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Abstract	This report describes the result of a study aiming at illustrating how models of winter road maintenance (WRM) performance measures can be applied to investigate the implications of different winter road maintenance level of service (LOS) standards under specific winter weather conditions. The study introduces a cost-benefit framework integrating the two primary cost and benefit components associated with winter road maintenance services, namely, material costs, safety and mobility benefits. Various maintenance input, output and outcome models are developed using five seasons of event-based data. The expected cost of maintaining a given highway route is captured by a salt application model, which relates the amount of salt used over a snow event to various event characteristics as well as the LOS class of the highway. The benefit from WRM for a highway route is quantified on the basis of the expected safety improvements, i.e., reduction in the number of collisions, and, the expected mobility improvements, i.e., increase in trip making utility and reduction in travel time. A case study is conducted to determine the optimal traffic threshold for demarcating the Class 1 and 2 highways in Ontario. The study has demonstrated the feasibility of applying the proposed quantitative approach when assessing alternative service standards under different climate conditions. Lastly, future research directions are highlighted at the concluding section.
Key Words	Levels of service, winter maintenance performance models, cost-benefit approach
Distribution	Unrestricted technical audience.

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Highway Standards Branch Report

HIIFP

Applications of WRM Performance Models for Evaluating the Implications of Varying Service Standards

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Published without prejudice as to the application of the findings.

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Introduction

Winter road maintenance (WRM) program commonly comprises of snow and ice control services delivered to keep highways safe and mobile during winter storms. Minimum levels of services (LOS) standards are established to ensure that consistent services are maintained on all highways over all winter seasons and snow events. For example, the Ministry of Transportation Ontario (MTO) defines five classes of highways based on winter traffic volume and highway type, and specifies different levels of service using performance measures such as maximum allowable accumulation of snow, maximum circuit time, and maximum bare pavement regain time (BPRT). This approach of varying service levels by traffic volume is to achieve a balance between the demand and cost so as to provide the services and the benefit that road users could obtain.

While most maintenance standards had been established on the basis of conceptually sound principles, few had quantitative justifications. For example, there is no clear explanation on why the BPRT was set for 8 hours (instead of 6 or 4 hours) for Class 1 highways in MTO's current Maintenance Management Information System (MMIS), and why a threshold of 10,000 winter average daily traffic (WADT) was used to separate Class 1 and Class 2 highways. It is commonly adopted that the traffic volume on a highway network is used to determine the magnitude of the benefit which could potentially be obtained from winter maintenance services. Also, climate change may result in differences in the type and number of storms in a region, overall demand as well as distribution for maintenance services. As a result, any changes in traffic and climate will have an impact on the benefit of winter road maintenance as well as the demand, and eventually cost of winter maintenance.

RESEARCH OBJECTIVES

Significant progress has been made on quantifying the impact of winter driving conditions on traffic safety and mobility (Usman et al., 2011, 2012; Fu & Usman, 2011; Fu et al., 2012; Donaher & Fu, 2013). The primary goal of this research is to demonstrate the applications of the performance models developed for evaluating alternative winter road maintenance service standards under different climate condition scenarios. In order to place the analysis within a cost-benefit framework, statistical models are also developed for estimating the demand for, and output of, winter road maintenance under different winter weather scenarios and level of service requirements. The project has the following specific objectives:

1) Review literature on policies and LOS standards on WRM and various performance measurement models;
2) Develop a framework for evaluating the cost and benefit implications of alternative LOS standards;
3) Conduct a case study to illustrate the applications of various performance models developed in this research.

Literature Review

This section provides a brief review of literature and practice on winter road maintenance (WRM) standards and maintenance demand analysis. Literature reviews on other related subjects such as safety and mobility impacts of winter weather and WRM are available elsewhere (Usman et al., 2011, 2012; Fu & Usman, 2011; Fu et al., 2012; Donaher & Fu, 2013).

WINTER MAINTENANCE STANDARDS

Road agencies representing different jurisdictions in Canada have established their own winter maintenance standards and levels of services that vary by highway type, traffic level or other criteria. Standards may be defined in terms of inputs, outputs or outcomes, with the level of complexity generally increasing in that order. Standards that are defined by inputs could include the number of plows assigned to a route, or the frequency of plowing. Outputs could be defined by bare pavement regain time (BPRT), traction levels, maximum depth of snow accumulation or other descriptors of the driving surface experienced by road users. Outcomes are measures of the impact to road users and society, such as accident rate, traffic speed or throughput.

Different standards are often established for different classes of roads. For example, highways in Ontario are grouped into five classes based on Winter Average Daily Traffic (WADT) threshold values, as shown in Table 1. Higher class roads are given higher priority for maintenance with shorter BPRT. For example, Class 1 roads should be restored to essentially bare condition within 8 hours after a storm ends while Class 3 roads are given a BPRT of 24 hours, as shown in Table 1.

Table 1: MTO Highway Classes and Level of Service Standards

Class of Highway Maintenance	Winter Average Daily Traffic (WADT)	Maximum Bare Pavement Regain Time (hours)*
Class 1	> 10,000	8
Class 2	2,000 to 10,000	16
Class 3	1,000 to 2,000	24
Class 4	500 to 1,000	24 (centre bare)
Class 5	< 500	snow covered, drivable

*****To be achieved in at least 90% of winter storms

However, the definition of LOS standards for highways differs considerably among jurisdictions, as shown in Figure 1. For example, the threshold traffic level separating Class 1 and Class 2 is 10,000 in Ontario as compared to 30,000 in Minnesota while the BPRT for Class 1 highways is 8 hours in Ontario but 3 hours in Minnesota. Ontario has a longer allowable BPRT than some other jurisdictions for Class 1 highways, but includes more highways with a lower traffic volume threshold. For the lowest highway class, regain time standards vary from 3 hours in New York to 36 hours in Minnesota.

LOS maintenance standards have a direct effect on the safety and mobility benefits of winter road maintenance and the amount of resources required to deliver the maintenance services during winter seasons. There is also a growing public concern pertaining to the excessive use of salt in snow and ice control as it is detrimental to the environment and corrosive to the vehicles and infrastructure (Transport Canada, 1999).

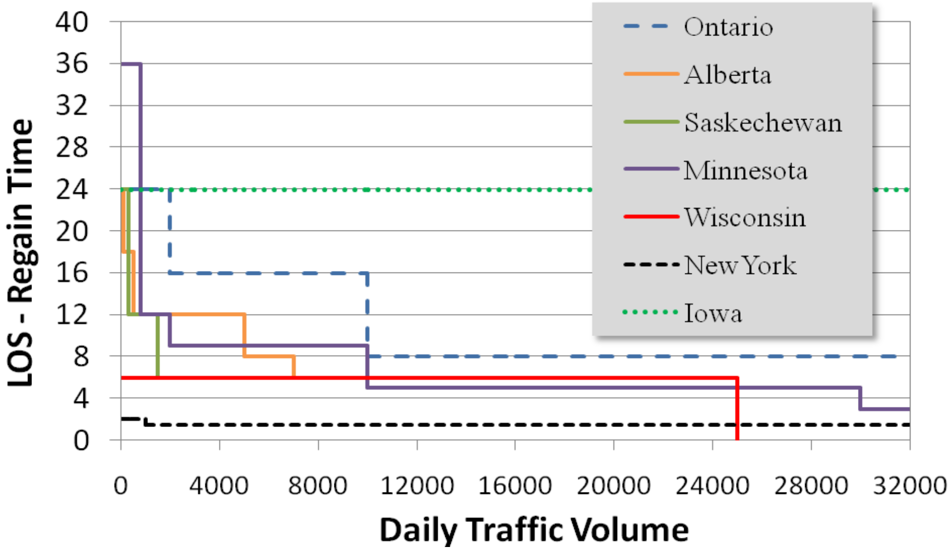

Figure 1: LOS Standards by Highway Class for Some Jurisdictions in North America

ESTIMATING MAINTENANCE DEMAND

The demand for various maintenance resources such as equipment, road salt and crew are affected by many factors such as winter severity, highway class, and maintenance practice. Therefore, the total cost of providing the services is determined by the level of service (LOS) to be maintained, the specific methods and materials employed by a contractor, the contractor's internal business practice, and the weather.

For example, the number of trucks required, the total work hours, and the total tonnes of road salt being used are different for a storm with light snowfall and temperatures near freezing than a storm with consistently cold temperatures. For a given highway and snow event, the number of plowing/salting trips and the amount of salts being applied also depend on the LOS to be achieved on the highway. Moreover, there are operation constraints in terms of the number of trucks/crew available for covering the operations and the extension of the highway network.

