1.122	0.000	-1.278	0.000	-1.229	0.000
	April	-0.729	0.005	-0.666	0.016	-1.125	0.000	-1.005	0.000	-0.912	0.000	-0.833	0.002	-1.134	0.000	-1.050	0.000
First hour (FH=1)		-0.285	0.001	-0.262	0.001	-0.271	0.002	-0.256	0.002	-0.313	0.000	-0.285	0.001	-0.302	0.001	-0.271	0.001
Other Wise (FH=0)		0.000				0.000		0.000		0.000		0.000		0.000		0.000	
Temperature						-0.012	0.009	-0.014	0.005					-0.011	0.021	-0.013	0.014
Wind Speed (Km/hr)		0.007	0.000	0.008	0.000	0.004	0.040	0.006	0.006	0.006	0.002	0.008	0.000	0.005	0.017	0.006	0.003
visibility (km)		-0.035	0.000	-0.033	0.000	-0.042	0.000	-0.038	0.000	-0.033	0.000	-0.033	0.000	-0.039	0.000	-0.038	0.000
Hourly Precipitation										0.082	0.140			0.097	0.079		
RSI		-2.763	0.000	-2.558	0.000	-2.667	0.000	-2.516	0.000	-2.728	0.000	-2.580	0.000	-2.594	0.000	-2.518	0.000
Ln(Exposure)		0.718	0.000	0.705	0.000	0.551	0.000	0.569	0.000	0.412	0.000	0.448	0.000	0.235	0.000	0.276	0.000
RDTYPE1										0.000		0.000					
RDTYPE2										-0.922	0.000	-0.937	0.000				
RDTYPE3										-1.049	0.000	-1.071	0.000				
RDTYPE4										-0.563	0.000	-0.596	0.000				
RDTYPE5										-0.820	0.000	-0.811	0.000				
RDTYPE6										-1.716	0.000	-1.617	0.000				

Variable		GNB1		PLN1		GNB2		PLN2		GNB3		PLN3		GNB4		PLN4	
		B	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	Sig	B	Sig
RDTYPE7										-1.738	0.000	-1.688	0.000				
RDTYPE8										-1.767	0.000	-1.671	0.000				
Region1						0.000		0.000									
Region2						-0.696	0.000	-0.586	0.000								
Region3						-0.922	0.000	-0.777	0.000								
Region4						-1.166	0.000	-1.027	0.000								
Region5						-0.340	0.000	-0.323	0.000								
	Sioux Narrows													-4.027	0.000	-3.904	0.000
	Elliot Lake													-3.522	0.000	-3.276	0.000
	Grand Bend													-4.011	0.000	-3.924	0.000
	Carleton													-3.875	0.000	-3.847	0.000
	Shabauqua													-4.010	0.000	-3.874	0.000
	Cochrane													-3.399	0.000	-3.293	0.000
	North Bay													-2.853	0.000	-2.723	0.000
S	Massey													-2.370	0.000	-2.252	0.000
	Nipigon													-3.090	0.000	-3.001	0.000
	Port Severn													-3.001	0.000	-2.886	0.000
	Graven Hurst													-2.483	0.000	-2.396	0.000
	Kenora													-2.518	0.000	-2.425	0.000
	Kaladar													-2.388	0.000	-2.289	0.000
	Snelgrove													-2.788	0.000	-2.732	0.000
	Simcoe													-2.196	0.000	-2.155	0.000

Variable		GNB1		PLN1		GNB2		PLN2		GNB3		PLN3		GNB4		PLN4	
		B	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	Sig	B	Sig
S	Shelburne													-2.595	0.000	-2.557	0.000
	Morrisburg													-1.727	0.000	-1.688	0.000
	QEW 2													-1.580	0.000	-1.671	0.000
	Hwy 410													-1.995	0.000	-2.055	0.000
	Dunvegan													-1.709	0.000	-1.650	0.000
	Port Hope													-0.732	0.000	-0.797	0.000
	Patrol 5													-1.747	0.000	-1.770	0.000
	QEW 1													-1.297	0.000	-1.375	0.000
	Patrol 4													-1.315	0.000	-1.288	0.000
	Kanata													-1.605	0.000	-1.619	0.000
	Woodstock													-0.969	0.000	-0.978	0.000
	Patrol 1													-1.038	0.000	-1.157	0.000
	Hwy 404													-1.298	0.000	-1.384	0.000
	Maple													-1.074	0.000	-1.140	0.000
	Patrol 3													-0.710	0.000	-0.789	0.000
	Patrol 2													0.000		0.000	
Ln(Alpha)																	
Constant		3.828	0.000			4.146	0.000			2.932	0.010			2.711	0.012		
RSI		1.692	0.000			1.537	0.000			1.487	0.000			1.347	0.000		
Ln(Exposure)		-0.301	0.001			-0.327	0.000			-0.231	0.024			-0.222	0.022		
Observations		122058		122058		122058		122058		122058		122058		122058		122058	
LL(Null)		-13095.64				-13095.64				-13095.64				-13095.64			
LL(Model)		-12118		-12036.25		-12036.94		-11990.92		-11877.64		-11885.65		-11647.45		-11716.16	

Variable	GNB1		PLN1		GNB2		PLN2		GNB3		PLN3		GNB4		PLN4	
	B	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	**Sig**	**B**	Sig	B	Sig
AIC	24265.99		24098.51		24113.89		24017.84		23801.29		23811.29		23388.91		23520.31	
BIC	24411.68		24224.77		24308.13		24192.66		24024.67		24017.25		23845.38		23947.65	
Number of level 1 units			122058				122058				122058				122058	
Number of level 2 units			10932				10932				10932				10932	

5. MAIN FINDINGS AND MODEL APPLICATION

5.1 FACTORS AFFECTING WINTER ROAD SAFETY

As discussed previously, the modeling results obtained in the previous section provide a basis for identifying the factors that had a statistically significant effect on collision occurrences under adverse winter weather conditions. Furthermore, the modeling results (**Equation 4-1**) can also be used to derive the elasticity of collision frequency with respect to each significant factor, which is defined as the percentage of change in the expected number of collisions for every percent increase in a given variable. For example, the coefficient associated with RSI is -2.594, which suggests that a 1% improvement in RSI would lead to approximately a (-2.594*RSI) % change in the expected number of collisions. Considering a base RSI of 0.6, a 1% increase in RSI will result in 1.6 % (-2.594*0.6) reduction in the mean number of collisions. **Table 5-1** provides the elasticities of the significant factors using their means (**Table 4-1**) as the base values.

