A Benefit-Cost Approach to Level of Service Standards for Winter Road Maintenance

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Abstract

Road management agencies must adapt to constraints on operating resources through adjustment to services such as winter patrolling, plowing and salting. While the resulting cost savings can be readily estimated, the adjustment must also consider changes to societal benefits and these may be difficult to estimate.

Improved availability of high resolution highway operations, weather and traffic data have allowed the modelling of relationships among road surface conditions, weather, accident rate and traffic flow that can be applied to estimate the benefits of winter maintenance under varying service levels.

This study combines previously developed road safety models with empirical characterizations of road surface conditions over a winter season to estimate the relative costs and benefits of winter maintenance on the highway network in Ontario. Case studies are used to illustrate the influence of service level and winter severity on the benefit:cost consideration in adjusting operating resources.

1. INTRODUCTION

Winter maintenance is a critical public service in high latitude and altitude areas of all quadrants of the globe subject to cold temperatures, frost and snow. By anticipating and monitoring winter weather and road conditions, plowing and applying chemicals or grit to maintain or restore a safe driving surface, highway agencies reduce the risk of accidents and support economic activities by improving traffic flow with minimal weather-related delays.

The direct cost of winter services can be high, including purchase and maintenance of specialized vehicles and equipment, extra or round-the-clock staffing, de-icing chemicals, grit, and road-weather information systems. The level of expenditure for winter maintenance is estimated to total more than $3Billion per year in North America alone (1). In addition, the materials used in winter maintenance generate indirect costs from their effects on vehicles and roadway or roadside infrastructure, roadside plants and drinking water (2).

Highway agencies are challenged to find the right level of winter maintenance services that provides the desired safety and mobility benefits at an affordable cost. Past studies have focussed on either the costs or benefits of winter maintenance or its components. For example, Environment Canada (2) lists representative unit costs of major equipment, materials and processes, which may be aggregated to estimate the costs at a particular location or characterize the cost-sensitivity of the activity to its various components. Venalainen and Kangas (3) illustrated how the costs vary with severity of climate. Ye at al (4), estimated the costs of road-weather information systems and the increment in benefits that they provide to winter maintenance. Veneziano et al (5) expanded this approach to develop a tool-kit for analyzing the direct and indirect costs and benefits of many individual components of the winter maintenance process, although they found that quantifying the benefits is a challenging undertaking. The main focus of this work was to establish whether the cost of implementation of new technologies can be recouped through direct savings in equipment or material use, and secondarily through indirect savings such as reduced accident rate and weather-related congestion. The studies were challenged in estimating the indirect savings, and this challenge has recently been addressed through development of empirical models relating changes in accident rate and traffic flow to road surface and weather conditions(6, 7, 8, 9).

Significant progress has been made in characterizing the costs of providing winter maintenance services, and in estimating direct benefits to highway agencies and indirect benefits to road users. Characterizing the costs and benefits is a signficant advance but does not provide the analysis that road agencies require to establish an appropriate level of service, where costs are balanced by benefits to society. The purpose of this study is to develop an analytical framework which can be used to establish a balance between direct costs and indirect benefits in service standards for winter maintenance.

2. WINTER MAINTENANCE STANDARDS AND LEVELS OF SERVICE

Demands for consistent driving conditions across jurisdictions and for public accountability have led many agencies to establish winter maintenance standards and levels of performance 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 descriptor 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.

Standards may vary by road classification. For example, highways in Ontario are grouped into five classes divided by Winter Average Daily Traffic (WADT) threshold values. High class road means these roads are given priority for maintenance intending to provide shorter BPRT time. For example, Class 1 roads should be restored to essentially bare condition witin 8 hours after a storm ends, as shown in Table 1.

However, the WADT threshold values used for road classification differ considerably among jurisdictions, as shown in Figure 1, which includes jurisdictions with measures similar to BPRT. For example the threshold traffic level separating the highest and second highest classes is 10,000 in Ontario compared to 30,000 in Minnesota, and the BPRT for the highest class highway is 8 hours in Ontario vs 3 hours in Minnesota, or 6 hours in Wisconsin. Ontario has a longer allowed regain time than some other example jurisdictions in its highest class of highways, but includes highways with a wider range of traffic in that class. For the lowest highway class, regain time standards vary from 3 hours in New York to 36 hours in Minnesota.