Several past studies have attempted to estimate the demand for winter road maintenance resources and those can be grouped into two main approaches. The first approach is developing an empirical model that relates the quantity of salt, sand, and equipment or the maintenance costs used in a season to winter weather variables representing the severity of the season (e.g., Andrey et al., 2003; Hulme, 1982; Voldborg & Knudsen 1988; Thornes, 1991; Cornford & Thornes, 1996; Gustavsson, 1996; Venäläinen & Helminen, 1998; Laine et al,. 2000; Venäläinen, 2001; Velanaina and Kangas, 2003). Most of these efforts were motivated by the need to develop a Winter Severity Index to capture the variation in demand for winter services. However, these studies have several limitations. First, they are highly aggregated considering large spatial and temporal units (e.g., whole region or city over a winter season). For example, the weather variables used (e.g., precipitation, temperature) are usually averages over a month or season, thus, resulting in loss of granularity and representativeness. Secondly, most of these demand models include only weather parameters without considering the LOS requirements and characteristics of the highways being maintained. These models therefore cannot be used for assessing the implications of different LOS standards.

The second approach is rule-based, which determines the plowing and salting operations over a given storm based on some general winter snow and ice control guidelines (e.g., Pisano et al., 2004). This approach relies on a decision support tool (e.g., MDSS) that must be calibrated for a specific jurisdiction. These guidelines are likely to have been set based on a common practise of maintenance, thus lacking a set model to capture the effects of external factors on policy making. Therefore, this approach cannot be immediately applied for assessing the impacts of climate change or of alternative service standards on the demand for winter maintenance services in Ontario.

Overview of Methodology

Figure 2 shows the proposed methodology to address the research objectives discussed previously. The first step is the calibration of various winter road maintenance performance models, including input model (salt usage), output models (road surface index or RSI and BPRT), and outcome models (collision frequency, traffic volume and traffic speed). A unique event based database covering six winter seasons for thirty one patrol routes are used to calibrate these models. Details about the data sources and the resulting models are given in the next section. Key factors such as weather conditions, event duration and maintenance practice are included as inputs to the model. Note that an event is defined as the start of a snowstorm until the regain of bare pavement. The span of an event therefore depends on the severity of weather and the maintenance practice. This variable is later used to model weather conditions of different severity levels.

The next step is the Cost-Benefit Analysis (CBA), which involves estimation of the costs and benefits of maintenance services as related to maintenance service standards. As mentioned in the previous section, highways in Ontario are categorized into five different winter road classes based on winter average daily traffic volume (WADT). Each class is thus associated with a specific level of service (LOS) standard (e.g., bare pavement regain time, BPRT) to be maintained during winter snowstorm events. Therefore, the costs and benefits associated with individual classes of highways vary. For this case study, the cost and benefit models developed from a sample of patrol routes (i.e., 31 Class 1 and 2 highways) are extrapolated to 138 Class 1 and 2 highway patrol routes in the province to estimate the total costs of winter maintenance. The detail explanation of CBA is presented in Cost-Benefit Analysis section.

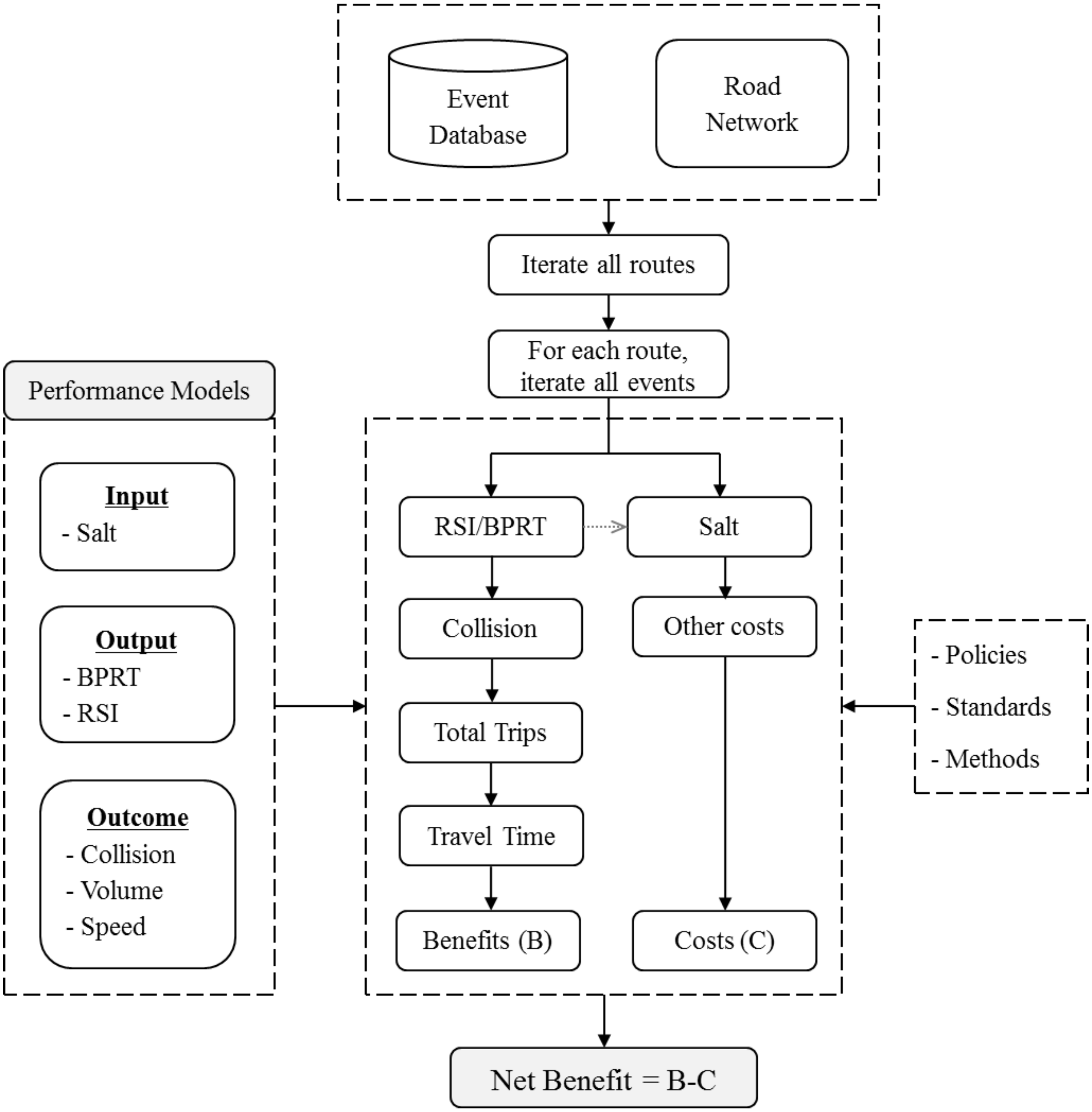

Figure 2: Proposed BCA Methodology

WRM Performance Models

The benefit-cost framework described in the previous section requires models for estimating winter road maintenance (WRM) performance, including inputs (e.g., maintenance resources such as material and labour), outputs (e.g., road surface conditions and bare pavement regain time), and outcomes (e.g., collision frequency and traffic speed). As discussed previously, salt usage will be used as the main input measure and also a surrogate measure of all maintenance inputs or resources while maintenance output is captured by two measures, namely, bare pavement regain time (BPRT), and road surface index (RSI). For maintenance outcome, only safety effect is considered. This section provides a short description of these models. More detailed discussions can be found in other related reports and publications by the authors.

DATA USED FOR CALIBRATING PERFORMANCE MODELS

Thirty-one maintenance patrol routes were selected from different regions of Ontario, Canada for salt usage, BPRT and RSI modeling. Later two models were subsequently used as inputs in the collision model. All these models were eventually used for the LOS analysis. The location of these patrol routes is shown in Figure 3.

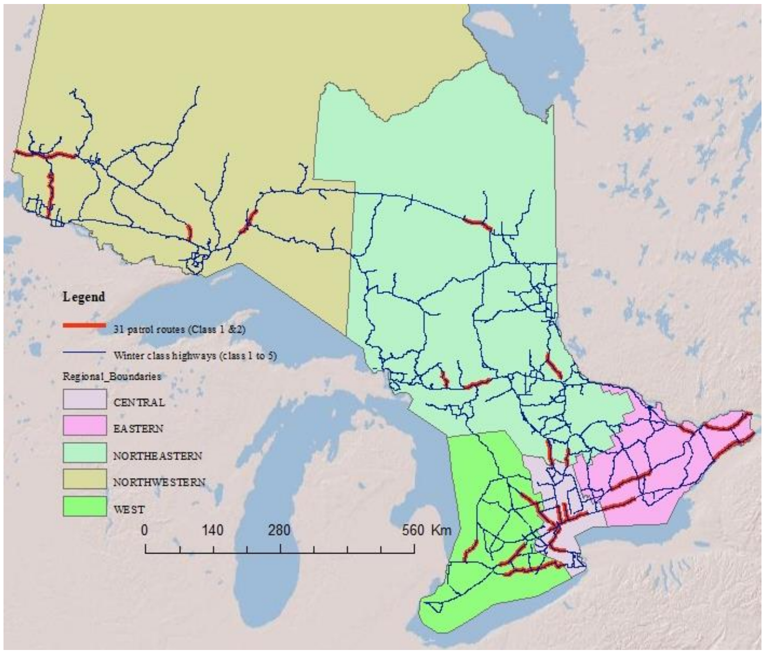

Figure 3: Thirty-one Class 1 and 2 Routes used for Model Calibration, Ontario, Canada

These models were developed from approximately 11,000 observations drawn from six winter seasons (2000 – 2006) (Table 2). Due to data limitations, the salt use and maintenance LOS analysis was based on thirty sites, and four winter seasons (2002– 2006) (Table 3). These routes were selected based on availability of traffic, weather, road surface condition and salt usage data. All these road sections belong to either Class 1 or 2 highways, including low volume rural two lane sections with WADT~2,000 through to high volume multi-lane urban freeways with WADT>300,000. For mobility analysis, traffic volume and speed models were calibrated using data from only twenty-one sites and three winter seasons (2003 – 2006) due to the availability traffic data for only these sites (Table 4: Descriptive Statistics for Data Used in Mobility Impact Modeling).