Table 5-1: Elasticities of Main Influencing Factors

Variable	Elasticity
Temperature	0.06
Wind Speed (Km/hr)	0.08
Visibility (km)	-0.44
Hourly Precipitation	0.02
RSI	-1.93
Ln (Exposure)	0.235

It has been found that most results obtained in our research with respect to winter road safety and associated factors are consistent with those reported in the literature, with a few exceptions. As shown in **Table 4 - 3** and **Equation 4 - 1**, the more severe is the storm condition, as indicated by temperature, visibility, wind speed and precipitation, the higher is the expected number of collisions. Specifically, the following observations can be made from the modeling results:

- **Road Surface Condition**
  The most interesting result is perhaps that the road surface condition index (RSI) was found to be a statistically significant factor influencing road safety across all sites, models and functional forms. RSI was used as a surrogate measure to capture the effects of winter road maintenance operations. The negative sign associated to the factor suggests that higher collision frequencies are associated with poor road surface conditions. This result makes intuitive sense and has confirmed the findings of many past studies (Norrman et al 2000; Wallman et al 1997), mostly from Nordic countries. However, this research is the first showing the empirical relationship between safety and road surface conditions at a disaggregate level, making it feasible to quantify the safety benefit of alternative maintenance goals and methods. The elasticity value for RSI shows that it is most influential factor affecting safety and a 10% improvement in road surface conditions will cause a reduction in mean number of collisions by almost 20%.
- **Visibility (Km)**
  Visibility is also found to have a statistically significant effect on collision frequency during a snow storm. The negative model coefficient also makes intuitive sense, as it suggests that reduced visibility was associated with an increased number of collisions. Note that this result is different from those from a past study by Hermans et al. (2006), which conducted a statistical study using data from 37 sites and found that visibility was significant only at two sites. Their study considered collisions occurring at different roadways related to a single weather station. This approach may have masked the effect of visibility due to confounding of missing factors and large aggregation levels in both space (coastal areas vs. inter cities) and time (seasonal variation). The elasticity value for visibility shows that, out of all the weather related factors, it is the most influential factor affecting winter road safety. An increase of 10% in visibility will result in almost 5% reduction in the mean number of collisions.
- **Precipitation Intensity (cm)**
  Hourly precipitation was also found to be significant with a positive sign suggesting that the mean number of collisions will increase with an increase in

precipitation intensity. This finding also confirms some previous results e.g. Knapp et al (2000), Andrey et al (2001), Fu et al (2006) etc. The elasticity value for precipitation shows that a 10% increase in precipitation intensity will cause the mean number of collisions to increase by 0.2%.

- **Air Temperature (C^o)**
  Air temperature was found to be significant with a negative sign suggesting that the mean number of collisions will increase as temperature starts decreasing. Moreover temperature also accounts for extra variation that is not captured by RSI. For the same RSI, different temperatures will represent different levels of variation in road surface conditions which will increase with decrease in temperature. A low temperature will therefore also affect expected collision frequency by offering extra variation in the road surface conditions. This result confirms some of the previous findings e.g. Fu et al. (2006). The elasticity value for air temperature shows that a 10% increase in precipitation intensity will cause the mean number of collisions to increase by 0.6%.
- **Wind Speed (km/hr)**
  Wind speed was found to be statistically significant and the positive sign indicates that higher wind speeds were associated with a higher number of collisions. The results make sense intuitively as high wind speed could cause blowing snow effects or impair the visibility of drivers during snowstorms. This is similar to results from the literature e.g. Knapp et al (2000). The elasticity value for wind speed shows that a 10% increase in precipitation intensity will cause the mean number of collisions to increase by 0.8%.
- **Exposure (MVKm, million vehicle kilometers traveled)**
  As expected, exposure, defined as million vehicle-kilometres traveled (product of the total traffic volume over a storm event and route length for aggregate data and product of the traffic volume per hour and route length for disaggregate data), was found to be significant, suggesting that an increase in traffic volume, storm duration, or route length would lead to an increase in the total number of collisions that would be expected to occur on the route over the snow event. Inclusion of this term ensures that traffic exposure is accounted for when estimating the safety benefits of some specific policy alternatives. The coefficient associated with the exposure term has a value less than one, suggesting that the moderating effect of exposure is non-linear with a decreasing rate. This result is consistent with those from road safety literature (e.g. Andrew and Barred 1998, Lord and Persaud 2000; NCHRP 2001; Roozenburg and Turner 2005; Mustakim et al 2006, Sayed and El-Basyouny 2006; Sayed and Lovegrove 2007, Jonsson et al 2007 and Lord et al 2008 etc.).

- **Monthly Variation**
  The general belief is that winter event starts experience more collisions than the end. This hypothesis was tested by including factors for different months. Results from this analysis show that the start of winter is more crash prone compared to other months. This could be due to adaptation of drivers to driving in snowstorm conditions with the passage of winter season. Similar results have been reported in the literature, e.g., Eisenberg and Warner (2005) and Maze and Hans (2007).
- **Hourly Effect**
  In addition to the month effect, an hour indicator was included in the analysis to test the hourly variation of safety that was not explained by the included factors related to weather and road surface conditions. Effect of first hour was found to be significant with a negative sign. This means that first hour of the storm had less number of collisions as compared to other hours. This could be due to the good road surface condition at the very start of the event as compared to the later hours.