Table1 - MTO's Standards and Levels of Service

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, driveable

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

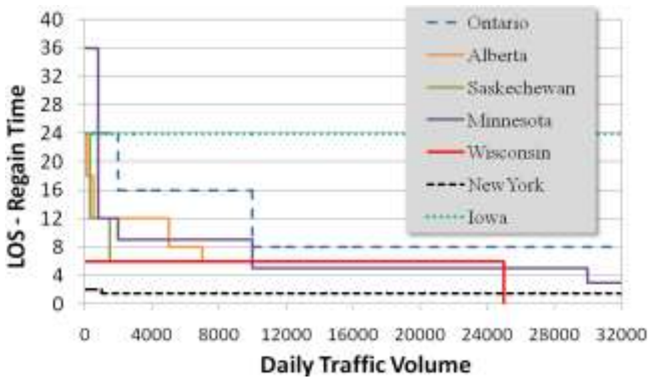

Figure 1 - Output Standards by Highway Class, for Various Jurisdictions in North America
Source: survey of agencies

3. Methodology

The overall approach to this study is to estimate the total direct and indirect costs associated with winter weather, and to analyse how the total costs vary with winter service level. The direct costs used in this study include road salt, spreading equipment and labour, and overheads. The indirect costs included in this model are the road user collision costs. The winter service levels included in this study are the Class 1 and 2 performance standards used in Ontario (Table 1). The cost models are applied to 31 Class 1 and 2 highways which are then extrapolated to all Class 1 and 2 highways in the Province, to estimate the total costs of winter weather. The variation in total costs is estimated as the traffic threshold between Class 1 and 2 is varied, to identify the most cost-efficient threshold under observed climate conditions, and also under less severe and more severe climates.

The direct costs and the indirect, collision costs are estimated from models that predict the duration of winter conditions (BPRT) during each storm event, and an index of the average road surface condition (Road Surface Index, RSI) during the storm event (Figure 2). The

RSI index (Usman et al, 2011) represents a surrogate measure of traction and corresponds to major classes of road surface conditions defined in the Ontario road condition reporting system (Figure 3). The models are calibrated from historical data at 31 Class 1 and 2 highway maintenance routes with a variety of traffic levels and distributed across all regions of the Province (Figure 4).

The calibrated models are applied to thirty-one patrol routes to estimate the expected amount of salt usage and collision numbers by considering each route as both Class 1 and 2 for winter season 2005-06. Thus, seasonal salt usage (kg/lane-km) and collision (number/WADT-km) are obtained for each patrol route. Furthermore, a range of arbitrary WADT threshold values are selected to compute the total maintenance and collision cost for a larger network consisting of all Class 1 and 2 highways in Ontario. In all the models except the collision model, Road Class was included as a categorical variable to reflect the implication of BPRT policy. The effect of Road Class was captured in the collision model by the RSI variable estimated from its corresponding model.

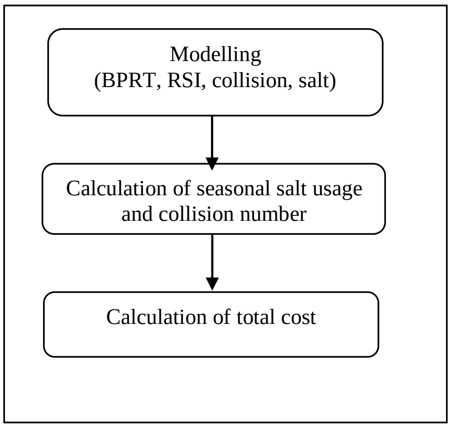

Figure 2 - Framework of Methodology

Figure 3 - Road Surface Classes and Road Surface Index

3.1 Data

Thirty-one maintenance patrol routes were selected from different regions of Ontario, Canada for BPRT and RSI modeling, which were subsequently used as an input in the collision model. The location of these patrol routes is shown in Figure 4.