Data were obtained from various sources:

- Collision data from MTO which was originally collected by Ontario Provincial Police,
- Weather data from the Ministry of Transportation's (MTO) Road Weather Information System (RWIS) and from Environment Canada (EC) weather stations,
- Road surface condition data from the MTO Road Condition System (RCS), and
- Traffic volume count from MTO loop detector and permanent data count stations.

The weather, road surface condition, traffic and collision data obtained from different sources were processed on an hourly basis and merged into a single hourly data set using date, time and location as the basis for merging with each site assigned a unique identifier to retain its identity. Only those hourly data, which represented snow storm events defined by start of event until the regain of bare pavement time, were extracted to the event dataset. For each event and patrol route, mass of road salt applied and the actual BPRT time were mapped with the data from MTO's Maintenance Management Information System (MMIS) database. Details of the sites, data and its processing are described by Usman et al. (2011).

A surrogate measure of road surface traction called road surface index (RSI) is used to represent the overall road surface condition of a patrol route. Figure 4 shows the definition of RSI corresponding to the major classes of road surface conditions defined in the Ontario road condition reporting system (Usman et al, 2011).

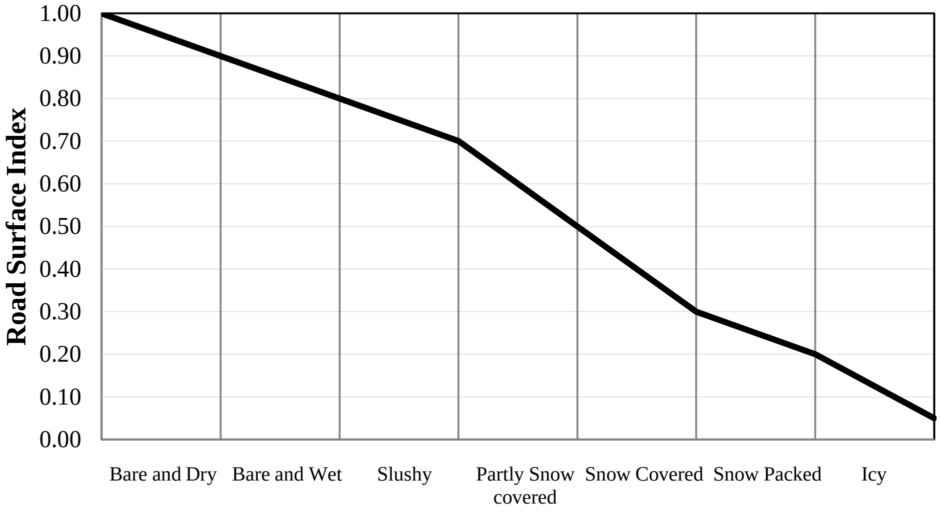

Figure 4: Road Surface Classes and Road Surface Index

Table 2: Descriptive Statistics for Data Used in Collision, RSI and BPRT Modeling

Average Event Based Data								
	Temp (C)	Wind Speed (km/hr)	Visibility (km)	Total Precip. (cm)	Collision	RSI	Event Duration (hr)	Total Traffic
Min	-29.8	0	0	0.02	0	0.25	2	3
Max	4.9	60.5	40.2	189.9	21	0.99	47	453626
Avg.	-4.3	15.75	11.84	3.91	0.28	0.80	11.17	18295
St.Dev	5.0	8.8	6.23	6.82	1	0.14	9.61	35162
Sample size: 10,932								

Table 3: Descriptive Statistics for Data Used in Salt Usage Modeling

Average Event Based Data								
	Temp. (C)	Wind Speed (km/hr)	Visibility (km)	Total Precip. (cm)	Salt Usage (kg/lane-km)	RSI	Event Duration (ED)	BPRT (hr)
Min	-29.87	0	0	0.02	0	0.25	2	0
Max	4.90	60.50	32.2	42.76	4691	0.99	47	44
Avg.	-5.15	14.62	11.84	3.67	256.9	0.77	11.9	1.54
St.Dev.	5.27	8.67	6.16	3.67	344.7	0.14	9.8	3.51
Sample size: 5207								

Table 4: Descriptive Statistics for Data Used in Mobility Impact Modeling

Average Event Based Data									
	Wind Speed (km/hr)	Visibility (km)	Total Precip. (cm)	Hourly Precip (cm/hr)	RSI	Temp (C)	Total Traffic Volume	Speed (km/hr)	v/c
Min	0.00	0.00	0.00	0.00	0.12	-29.9	1	60.00	0.00
Max	60.50	26.82	40.00	13.80	1.00	5.00	191154	125.00	0.70
Avg.	12.85	10.48	2.34	0.50	0.76	-4.46	5783	96.82	0.09
St. Dev.	8.88	6.94	3.16	0.76	0.16	4.88	14863	10.75	0.12
Sample size: 2411									

Note: v/c is volume to capacity ratio

INPUT MODEL - SALT USAGE

In winter road maintenance, salt is the most widely used material and represents the largest share of expenditure among the other alternative materials such as sand. According to Wisconsin Department of Transportation, salt accounts for approximately 38% of total maintenance cost (34 million out of 91.1 million) while other alternative materials such as sand and liquid used for the treatment represent only 2% of the total cost (DoT Wisconsin, 2013). The specific ratio and cost of salt usage may vary widely among agencies, as this could be a function of weather severity, service standards (LOS), traffic levels, and local costs of materials, equipment and labour. In this study, due to the lack of detailed maintenance cost data for specific routes, the salt usage is estimated and subsequently used to determine the total maintenance cost using a conversion factor as explained in later section.

A linear regression model is developed for the salt application rate being used on a maintenance route over a specific event using the event based dataset described in the previous section. Factors such as weather conditions, traffic volume, event duration, maintenance practice and road class were used as the potential explanatory variables. Weather conditions included average temperature, total precipitation and wind speed. Similarly, maintenance practice included whether or not the anti-icing was performed prior to the salting.

Equation 1 shows the results obtained from the model calibration with all the variables found significant at 95% level of confidence. This salt usage model could be used for estimating the event based maintenance cost, as discussed in Cost-Benefit Analysis section.

$$\mathrm{R} = 57.6 - 0.64\ \mathrm{T} - 1.36\ \mathrm{W} + 26.65\ \mathrm{P} + 50.56\ (\mathrm{Road\_class}) + 8.66\ \mathrm{D} + 0.01\ \mathrm{Q} + 32.26\ (\mathrm{Anti\_icing}) \qquad (1)$$

Where,

R = Salt application rate per event (kg/lane-km)
Q = Total traffic volume over the event
T = Average temperature during the event (C)
W = Average wind speed during the event (km/hr)
P = Total precipitation during the event (cm)
D = Event duration (hr)
Road_class = 1 if it is Class 1 highway; 0 otherwise
Anti_icing = 1 if anti-icing is deployed; 0 otherwise

The model result shows that higher amounts of salt usage were associated with severer weather conditions (e.g., temperature, precipitation). Anti-icing, which is included as a categorical variable, shows an increase in salt usage compared to the case without anti-icing operation. This could be due to the fact that anti-icing is normally used on very high traffic roads with lower road user tolerance for snow conditions.

OUPUT MODEL – BARE PAVEMENT REGAIN TIME (BPRT)

Bare pavement regain time (BPRT) is measured from the end of storm to the time when the road surface returns to bare wet condition. This time is likely to depend on characteristics of a storm such as amount of snowfall and the air temperature as well as the intensity of road maintenance services applied. Services are applied at different rates on Ontario's highways to correspond to the BPRT policy for different road classes (see Table 1). As a result, Class 1 highways are expected to have a lower BPRT time compared to Class 2 highways. In order to capture the effect of a highway class as well as other influencing factors, the following multivariate linear regression model is calibrated (Equation 2).

$$BPRT = 0.16 - 0.19 * T - 0.01W + 0.19P - 0.33\ (Road\_Class) \qquad (2)$$

Where,

BPRT = Bare pavement regain time (hours)
T = Average temperature during the event (C)
W = Average wind speed during the event (km/hr)
V = Average visibility during the event (km)
P = Total precipitation during the event (cm)
Road_Class = 1 if it is Class 1 highway; 0 otherwise

The regression analysis shows that average temperature, average wind speed and total precipitation of a particular snow storm event are significant. Similarly, a road class indicator was also found significant such that Class 1 had lower BPRT time than Class 2. Note that the BPRT estimate is needed for estimating salt usage and number of collisions of a patrol route over an event, as to be discussed later.