The effect of each of those factors can also be illustrated using the concept of relative risk (RR), which is defined as the ratio of the collision frequency at a given level of a variable (e.g., precipitation intensity (HP) = 2.0 cm/hr) to the one at the base level (HP = 0 cm/hr) while holding other factors constant. **Figure 5-1** shows the effect of the six main factors on the relative collision risk, which clearly shows that road surface conditions is the most influencing factor affecting road safety while temperature and wind speed have the least effect.

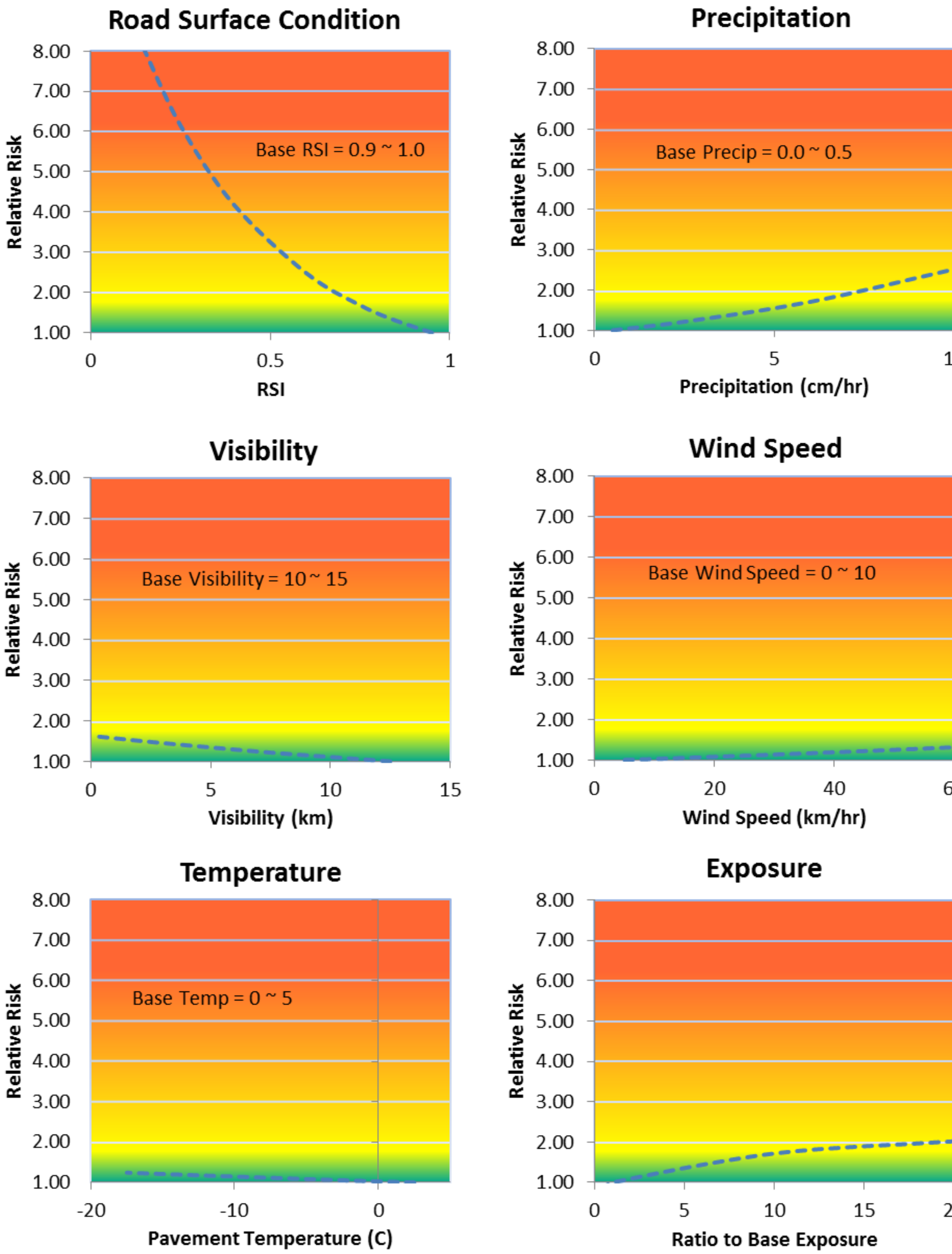


Figure 5-1: Effect of Different Factors on Relative Risk

5.2 SAFETY BENEFITS OF SALTING – GENERAL ANALYSIS

The collision model developed in this research includes an indicator of road surface conditions – RSI, which is defined on the basis of the snow and ice coverage and slipperiness of pavement surface. The RSI values of a road segment therefore reflect the combined effects of the snow event and winter road maintenance operations, such as salting and plowing, on the surface conditions of the road. As a result, this variable can be used as an instrument for quantifying the safety benefit of salting and plowing. In a separate effort, we have shown that it is feasible to link RSI to maintenance operations as well as other variables weather and traffic (Feng et al., 2010).

Based on **Equation 4 - 1**, if all factors except RSI are held constant, the benefit of salting in terms of relative reduction in the expected number of collisions due to salt effect can be derived as shown in **Equation 5-1**.

$$R = \left(\frac{\mu_B - \mu_A}{\mu_B}\right) * 100\% = \left\{1 - e^{-2.594\,(RSI_A - RSI_B)}\right\} * 100\% \qquad \textbf{(5-1)}$$

where R = percent reduction in the mean number of collisions due to salting;
μ_B, μ_A = mean number of collisions before and after salting, respectively;
RSI_B, RSI_A = road surface index before and after salting, respectively

Note that **Equation 5-1** also holds when the reduction is defined in terms of collision rate as long as the exposure term is held constant. **Figure 5 - 2** shows the percentage of reduction in the expected number of collisions on a highway over a given hour as a function of the improvement in road surface conditions (i.e., increase in RSI). As expected, the benefit of salting, or winter road maintenance in general, varies significantly from less than 20% to as high as over 85%, depending on the base conditions when salt was applied and the end improved conditions due to the deicing effect of salt.