These models were developed from almost 11,000 observations drawn from six winter seasons (2000 – 2006) (Table 2). Due to data limitations, the salt use and maintenance cost analysis was based on thirty-one 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 1or 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.

Data were obtained from varous 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),
- traffic volume count from MTO loop detector and permanent data count stations.
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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 was mapped with the data from MTO's Maintenance Management Information System (MMIS) database. The sites, data and its processing, are described in detail by Usman et al. (10). Further, for the cost analysis, 145 patrol routes (20,352 equivalent lane-kilometers) representing all Class 1 and 2 highways in the Ontario Provincial network were considered. These routes were selected based on availability of basic inventory data required for cost analysis such as WADT, section length and equivalent lane kilometre (Figure 5).

Table 2 - Descriptive Statistics for Data Used in Collision, RSI and BPRT model

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	0.248	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	0.802	11.17	18295
St.Dev	5.0	8.8	6.23	6.82	1	0.136	9.61	35162
Sample size: 10,932								

Table 3 - Descriptive Statistics for Data Used in Salt Usage Model

Average Event Based Data								
	Temp. (C)	Wind Speed (km/hr)	Visibility (km)	Total Precip. (cm)	Salt Usage (kg/lane-km)	RSI	Event Duration	BPRT (hr)
Min	-29.87	0	0	0.02	0	0.247	2	0
Max	4.90	60.50	32.2	42.76	4691	0.989	47	44
Avg.	-5.15	14.62	11.84	3.67	256.91	0.772	11.88	1.54
St. Dev.	5.27	8.67	6.16	3.67	344.70	0.137	9.77	3.51
Sample size: 5207								

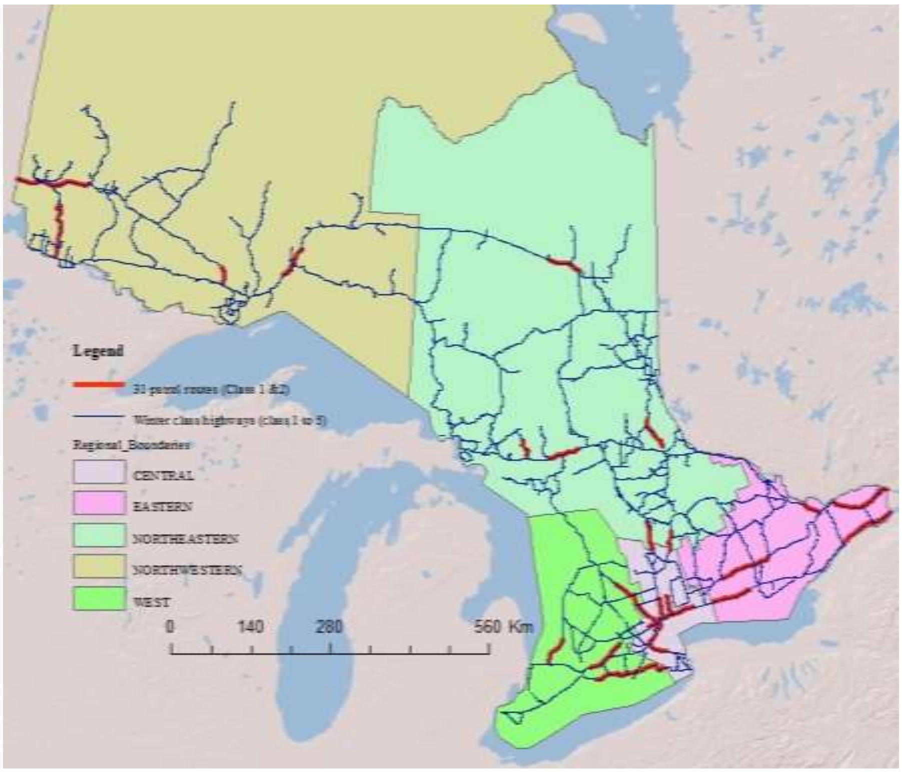

Figure 4 - Thirty-one Class 1 and 2 routes used for model calibration, Ontario, Canada