OUPUT MODEL – ROAD SURFACE INDEX (RSI)

Average road surface condition within a snow storm, as represented by road condition index (RSI), is expected to be a function of weather factors and level of maintenance operations. The latter can be captured by the maintenance LOS class of the highway. This hypothesis was explored using a linear regression model. Since, the variable RSI takes values ranging from 0 to 1, a logit transformation ($\mathrm{RRSI} = \ln\left(\frac{\mathrm{RSI}}{1-\mathrm{RSI}}\right)$) was first performed to obtain a new dependant variable – relative road surface condition index. The calibrated model is given in Equation 3.

$$RSI = \frac{1}{1+e^{-RRSI}} \tag{3}$$

Where:

$$RRSI = 1.96 + 0.01\,T + 0.01\,W - 0.03\,P - 0.03\,D + 0.17\,(Road_{Class})$$

It was found that factors such as temperature, wind speed, total precipitation and event duration were significant. Similarly, road Class 1 has higher RSI value compared to Class 2 which could be due to the proactive maintenance carried for Class 1 to meet BP standard.

OUTCOME MODEL – COLLISION OCCURANCES

Collision costs represent the indirect cost associated with winter road maintenance. In our recent effort, we have conducted a benefit analysis of winter road maintenance based on an event based collision model (Fu et al., 2012). In road safety literature, the most commonly employed approach to modeling accident frequencies is the generalized linear regression analysis. In particular, the Negative Binomial (NB) model and its extensions such as Generalized Negative Binomial (GNB) model have been found to be the most suitable distribution structures for collision frequency (Hauer, 2001; Miaou and Lord, 2003; Miranda-Moreno, 2006; Sayed and El-Basyouny, 2006). For this reason, a GNB model was calibrated with inclusion of weather, road surface condition, traffic, season and site-related variables. As this particular study is based on the same road network used in the study by Fu et al. (2012), the same collision model was adopted here.

Equation 4 gives the event based collision frequency model. In this model, road surface condition, as represented by Road Surface Index (RSI), was found significant. Note that

RSI can be estimated using the RSI model (Equation 3). As discussed previously, under a same snow event, the average RSI of a Class 1 highway is expected to be higher than one of a Class 2 highway, thus lower number of collisions.

$$\mu = Exp^{0.648} * e^{-3.912-0.018\,T*0.009\,W-0.044\,V+0.014\,P-4.42RSI+M+\Psi} \qquad (4)$$

Where,

μ = Expected number of collisions of a highway
T = Average temperature during the event (C)
W = Average wind speed during the event (km/hr)
V = Average visibility during the event (km)
P = Total precipitation during the event (cm)
RSI = Road Surface Index
Exp = Exposure (equal to total traffic in an event multiplied by length of the road section)
M = Indicator for month of the year (Appendix A, Table A.1)
Ψ = Indicator for site (Appendix A, Table A.1)

For application of the model, the above collision frequency model can be converted to a collision rate model by dividing frequency (μ) by the exposure (Exp).

OUTCOME MODEL – TRAFFIC VOLUME

Winter snow storms have been found to have a significant effect on the traveling public's decisions on whether or not, when, and how to make their trips (Fu et al., 2012). These travel behaviour responses to the winter events are manifested in the variation in traffic volumes on highways. A Poisson regression model has been developed to relate traffic volume on a highway to various factors (Equation 5).

$$\ln(Q - \overline{\mathrm{Q}}) = 0.264 - 0.004 * W + 0.005 * V - 0.007 * \mathrm{P} + 0.265 * RSI + \Omega \qquad (5)$$

where,

Q = Expected total traffic volume during an snow event
$\overline{\mathrm{Q}}$ = Expected total traffic volume during the event period under normal conditions (as if the event had not occurred)
T = Average temperature during the event (C)
W = Average wind speed during the event (km/hr)
V = Average visibility during the event (km)
P = Total precipitation during the event (cm)
RSI = Road Surface Index

Ω = Indicator for site (Appendix A, Table A.2)

This model indicates that high wind speed, low visibility, and high precipitation all could lead to reduction in traffic volume. Road surface conditions were also found to have a significant effect on traffic volume, which provides a way to capture the implication of maintenance service standards (i.e., Classification). As we have seen in the output model (i.e., RSI model) a highway maintained at Class 1 LOS standards is expected to have higher RSI values compared to the case that it is maintained as a Class 2 highway. Equation 5 shows a positive correlation of RSI factor on traffic volume, which suggests that the relative traffic impact of a snow event on a highway would be smaller if it is maintained as a Class 1 than as a Class 2. The reduction in traffic volume due to the event is a representation of lost mobility (the number of trips being canceled or shifted to other times of day), which can be converted into equivalent monetary value as discussed in the later section.

OUTCOME MODEL – TRAFFIC SPEED

In addition to the effect on traffic volume, winter weather events could slow down traffic, causing significant delay. The magnitude of the effect is expected to depend on many factors such as precipitation, visibility, road surface conditions, and road characteristics. A empirical study has shown that the underlying relationship can be captured by Equation 6 (Fu et al., 2012).

$$S = 69.082 + 0.089 * T - 0.078 * W + 0.310 * V - 1.258 * \mathrm{H}P + 16.974 * RSI - 4.325 * x + PSL + \Phi \tag{6}$$

where,

S = Average speed over the duration of the event (km/hr)
T = Average temperature during the event (C)
W = Average wind speed during the event (km/hr)
V = Average visibility during the event (km)
HP = Average precipitation intensity (cm/hr)
RSI = Road Surface Index
x = Volume to capacity ratio
PSL = Posted speed limit (0 if PSL 80 km/hr; 1.95 if 90 km/hr and 12.62 if 100 km/hr)
Φ = Indicator for site (Appendix A, Table A.2)

As in the traffic volume effect model, wind speed, and precipitation all could lead to reduction in traffic volume. RSI has a positive correlation with traffic speed and Road Class 1 is expected to have higher RSI value than in Class 2, this results into comparatively higher travel speed in Class1 highways.

Cost-Benefit Analysis

This section illustrates how the performance models of inputs, outputs and outcomes of WRM described in the previous section can be applied within a cost-benefit framework to assess alternative service standards under different climate scenarios. As discussed previously, highways in Ontario are classified into different classes with different LOS standards based on winter average daily traffic volume (WADT). A case study is conducted to determine the sensitivity of the relative benefit of WRM to the WADT threshold that is used to define Ontario's Class 1 and Class 2 highways. A sensitivity analysis on different scenarios of weather conditions is conducted to examine the implications of climate conditions of different winter severity.

The direct costs of winter maintenance include those of materials (e.g., road salt), equipment, and labour. The higher the LOS standard is to be maintained, the higher the direct maintenance cost will be, as more resources will need to be mobilized. The benefits of maintenance activities are related to improved safety and mobility; higher LOS standards lead to better road surface conditions, and thus better safety and mobility. The following section provides a detailed discussion about these models.

The CBA analysis included in this study is based on the Class 1 and 2 performance standards used in Ontario (Figure 5). The cost and benefit models developed from a sample of patrol routes (31 Class 1 and 2 highways) are extrapolated to Class 1 and 2 highways in the province to estimate the total costs of winter maintenance. The total costs are estimated as a function of the traffic threshold between Class 1 and 2, which is then used to identify the most cost-efficient threshold under three climate condition scenarios: observed, mild climate, and severe climates. More details are explained later in this section.

For this particular analysis, 138 patrol routes with 20,315 equivalent lane-kilometers representing Class 1 and 2 highways in the Ontario Provincial network were considered. These routes were selected based on the availability of basic inventory data required for cost analysis such as WADT, section length and equivalent lane kilometers (Figure 5).