It must be emphasized that these estimated benefits are valid for the conditions of a highway over a particular hour under the assumed improvement in road surface conditions. As a result it should be cautious to make general statements on the effect over a whole event or winter season for the simple reason. An analysis of the average effect or benefit of salting over a given event is provided in the following section.

It should also be noted that, instead of relative reduction, the absolute value could also be determined using the developed models, which would depend on the type of highway being considered (e.g., traffic volume) as well as other weather variables such as precipitation, visibility, wind speed and temperature.

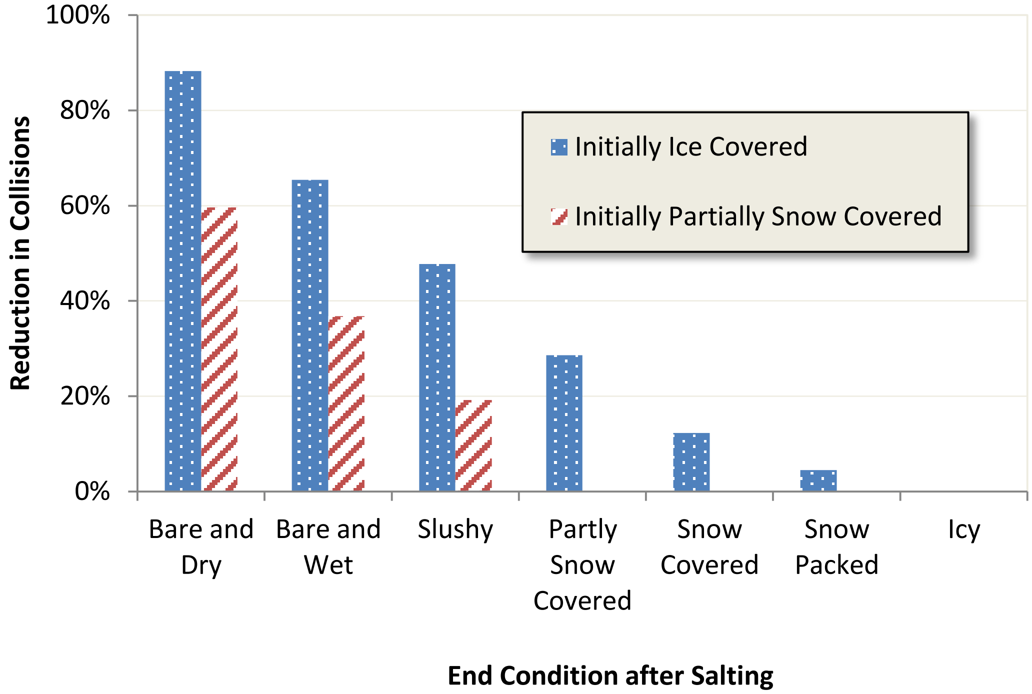


Figure 5-2: Safety Effect of Salting

5.3 SAFETY BENEFITS OF SALTING – EVENT-BASED ANALYSIS

The calibrated model can be applied to analyze the safety effects of winter road maintenance treatments such as salting and plowing under specific snowstorm conditions. This section describes a hypothetical case study to illustrate three examples of such applications. The case study site belongs to one of the 31 sites considered in model calibration discussed in the previous section – 30 km stretch of Highway 401 consisting of 5 lanes with an average traffic volume of 10,000 vehicles per hour or 2000 vehicles per hour per lane.

1) Combo Operations of Plowing and Salting

A specific snowstorm is assumed with the following characteristics:

- Precipitation rate = 3 cm/hr
- Air temperature = -5 C
- Visibility = 4 km

- Duration = 8 hours

For the analysis, the road surface conditions of this route, as represented by RSI, are assumed to vary over the event as follows:

- At the start of the event, the road surface is bare and dry with a RSI of 1.0 at the start of the first hour.
- The road surface condition is assumed to deteriorate to the condition of "SNOW PACKED WITH ICY" with an RSI value equal to 0.2 at the end of the fifth hour. The initial RSI is assumed to be 1.0, which decreased to 0.5, 0.4, 0.3, and 0.25 after 1, 2, 3 and 4 hours, respectively.
- In the case that no maintenance operations are done, the road surface would remain in this condition (with RSI = 0.2) from Hour 6 till the end of the event (i.e., 8 hours).
- For the case with maintenance operations, a combination of plowing and salting operations is applied, which would improve the road surface condition to a mixed state of slushy, wet, and partially snow covered with an equivalent RSI of 0.8.
- It is assumed that the effect of salt would last for five hours. The RSI of the road surface conditions would decrease linearly from 0.8 to 0.2 (SNOW PACKED WITH ICY) within the storm period.

The safety benefit of winter road maintenance is defined as the difference in the expected total number of collisions between the conditions of with and without winter road maintenance over the storm period. To show how this benefit is calculated, we consider the above storm with the maintenance operations (plowing and Salting) completed at the start of the second hour. As shown in **Figure 5 - 3**, the shaded area represents the difference between doing nothing (no maintenance) and salting & plowing.

Similarly, the safety benefit of other maintenance start/completion times can be calculated, as shown in **Figure 5 - 4**. Depending on the timing of the maintenance operations, the overall benefit achieved in terms of percent reduction in total number of collisions varies from 26% to 42%. It should be noted that these estimates are valid only for the event considered and the effects assumed for the maintenance operations. However, the example does illustrate the power of the model for quantifying the benefit of maintenance operations.