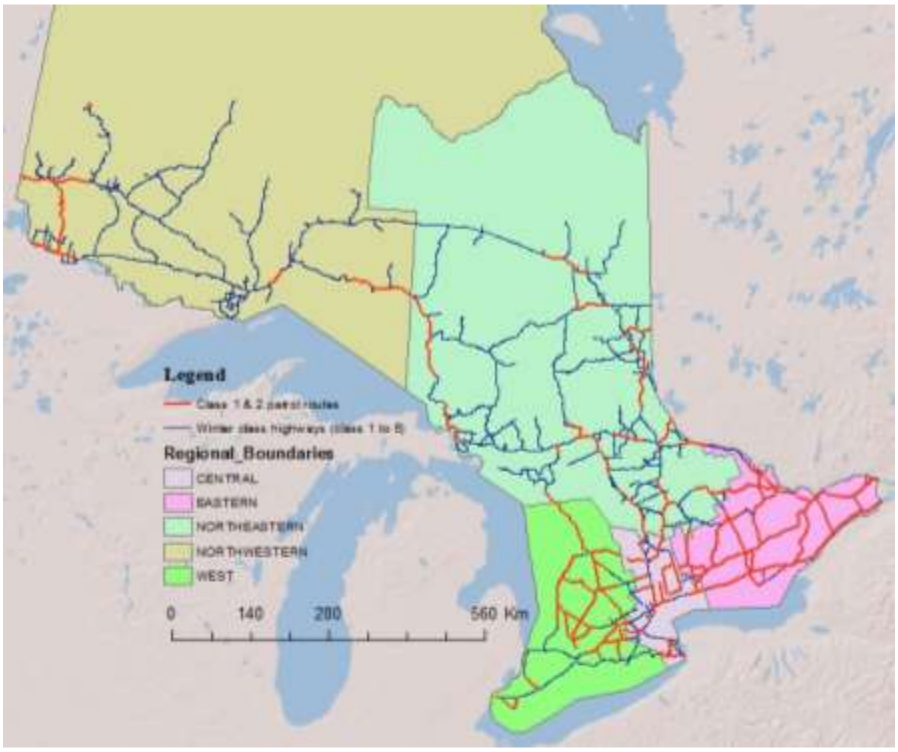

Figure 5 - 145 Class 1 and 2 patrol routes, Ontario, Canada

4. Modelling

4.1.1 BPRT and RSI Model

Bare pavement regain time (BPRT) is measured from the end of storm to the time until 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, road Class 1 is expected to have less BPRT time compared to road Class 2. In order to capture all these potential influencing factors, a multivariate linear model was calibrated (Equation 1). The result shows that temperature, wind speed and total precipitation within that particular snow storm event are significant. Similarly, road class was included as a categorical variable such that Class 1 has lower BPRT time than Class 2. The coefficient for road class is 0 if Class is 2.

$$BPRT = 0.16 - 0.19 * T - 0.01WS + 0.19TP - 0.33\,(Road\ class\ 1) \qquad \text{Eq. 1}$$

Where,
T= Temperature (C)
WS= Wind Speed (Km/hr)
V = Visibility (Km)
TP= Total precipitation (cm)

Similarly, average RSI condition over a snow storm event could be a function of weather factors and road class. This hypothesis was explored using a linear regression model. Since, RSI value lies between 0 and 1, to meet this requirement RSI was transferred using the logit formulation $\ln\left(\frac{\mathbf{RSI}}{\mathbf{1-RSI}}\right)$. The calibrated model result is given in Equation 2. The factors such as temperature, wind speed, total precipitation and event duration were found 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.

$$RRSI = 1.96 + 0.01 * T + 0.01WS - 0.03TP - 0.03\ ED + 0.17\ (Road\ Class\ 1)$$
$$RSI = \frac{1}{1 + e^{-RRSI}}$$ Eq. 2

Where,
ED- Event duration

4.1.2 Collision Model

In our recent effort, we have conducted a benefit analysis of winter road maintenance based on an event based collision model (6). In road safety literature, the most commonly employed approach for 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 (11, 12, 13, 14). 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. (6), the same collision model was adopted here.