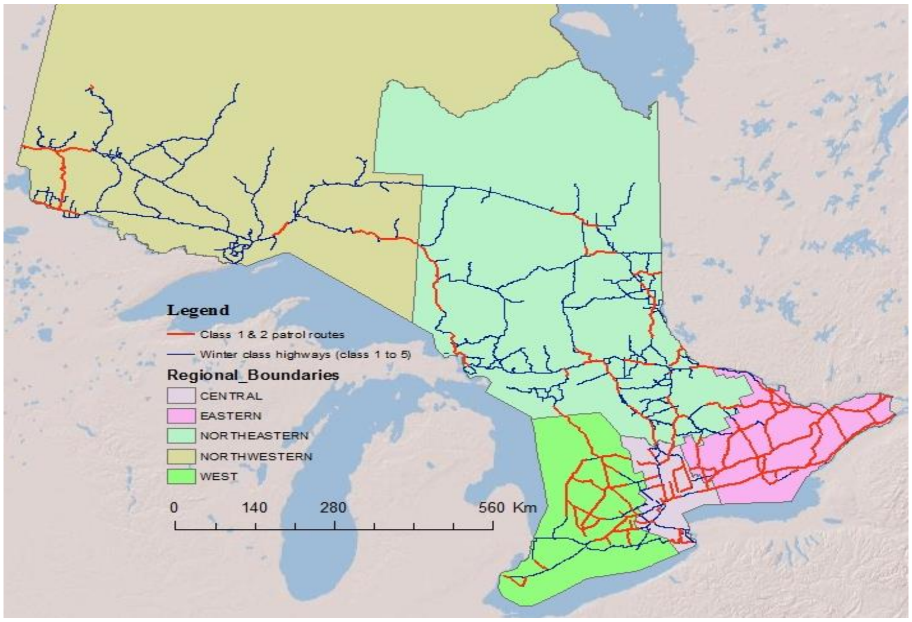

Figure 5: Class 1 and 2 Patrol Routes, Ontario, Canada

ESTIMATION OF SALT USAGE, COLLISIONS AND MOBILITY EFFECTS

Figure 6 is a flow chart showing steps involved in estimating the total amount of salt, the total number of collisions and mobility benefits over a given winter season for the given 31 routes of which the performance models were calibrated. The 2005-06 winter season is considered with all winter events being extracted from the event database. For each patrol route, the expected salt usage as well as BPRT and RSI are first estimated over each event of the season under the assumed class (Class 1 or 2), which are subsequently used to estimate the expected number of collisions, total traffic volume and traffic speed. While for the total seasonal salt usage and collision occurrences, the unit absolute seasonal cost were estimated by summing the estimates from individual events for each class scenario, for each mobility component (i.e., volume and travel time), net seasonal benefits was calculated summing the difference of corresponding measures between the Class 1 and Class 2 estimation. The results obtained are average seasonal salt application rate (kg/lane-km/season), the average seasonal collision rate as represented by the number of collisions per million winter vehicle kilometers (collisions/WADT-km/season), benefits of trip making (trips/lane-km/season), and travel time saving (hrs/ lane-km/season)

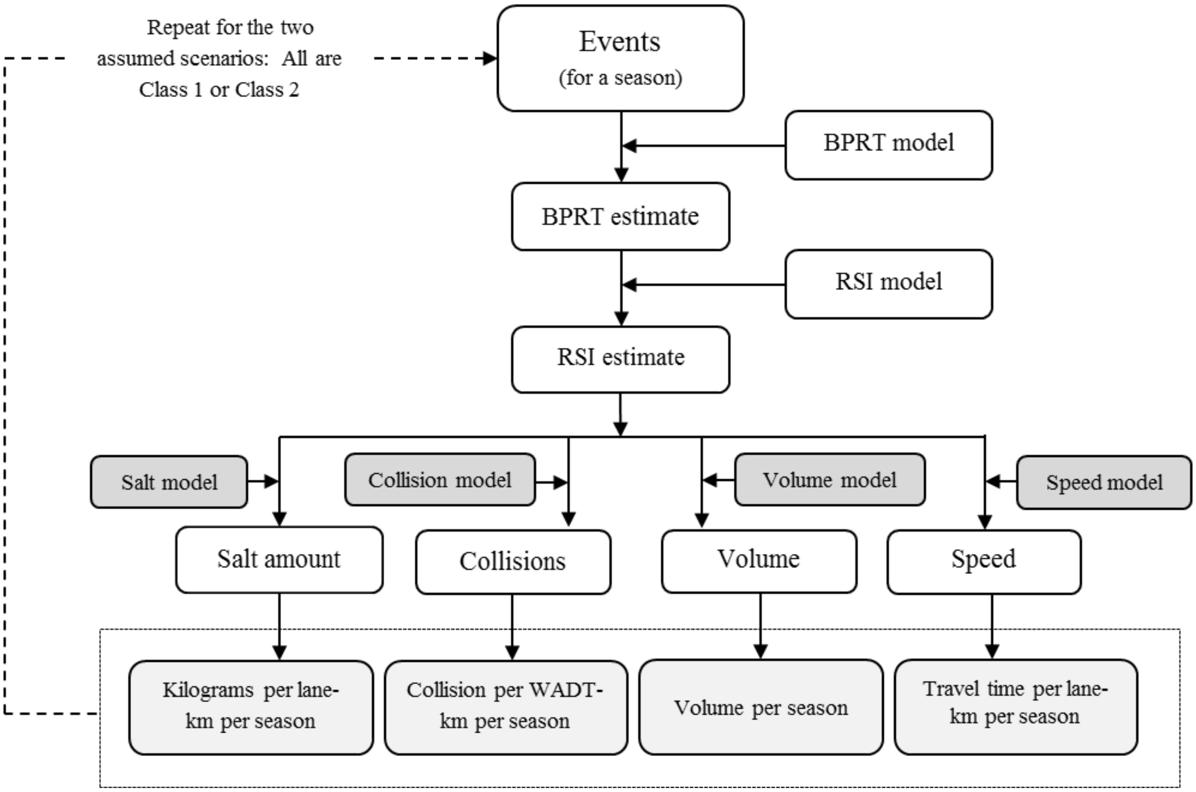

Figure 6: Framework for Calculation of Seasonal Salt Usage and Collision Occurrence and Mobility

ESTIMATION OF MAINTENANCE COSTS

The estimated average seasonal salt application rate for a highway route under a given service class (Class 1 or 2) can be used to estimate the total maintenance cost of the route based on the unit cost of salt and the relative proportion of other costs (e.g., labor, equipment) as compared to salt costs (Figure 7). The salt price is assumed to be $70 per ton. The proportion of other costs is determined on the basis of the cost statistics from Wisconsin DOT (Table 5), which shows that the ratio of total salt cost to total other cost is approximately 1.68. A multiplication factor of 2.68 can therefore be used to covert salt cost to total maintenance cost. However, highways of higher maintenance standards demand higher levels of resources such as fleet and crew sizes. To model this cost differential, Class 1 and 2 highways are assumed to have a different cost factors. In this case analysis, the cost multiplication factor is assumed to be 2.8 and 2.5 for Class 1 and Class 2 highways, respectively.

Table 5: Derivation of Multiplication Factor for Total Maintenance Cost Based on Wisconsin DOT Maintenance Cost Data

Items	**Cost ($ million)**
Salt (A)	34
Equipment related cost	27
Labour cost	25.3
Other materials cost	2.6
Administrative cost	2.2
Total operation cost (equipment and labour) (B)	57.1
Operation and salt cost ratio (B/A)	1.68
Multiplication factor for total maintenance cost	2.68

Source: Wisconsin DOT, 2013

ESTIMATION OF COLLISION COSTS

The expected number of collisions of a highway can be converted into equivalent monetary cost based on the concept of willingness-to-pay as suggested by Transport Canada. According a study on the total social economic cost of collisions that occurred on Ontario highways in 2004 (Vodden et al, 2007), the average unit collision cost is approximately $77,035 per collision, which includes direct cost such as fatality, injury, property damage, and indirect cost such as travel delay, fuel and pollution cost. Assuming an inflation rate of 1.17, the average cost of collisions is $90,131 per collision.

ESTIMATION OF MOBILITY COSTS

Trip cancellation and travel time increase can be converted into mobility costs using Equations (7) and (8).

$$VC = (Q - \overline{Q}) * VOC \tag{7}$$

$$TC = (T - T_0) * Q * VOT \tag{8}$$

where,

VC = Total equivalent monetary loss of trip cancellations or changes

TC = Total equivalent monetary loss of lost time

Q and $\overline{Q}$ = Expected total traffic volume under an snow event and normal conditions, respectively (Equation 5)

T = Average route travel time during a snow event, which can be estimated based on route length and average speed (Equation 6)

T_0 = Average route travel time under normal condition (the posted speed is assumed for simplicity)
VOC = Average value of a canceled trip, assumed to be \$10 per trip
VOT = Average value of time, assumed to be \$20 per hour

ESTIMATION OF NET BENEFITS

In order to cast the analysis into a cost-benefit framework for determining the net benefit of WRM, a base scenario - commonly a do-nothing option (i.e., there had been no maintenance conducted at all) - is used to estimate the incremental cost and benefit of WRM under a given LOS standard, i.e., classification scheme. However, do-nothing or zero maintenance is not a realistic base scenario as it would be unimaginable in a most real world application environment. Instead, for this particular case study, we assume a base scenario that considers all highways in the existing Class 1 and Class 2 network being maintained according as Class 2 highways. For any given WADT threshold (x) that is used to classify the highway network, the increase in maintenance costs and the reduction in collision and mobility costs can be determined accordingly. The total net benefit of WRM under a given classification threshold, denoted as NB_x, can therefore be determined by Equation (11).