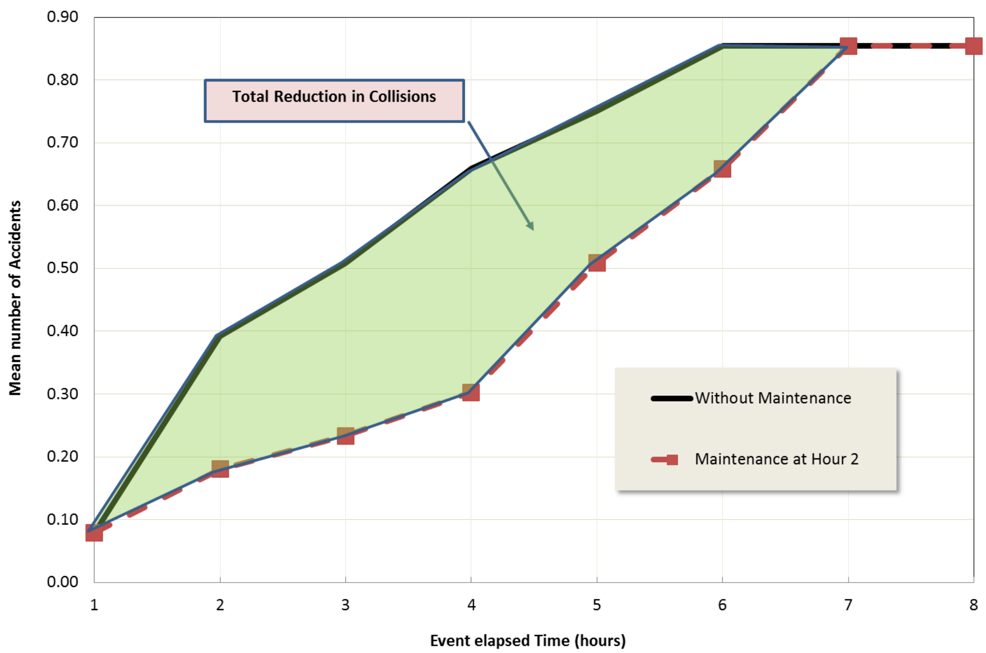


Figure 5-3: Safety Effect of Plow & Salting (Operation Done at Hour 2)

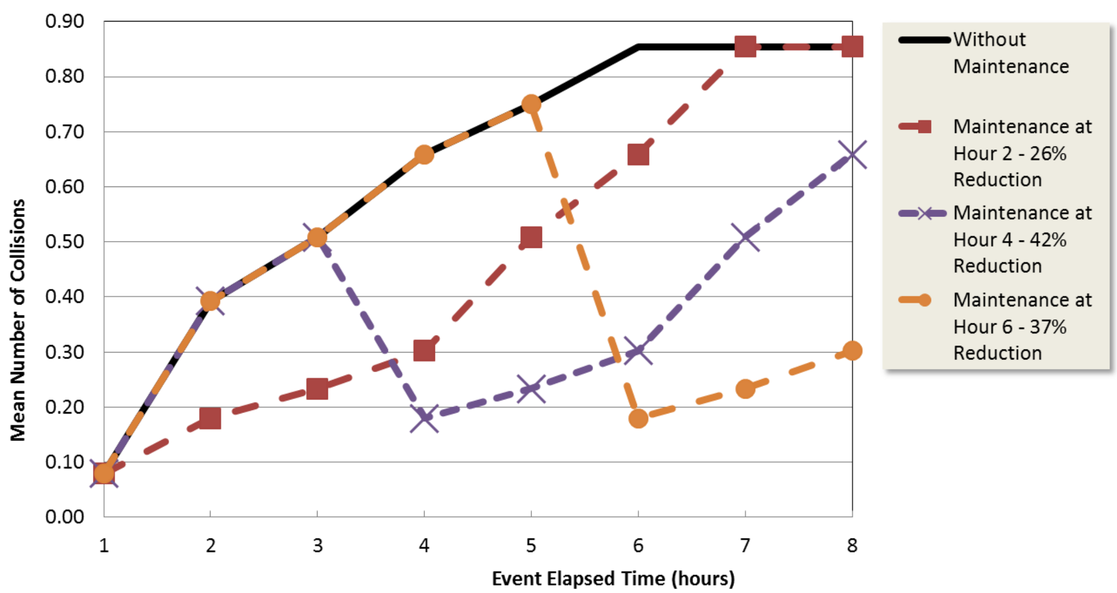


Figure 5-4: Safety Benefit vs. Maintenance Timing

2) Salting Only Operations

The previous example considers the kind of storm conditions under which both plowing and salting are normally applied in order to improve the road surface conditions. As a result, it is not possible to determine the benefits of the two operations separately. In this example, we attempt to quantify the benefit of salting alone by considering a special type of weather events that requires only salting operations. The event is assumed to start with a quick drop of temperature from positive to -10 C with no precipitation. The event is assumed to last for eight hours with no visibility problem. Furthermore, the following specific assumptions are introduced on the road surface conditions:

- At the start of the event, the road surface is bare and wet with a RSI of 0.9 at the start of the first hour.
- Due to the sudden temperature drop, the road surface becomes icy at the start of the second hour with an RSI of 0.1.
- If salt is not applied, the RSI would remain at 0.1 after the first hour and until the end of the event.
- In the case that the road is salted at the start of a specific hour, the road surface condition would be improved to a mixed state of wet and slushy with an equivalent RSI of 0.8.
- It is assumed that the effect of salt would last for five hours with RSI decreasing linearly from 0.8 to 0.1.

Results are shown in **Figure 5-5**. Depending on the salt application time, the safety benefit of a single salting operation applied in the early stage of the storm is over 35%. As expected, the safety benefit decreases as the salting application approaches the end of the event.