The summary of calibrated results is given in Equation 3. In this model, road surface condition, expressed in RSI as a surrogate measure of pavement friction, was found significant. As we have observed from the RSI model that the Class 1 roads have higher RSI values, representing better road surface condition demanded by a higher LOS standard, this implication of road classes will be reflected in the collision model. The higher RSI indicates that there is less likelihood of collision occurrence.

$$\mu = Exp^{0.648} * e^{-3.912-0.018T-0.009WS-0.044V+0.014TP-4.42RSI+M+S}$$ Eq. 3

Where,
μ = Expected number of collision
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 (Fu et al., 2012)
S= Indicator for site (Fu et al., 2012)

4.1.3 Salt Usage Model

For winter road maintenance operation, 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 (15). 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 using a linear model which is subsequently converted to total maintenance cost using a reasonable conversion factor.
Equation 3 shows the results obtained by model calibration. The severity of weather condition (e.g., temperature, precipitation) increases the amount of salt usage. 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,.

$$Salt = 57.6 - 0.64 * T - 1.36WS + 26.65TP - 50.56\ (Road\ class\ 1) + 8.6ED + 0.01TT + 32.26\ (if\ Anti-icing)$$ ~~Eq. 4~~

Salt=57.6-0,64*T-1,36WS+26.65T+50.56 Road Class 1 + 8.6ED+0.01TT+32.26(Anti-icing) Eq. 4

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Where,
Salt = kg/lane/km
TT- Total traffic volume

5. Cost Analysis

5.1 Seasonal Salt Usage and Collision Occurrence

Seasonal salt usage and collision occurrence was estimated for all thirty patrol routes by considering each route as both Class 1 and as Class 2. For this, data from a winter season 2005-06, which has the most complete set of winter snow storm event data (i.e., weather conditions, precipitation duration and traffic volume) compared to the other seasons, was used. Previously developed models were implemented at different stages as presented in Figure 6.

First, BPRT model was used to estimate BPRT time for each snow storm event. This BPRT time was then added to total precipitation time to compute estimated event duration. As seen in all the models, event duration is one of the significant factors in all models. Second, RSI model was used to calculate average RSI for that particular event duration. After estimating event duration from BPRT model and RSI from RSI model for each event, these were further used as input variables to estimate salt usage and collision using their respective models (i.e., Equation 3 and 4). Furthermore, total salt usage and collision number was aggregated based on sites (30 patrol routes) and Road Class. This lead to a final output of seasonal salt usage (kg/lane-km) and collision (number/WADT-km) for each patrol route for both the Road Class scenarios.