$$NB_x = B_c + B_Q + B_V - C_m \tag{11}$$

Where,

$C_m = MC_x - MC_0$
$B_c = AC_0 - AC_x$
$B_q = VC_0 - VC_x$
$B_t = TC_0 - TC_x$

Where,

C_m = Increase in maintenance costs as compared to the base scenario
B_c = Reduction in collision costs as compared to the base scenario
B_q = Reduction in trip cancellation costs as compared to the base scenario
B_t = Reduction in travel time costs as compared to the base scenario
MC_x = total maintenance cost under a given classification scheme, i.e., highways are classified into Class 1 and Class 2 based on a given WADT threshold (x) and maintained accordingly
MC_0 = total maintenance cost of base scenario, i.e., all highways are maintained as Class 2
AC_c = total accident cost under a given classification scheme, i.e., highways are classified into Class 1 and Class 2 based on a given WADT threshold (x) and maintained accordingly
AC_0 = total accident cost base scenario, i.e., all highways are maintained as Class

2

VC_x = total trip cancellation cost under a given classification scheme, i.e., highways are classified into Class 1 and Class 2 based on a given WADT threshold (x) and maintained accordingly

VC_0 = total trip cancellation cost of the base scenario, i.e., all highways are maintained as Class 2

TC_x = total travel time cost under a given classification scheme, i.e., highways are classified into Class 1 and Class 2 based on a given WADT threshold (x) and maintained accordingly

TC_0 = total travel time cost of the base scenario, i.e., all highways are maintained as Class 2

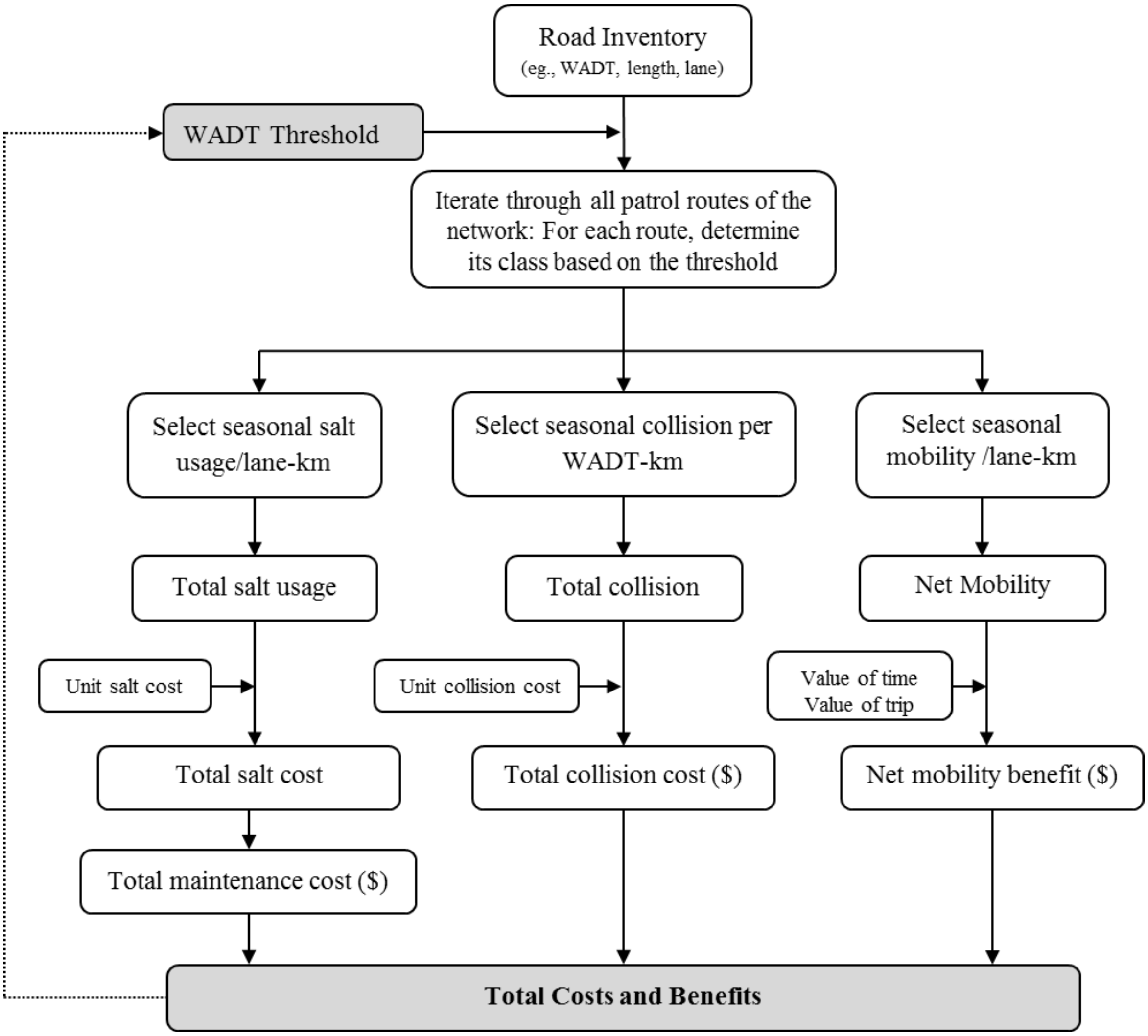

Figure 7: Framework for Calculation of Costs and Benefits

COST-BENEFIT ANALYSIS OF VARYING SERVICE STANDARDS

The cost-benefit estimation method introduced in the previous section is applied through a case study to investigate how the total cost varies with respect to varying service standard (e.g., traffic volume threshold). The case analysis network includes a total of 138 patrol routes covering the major portion of Class 1 and 2 highways in Ontario with a total of 20,315 equivalent single lane kilometers (Figure 5). The WADT distribution of these highways is shown in Figure 8. Note again that Class 1 represents a higher maintenance standard with a bare pavement regain time (BPRT) of 8 hours when compared to Class 2, which has a BPRT of 16 hours.

Figure 9 shows the relationship between the maintenance cost and safety cost, and WADT threshold values. As the threshold value increases, fewer roads are classified into Class 1 but more into Class 2, resulting in decreased total maintenance cost since less amount of salt is used on average on Class 2 roads than it is on Class 1 roads. In contrast, the expected number of collisions (thus collision costs) will increase as more highways are maintained at a lower standard. Therefore, the relative benefit of WRM (Safety benefits) will decrease as the threshold value increases.

Figure 10 (a) shows the net annual benefit of WRM as a function of the threshold WADT for the winter season 2005-2006 as well as two hypothetical winter scenarios. The hypothetical winter severity scenarios were created by increasing and decreasing the duration of snow events of the base scenario by 20%, which are intended to investigate the cost and benefit implications of different degrees of winter severity. As expected, the relationship exhibits a convex form, indicating an optimum WADT threshold exists under which the net benefit of WRM reaches the maximum for the given network. For the base condition, the optimum threshold WADT lies around 20,000, which corresponds to the net seasonal benefit of greater than 4.2 million dollars (Figure 10-b). The WADT threshold currently being used to demarcate Class 1 and 2 highways in Ontario is 10,000, of which the net benefit is approximately $4 million dollars. The same conclusions could be reached if only the safety benefit is considered (Figure 10-a).

As shown in Figure 10, the net annual benefit of WRM as well as the optimal maintenance policy depends on the winter severity. As expected, the net benefit of WRM increases as the severity of winter weather increases. If the highways were classified under the optimal WADT threshold, a 20% increase in winter severity (event duration) would result in over 40% increase in net benefit. The more severe the winter season, should the optimal threshold value be lower, or LOS standard be higher.

It is important to note that the results of the case analysis, while making an intuitive sense, should not be taken in an absolute sense for the following reasons. First, the analysis includes a number of model parameters, including value of time (VOT), value of trip-making, and maintenance cost ratio between Class 1 and Class 2 highways (Appendix B). Secondly, not all of the costs and benefits incurred due to WRM have been accounted in the case study. For example, changes in highway standards are expected to have an effect on vehicle operations thus fuel consumptions and emissions, meaning that higher benefits are associated with the WADT threshold. Also, road salts have been shown to have a detrimental effect on the environment, the infrastructure, and the vehicles, all of which should be considered in a comprehensive cost-benefit analysis as they represent indirect costs of WRM. The inclusion of these additional cost and benefit factors may lead to different patterns for the net benefit curve of WRM and thus the optimal WADT threshold.