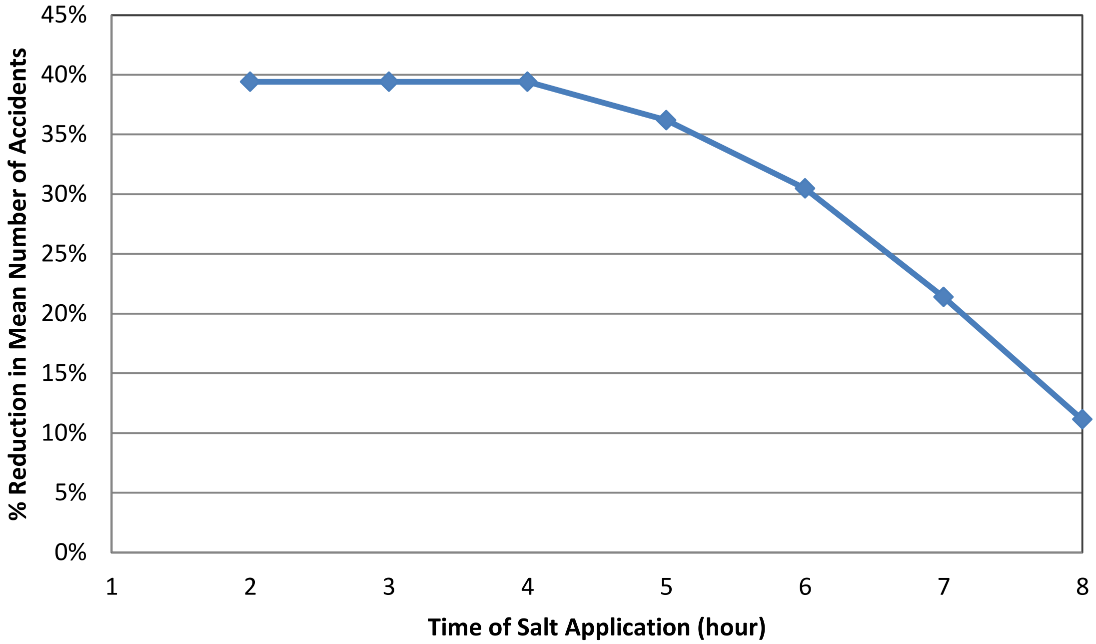


Figure 5-5: Safety Benefit of Salting

6. Simple Before-After Analysis on the Benefits of Salting

As discussed in Literature Review, a couple of past efforts have attempted to quantify the benefits of salt application for snow and ice control in terms of reduction in road collisions and those are the Technical University of Darmstadt study (1989) and the Marquette University study (1992). The approach taken in these studies is the so-called simple Before-After (B-A) analysis where the collision rates over the hours before and after salt application are compared and the percent reduction calculated. The following section describes the procedure and limitations of this approach. We will focus particularly on comparing our findings with those from Marquette University (1992).

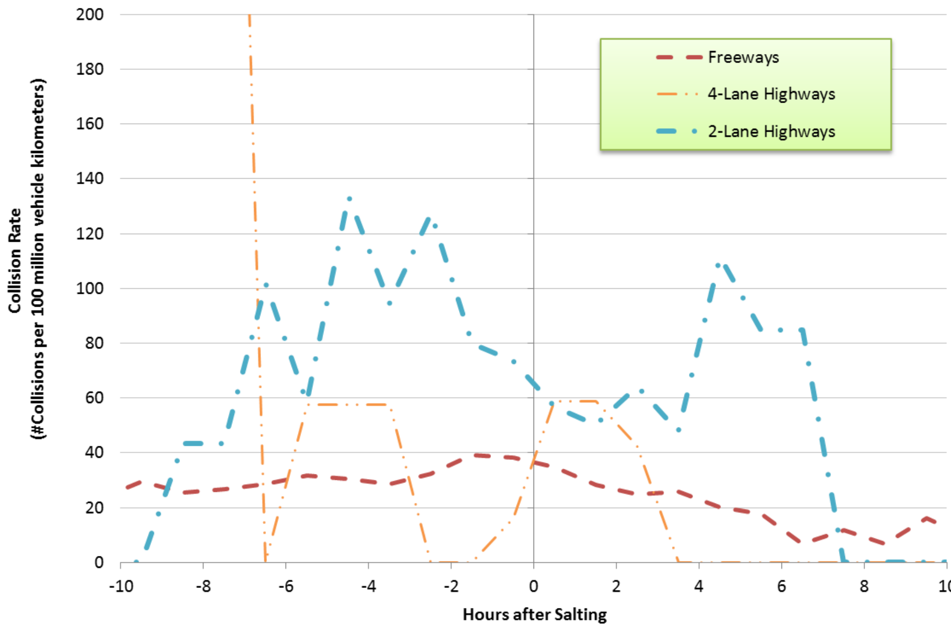
6.1 Results of B-A Analysis

This section summarizes the results from an analysis similar to the Marquette study but using the Ontario data that have been used in our analysis described in this report. For the purpose of this analysis, two different types of events were extracted from the main database– events where either salting was the sole operation or events where salting was applied in conjunction with plowing. The former allows us to gauge the sole effects of salting operations on winter road safety.