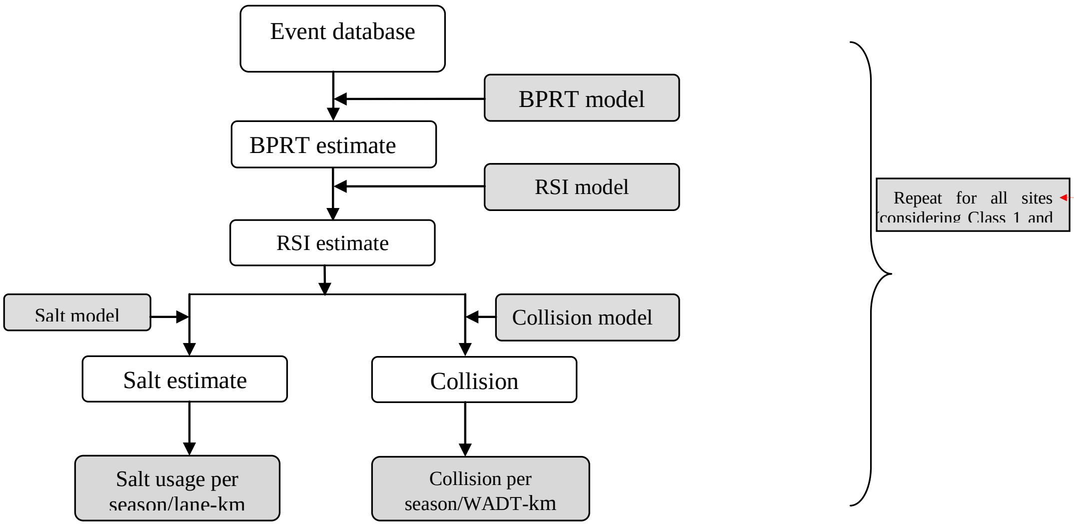

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Figure 6 - Framework for Calculation of Seasonal Salt Usage and Collision Occurrence

5.2 Maintenance and Collision Cost

A cost analysis approach was carried out for the larger road network consisting of 145 patrol routes including both the Class 1 and 2 highways. These routes were selected based on availability of basic inventory data such as WADT, section length and equivalent lane kilometre required for cost calculation. This road network represents total of 20,315 equivalent lane-km (Figure 5). Figure 7 shows the frequency distribution of WADT for the Class 1 and 2 routes, and where over 80% of total routes have WADT below 20,000.

Figure 8 illustrates the methodology for calculation of direct cost. First, a certain arbitrary WADT threshold value was selected and, this was used to classify each patrol route into either Class 1 or 2 highway. This is then followed by two parallel cost calculations i.e., maintenance and collision cost. First, for each patrol route, seasonal salt usage is extrapolated to each Class 1 or 2 highway based on the per km application at one of the 30 sample sites with similar WADT and within the same geographically-based administrative region (Figure 4,5). This was multiplied by lane-km of respective routes to estimate the total amount of salt needed for maintenance. The cost of salt for each patrol route was obtained by taking product of total salt usage and unit cost of salt (Table 4). All the patrol costs were added to obtain the total salt cost. According to Department of Transportation, Wisconsin, the ratio of salt cost to operation cost is approximately 1.68. Therefore, the multiplication factor 2.68 was used to covert salt cost to total maintenance cost (Table 5).

Table 4 – Unit Cost Assumptions

Cost Assumption	Value	Reference/Source
Unit collision cost ($)	77,035	~~TAC, 2004~~TC, 2007
Unit salt cost ($ per kg)	0.06	MTO, 2004
Inflation rate for year 2004-2013	1.17	Bank of Canada, 2013

Table 5 - Derivation of Multiplication Factor for Total Maintenance Cost

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: (15)

Similarly, seasonal collision number was also allocated to each patrol route based on the geographical region and closeness to WADT values as reference to thirty sites. This unit seasonal collision rate was used to calculate collision number for the specific route based on their WADT-km. Transport Canada has carried out a study quantifying the total social cost incurred by collision in Ontario's highways based on 2004 statistics (16). This study was based on willingness- to-pay approach which included direct cost such as fatality, injury, property damage, and indirect cost such as travel delay, fuel and pollution cost. According to this study, the average per unit collision cost was $ 77,035.00. This unit cost was multiplied to collision number to obtain collision cost for each patrol route. All the patrol cost was added to obtain the total collision cost. Note that both the maintenance and collision costs were converted to present cost using inflation rate of 1.17. The whole process was then repeated for a range of arbitrary WADT threshold values.