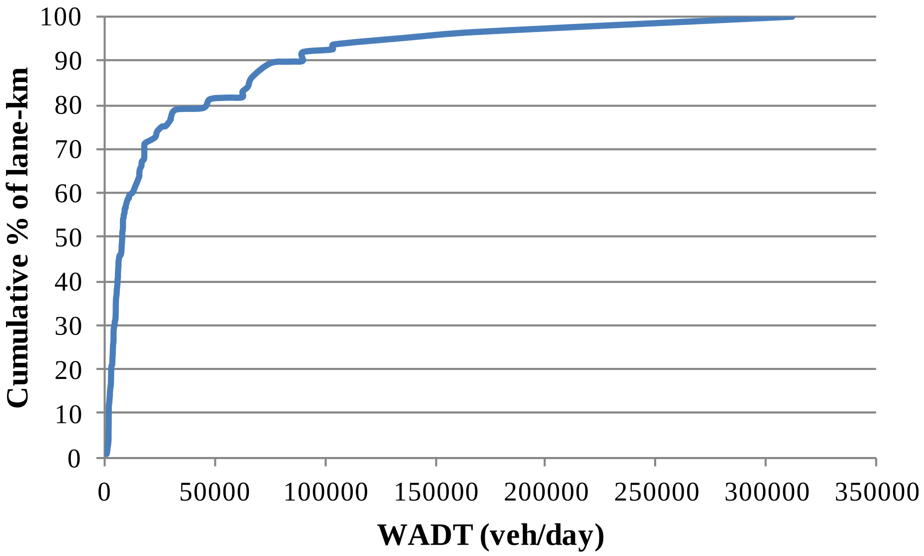

Figure 8: WADT Distribution of Lane-km of Class 1 and 2 Highways in Ontario

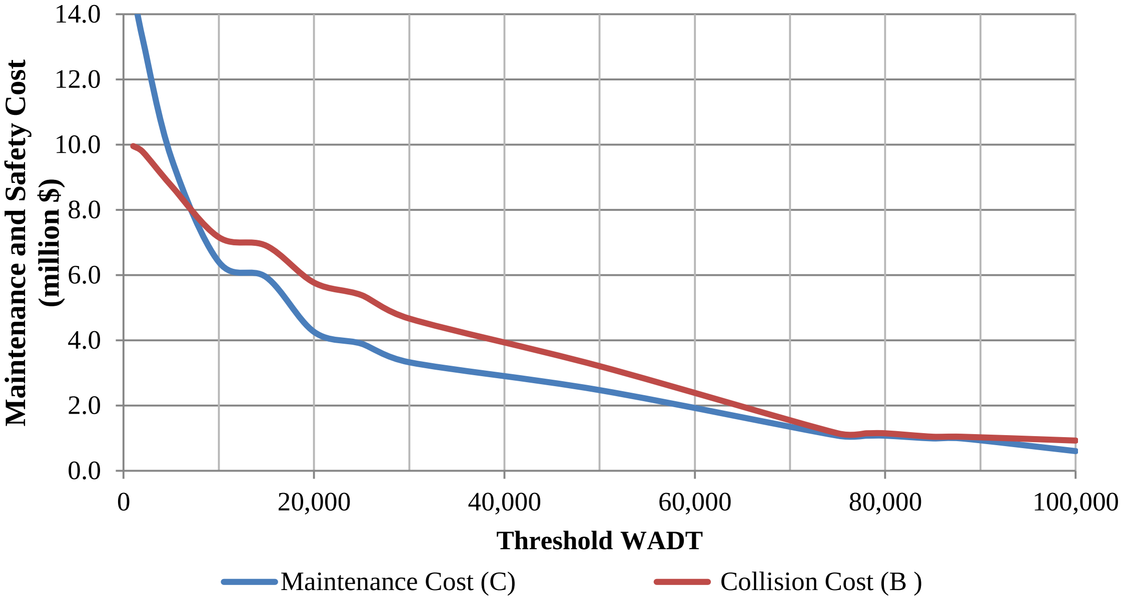

Figure 9: Maintenance Cost and Safety Benefit under Different WADT Threshold

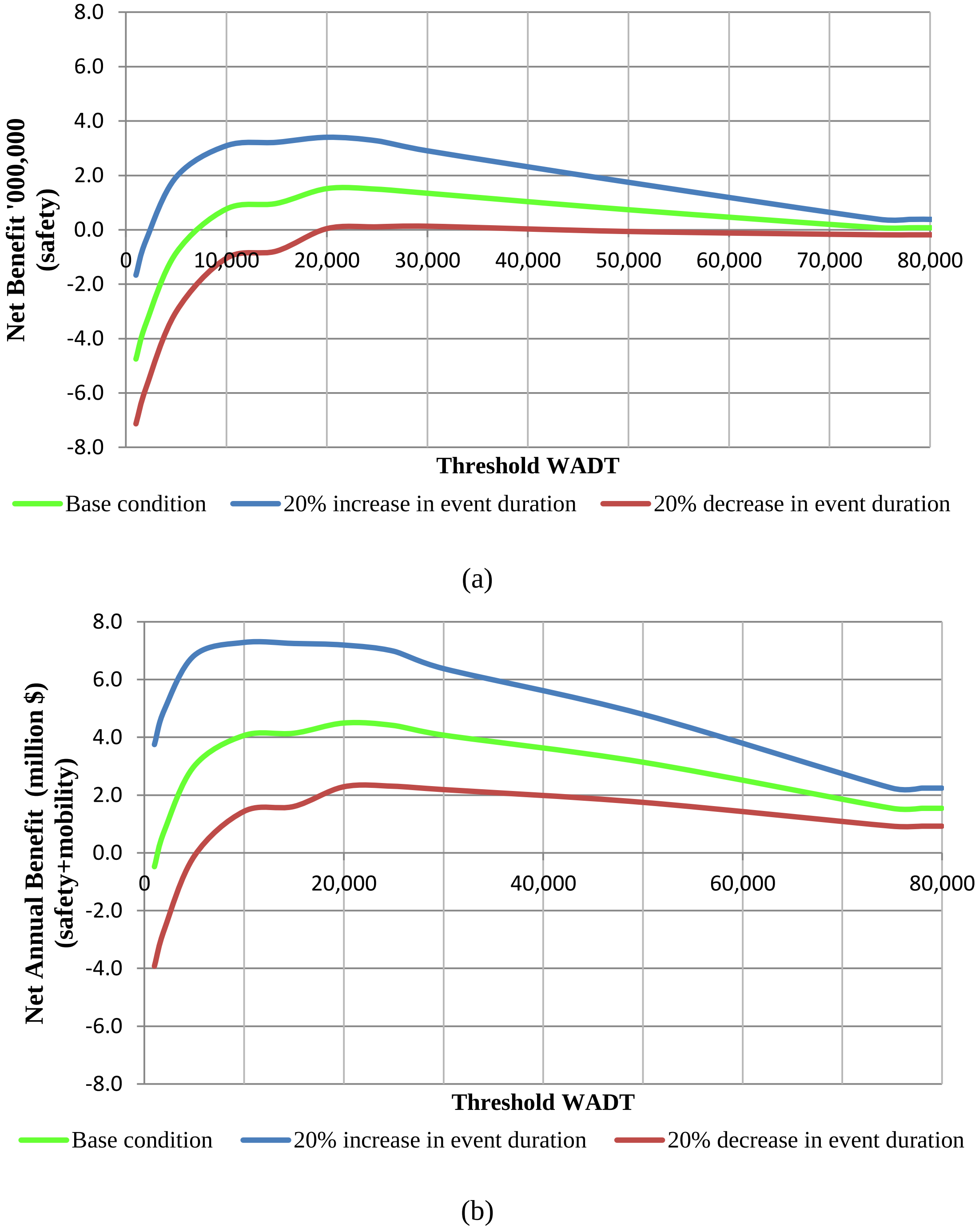

Figure 10: Sensitivity of Net WRM Benefit to Threshold WADT under Three Weather Scenarios

Conclusions and Future Research

This report summarizes the results from a study with the objective of applying various performance measurement models for evaluating alternative winter road maintenance service standards. A cost-benefit framework is proposed, which integrates both maintenance costs and benefits. Maintenance costs are captured by a salt application model, which relates the amount of salt used in a winter event to various weather variables as well as the class of the highway. The maintenance benefit is represented as the reduction in collisions, reduction in trip cancelation, and saving in travel time due to differential levels of service and thus maintenance services between different classes of highways. A case study has demonstrated the feasibility of applying a quantitative approach to assessing alternative service standards under winter weather of different severity.

The research can be extended in several directions as follows:

- The research has focused on a sub highway network consisting of only two classes of highways (Class 1 and Class 2 highways). Further research should be conducted to determine the optimal thresholds for multiple service classes.
- Cost models should be improved to capture the capital costs of WRM, such as patrol yards, fleet size of maintenance vehicles and staffing, as related to maintenance LOS standards.
- Further efforts should be followed to investigate the sensitivity of the benefit cost results to various model assumptions.
- Maximum allowable bare pavement regain time (BPRT) is commonly used as the main performance measure defining the LOS of different classes of highways. The proposed benefit-cost framework and related input, output, and outcome models can be applied to determine the optimal allowable BPRT for individual classes.
- In future research, other maintenance benefits such as reduced fuel consumption and emissions should also be incorporated into the cost-benefit analysis framework.
- With the outcome models described in this report, more comprehensive performance measures could be developed to capture the main effects of weather and maintenance on road safety and mobility. For example, a storm based winter severity index could be defined on the basis of relative increase in collision risk and reduction in traffic speed. Similarly, a comprehensive winter maintenance performance index could be developed by considering the relative improvement in

safety and mobility that could be attributed solely to maintenance activities. Such an outcome-based performance measure is capable of capturing both the overall road surface conditions during a storm and the bare pavement regain time.