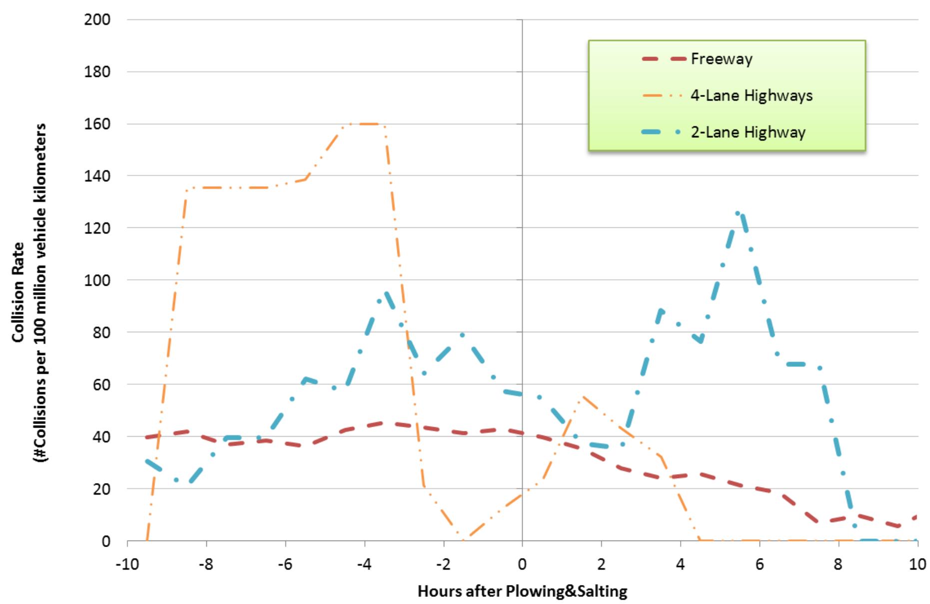
Following the Marquette study, each event was divided into two parts – before and after the last maintenance operation (salting or plowing and salting combo). Traffic, road weather and collisions over the periods 10 hours before and after the last operation were analyzed, as are described in **Table 6 – 1**. **Figure 6 - 1** shows the hourly collision rate over the periods before and after maintenance treatments while **Table 6 - 2** summarizes the average collision rates and the percent reduction. Overall a reduction of 51% was observed in the collision rate before and after salt application while a total of 65% reduction was associated with the combo operations of plowing and salting. While these benefit estimates are lower than those obtained by the Marquette study (which showed over 78% reduction in collisions on freeways and 87% reduction on two-lane highways), this analysis has nevertheless confirmed the overall findings of the Marquette study. It should again be noted that due to the limitation of the analysis approach, the magnitude of the benefit estimates should be taken cautiously.

Table 6-1: Comparison of the Two Studies

Marquette University Study	University of Waterloo Study
Study Duration	
December 1989 to March 1991 (December to March each year) 3979 events for 2 lane and 630 events for freeway	October 2000 to April 2006 (October to April each year) 1398 events with "only Salting" as the maintenance operation and 1959 events with "Salting + Plowing" as the maintenance operation
Physical Characteristics	
520 miles of 2 lane undivided and 50 miles of multilane divided highways	Covers a wide range of highways from 2 lanes undivided to multilane freeways.
Traffic Volume	
Hourly traffic volume is estimated using an equation (3.1 on page 100) from AADT. Hourly traffic volume over snow storms were estimated on the basis of some assumed factors.	Hourly traffic volumes were observed using loop detectors.
Weather Data	
• Storm period (Start and end) • High and low temperature • Total snowfall • Type of snow (dry, wet, sleet, or freezing rain)	• Storm period is obtained from weather stations • Hourly temperature • Hourly snowfall is estimated from the total daily snowfall assuming uniform precipitation rate over the storm hours. • Type of snow (Other, snow, or freezing rain) • Visibility and wind speed
Before-After Analysis	
12 hours before and after the last application of salt were considered for the analysis. It was assumed that prior salt applications are partial	For Comparison, similar approach was followed
The events that had over 6 inches of precipitation, lasted over 3 days, or had multiple operations were excluded	The events that lasted for over 3 days or involving multiple maintenance operations were excluded
Three types of operations were considered: salt only, abrasive only, and salt mixture	There were seven types of operations: salting, sanding, plowing and combinations, but only salting and plowing plus salting were considered.
• Data was compiled for each testing section and then all the data for all sections (2 lanes or freeway) were totaled in a single event. • Collisions were calculated in the post and pre salting period • Exposure was calculated for the same periods • Collision rate before and after salting was calculated • Effectiveness was calculated as (Before collision rate – After collision rate)/Before collision rate	• Same



a) Salting Only



b) Plowing and Salting

Figure 6-1: Collision Rates Before and After Maintenance Operations

Table 6-2: Collision Rates Before and After Maintenance Operations and Percent Reduction

	Average 12 hours before	Average 12 hours after	Percent Reduction
	*Events with **Salting** Only*		
All Highways	31.27	15.44	51%
Freeways	29.99	14.63	51%
4 - Lane	142.43	10.64	93%
2 - Lane	64.25	37.30	42%
	*Events with **Plowing and Salting** Combo*		
All Highways	42.69	14.78	65%
Freeways	41.62	13.98	66%
4 - Lane	76.99	8.03	90%
2 - Lane	56.10	39.02	30%

6.2 Limitations of B-A Analysis

The B-A analysis approach, while simple and intuitive, suffers several critical limitations. For example, due to the uncontrolled nature of the problem environment, the difference in collision occurrences before and after salt application could well be caused by changes in other circumstantial factors such as weather conditions (e.g., visibility and speed) and traffic (e.g., volume and speed) instead of the improved road surface conditions due to the deicing effect of salt. This underlying issue is commonly known as confounding where an extraneous variable (e.g., precipitation) correlates with both the dependent variable (collision rate) and the independent variable (salting). The direct consequence of confounding is that the actual benefit of salting could be underestimated or overestimated. **Figure 6 - 1** illustrates these possibilities using three example factors, including precipitation (Case 1), traffic volume (Case 2) and multiple maintenance treatments (Case 3). For example, in Case 1, salt was applied at the end of the event, which means reduction in collisions may also be due to the fact that precipitation had stopped, causing over estimation of the benefit.

Another issue with B-A analysis is that it is highly aggregate, lacking of the granularity needed for determining the effects of maintenance operations under some specific road weather and traffic conditions. As shown in **Section 4**, the absolute magnitude of the safety benefit of salting depends on a number of factors, including the characteristics of the highway (e.g., class and traffic volume), the event (e.g., precipitation rate and visibility) and the maintenance treatments (e.g., RSI). The reduction rates obtained from a B-A analysis are not linked to these condition variables.