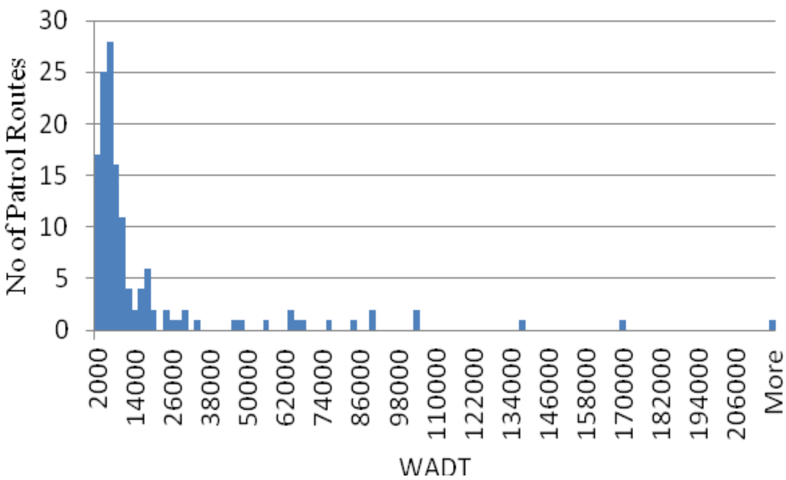


Figure 7 - Histogram of WADT for 145 Class 1 and 2 Patrol Routes

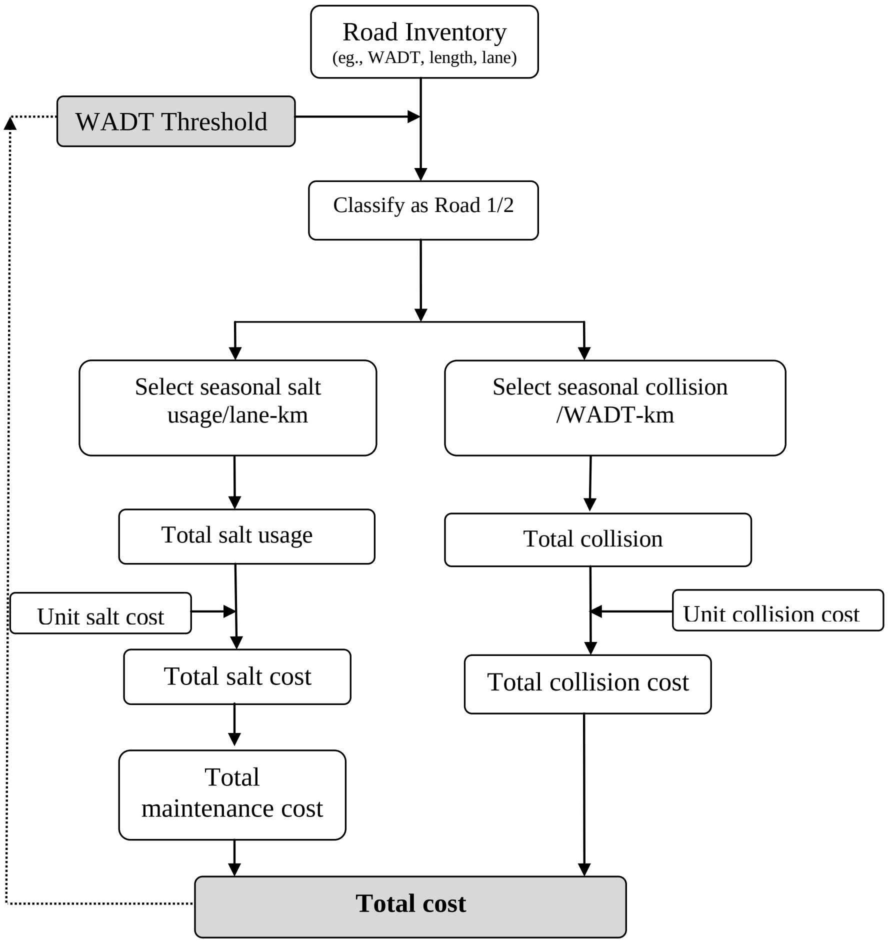


Figure 8 - Framework for Calculation of Total Cost

6. Results and Discussion

The relation between WADT threshold values, collision and maintenance costs is illustrated in Figure 9. As the threshold value increases, fewer roads are grouped in Class 1 with 8 hour BPRT standard and more are grouped in Class 2 with 16 hour BPRT standard, therefore, the collision cost increases with increasing exposure to snowy conditions. On the contrary, maintenance cost decreases as the threshold of WADT increases because less salt is used on average on Class 2 roads than on Class 1 roads. The sensitivity of costs to WADT is highest at low values of WADT, reflecting the distribution of WADT values of Class 1 and 2 highways in the Ontario network (Figure 7).