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Appendix A:

Table A.1: Values for Month and Site Indicators for the Collision Model

Variables		Coefficients	Sig.
M	October	0.000	
	November	-1.048	0.000
	December	-1.229	0.000
	January	-1.193	0.000
	February	-1.537	0.000
	March	-1.248	0.000
	April	-1.049	0.000
S	Site 1	-2.607	0.000
	Site 2	-1.232	0.021
	Site 3	-2.815	0.000
	Site 4	-3.317	0.000
	Site 5	-2.464	0.000
	Site 6	-1.936	0.000
	Site 7	-1.456	0.000
	Site 8	-1.268	0.000
	Site 9	-2.181	0.000
	Site 10	-2.128	0.000
	Site 11	-1.782	0.000
	Site 12	-1.374	0.000
	Site 13	-1.287	0.000
	Site 14	-2.139	0.000
	Site 15	-1.497	0.000
	Site 16	-2.019	0.000
	Site 17	-1.467	0.000
	Site 18	-1.410	0.000
	Site 19	-1.631	0.000
	Site 20	-1.459	0.000
	Site 21	-0.628	0.000
	Site 22	-1.384	0.000
	Site 23	-1.143	0.000
	Site 24	-0.997	0.000
	Site 25	-1.635	0.000
	Site 26	-0.810	0.000
	Site 27	-1.175	0.000
	Site 28	-1.606	0.000
	Site 29	-1.216	0.000
	Site 30	-0.986	0.000
	Site 31	0.000	

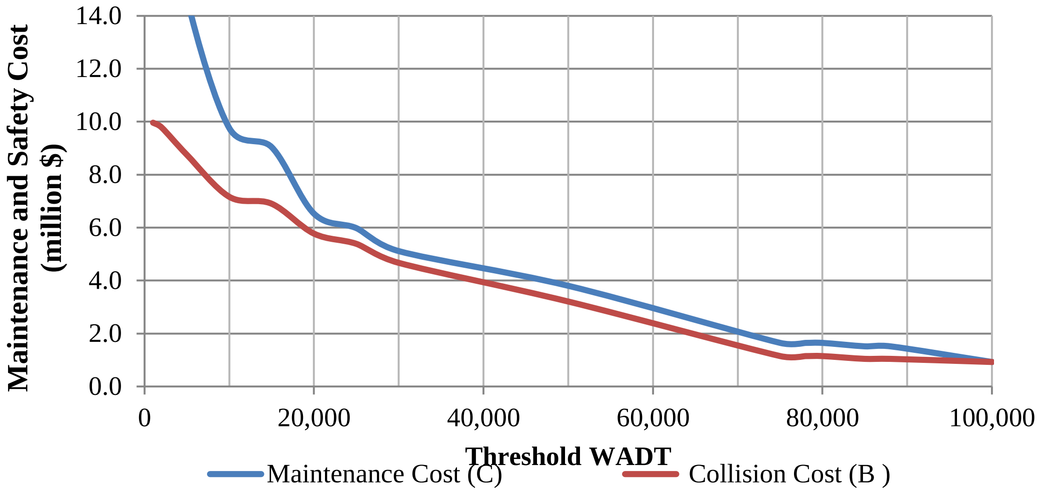
Table A.2: Values of Site Indicators for Traffic Volume and Speed Models

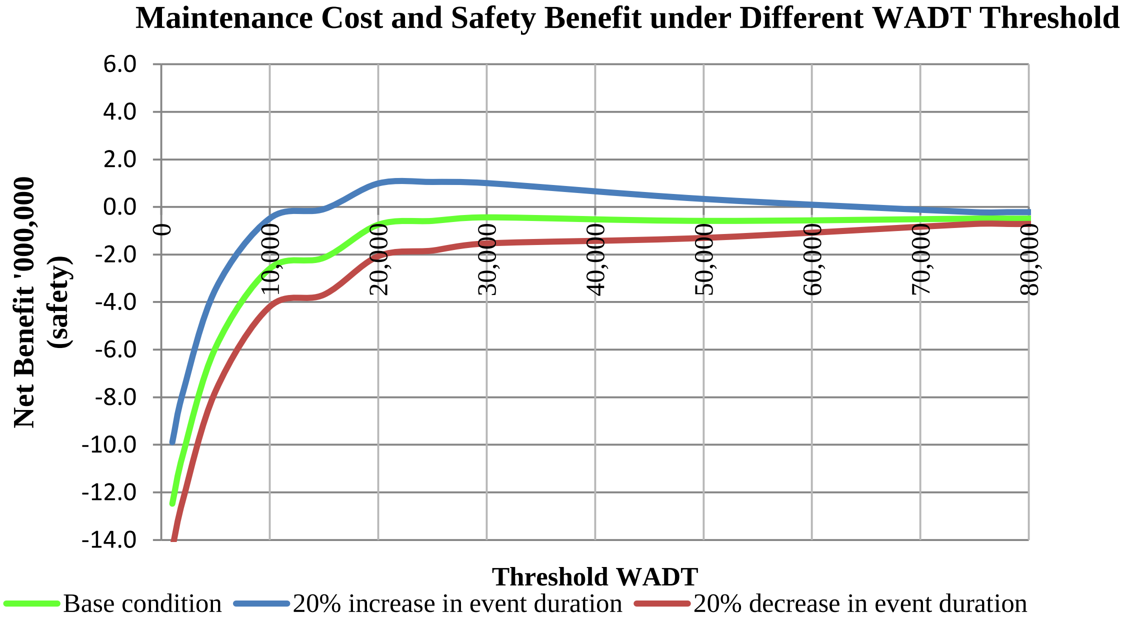
Variable		Traffic Volume		Median Speed	
		B	Sig	B	Sig
S	Site 1	0.041	0.000	0	
	Site 2	-0.129	0.000	-4.521	0.000
	Site 3	-0.019	0.000	7.664	0.000
	Site 6	0.041	0.000	12.023	0.000
	Site 7	0.071	0.000	12.459	0.000
	Site 8	-0.017	0.000	12.812	0.000
	Site 9	0.068	0.000	7.825	0.000
	Site 10	-0.008	0.000	10.295	0.000
	Site 11	0.025	0.000	17.189	0.000
	Site 12	0.063	0.000	11.380	0.000
	Site 13	-0.021	0.000	10.031	0.000
	Site 14	0.084	0.000	7.244	0.000
	Site 15	0.006	0.006	0	
	Site 16	0.0003	0.827	8.408	0.000
	Site 17	-0.0003	0.875	9.897	0.000
	Site 20	-0.069	0.000	8.411	0.000
	Site 21	-0.025	0.000	15.273	0.000
	Site 25	-0.031	0.000	0.740	0.276
	Site 27	-0.003	0.000	13.331	0.000
	Site 29	0.043	0.000	8.230	0.000
	Site 31	0		0	

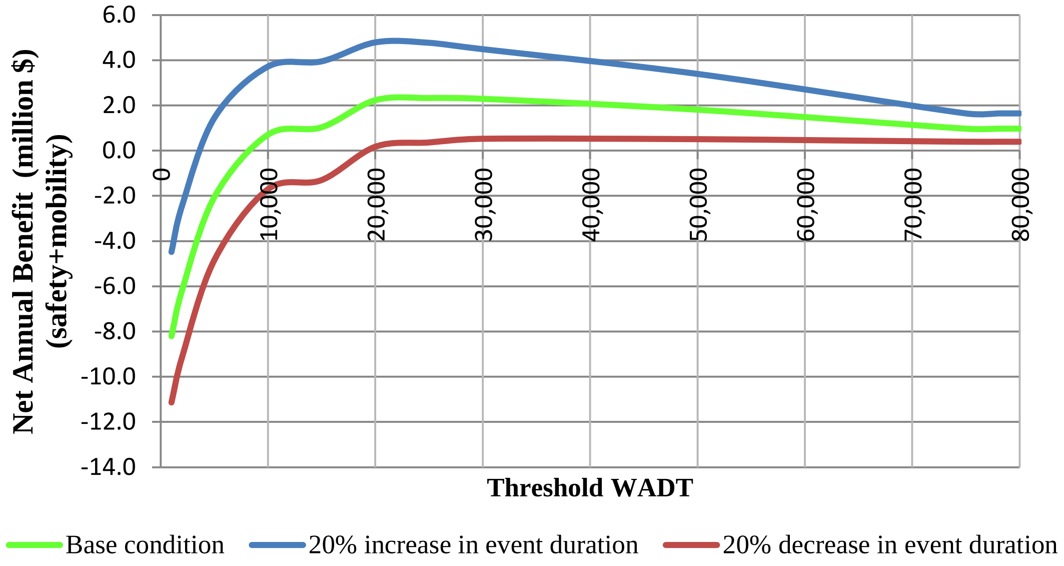
Appendix B:

Different multiplication factors assumed for calculating the maintenance costs

Road Class 1= 3
Road Class 2= 2.3







Sensitivity of Net WRM Benefit to Threshold WADT under Three Weather Scenarios