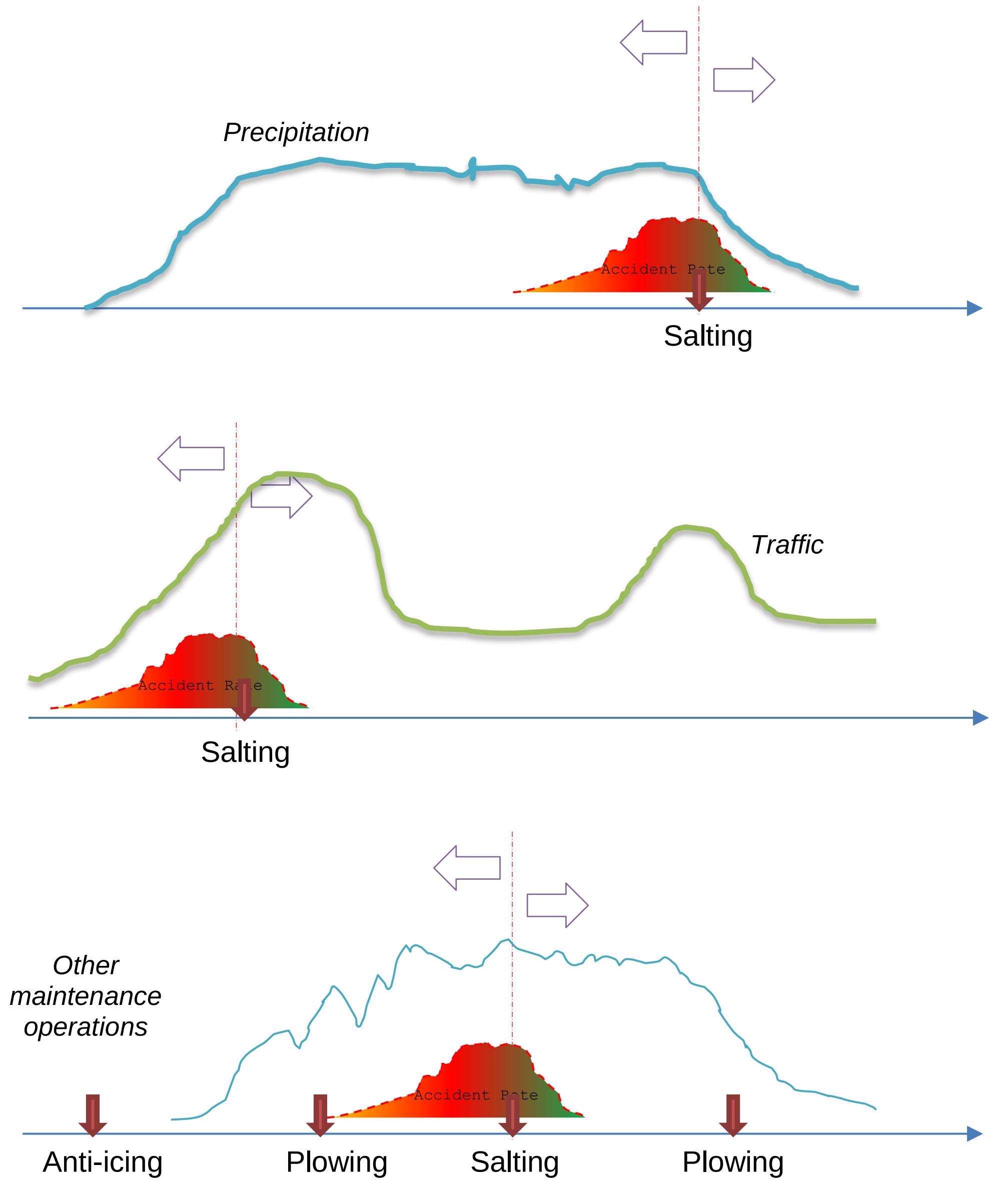


Figure 6-2: Illustration of Factors That May Confound the Effect of Salting

7. CONCLUSIONS AND RECOMMENDATIONS

This report has presented the results of an analysis aimed at explaining the variation of road collisions during snowstorm events and quantifying the benefits of winter road maintenance such as salting on reducing collisions. The proposed approach introduces a comprehensive road surface condition measure called road surface condition index (RSI) to model the expected effects of weather (precipitation), traffic and maintenance treatments (e.g., plowing and salting). Detailed hourly data on road weather and surface conditions, traffic, and collision history on 31 highway routes in Ontario, Canada, were obtained and used to calibrate various generalized linear regression models. It was found that the key weather factors, including visibility, precipitation, wind speed and air temperature, all have a statistically significant effect on road safety. The model also shows that there is a statistically significant link between road surface conditions and road safety. Case studies are conducted to illustrate the applications of the developed model for quantification of the safety benefits of maintenance operations (plowing/salting).

In the future research, it would be interesting to incorporate data of more winter seasons so that the stability of these modeling results over time could be assessed. This analysis was conducted using data from MTO's Class 1 and 2 highways only. A similar analysis should be conducted on collisions from other classes of highways which usually have different WRM standards. The spatial analysis unit considered in this research is highway patrol route, which could be further decomposed into shorter sections with similar geometric features. An analysis on these shorter sections could make it feasible to identify the effects of some geometric features of the highway on winter road safety, such as curvature, grade, and location (e.g., ramps, bridges). The main objective of this research was to use safety as a performance measure for evaluating the benefit of salt application. Improved mobility due to salt application should also be accounted as part of the overall benefit of maintenance operations.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance MTO staff for providing the data for this project in particular Max Perchanok, Heather McClintock, Jim Young, John Zajac, Marry Anne, Zoe Lam, and David Tsui.

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