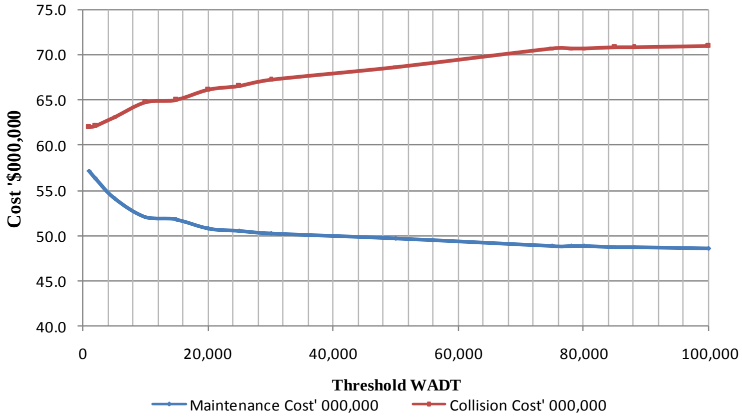
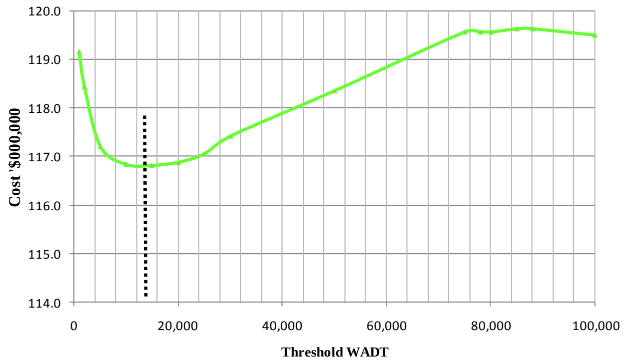


Figure 9 -Total Maintenance and Collision Cost

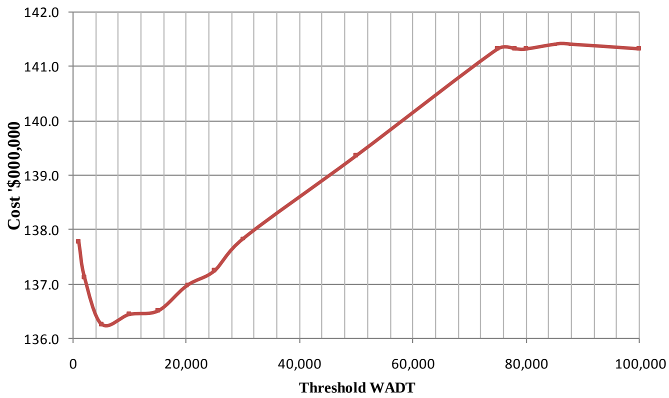
An optimum threshold of WADT between Classes 1 and 2 , defined as the minimum total cost incurred to the road maintenance agencies and users, is approximately 12,000 for the Ontario highway network used in this study (Figure 10a). Again, the sensitivity of total cost to WADT reflects the particular distribution of WADT for the Ontario highway network, which includes many routes at the low end of the WADT range and fewer at the high end. The measure of routes produces somewhat different results than would a more generic measure of highway kilometres, but since route length is defined by plowing and spreading cycle times the lengths are somewhat standardized across the network.

The estimated total cost shown in Figure 10 includes direct maintenance costs and indirect costs of collisions. Some costs that might be considered in the analysis are not included, principally environmental costs associated with road salt, and the indirect cost of traffic congestion to road users. Environmental concerns have recently been introduced as a factor in planning of highway operations (ref for EC road salt mgt, and for FHWA and salt institute sustainability charts) but have not yet been factored in cost analyses. It may be assumed that the environmental cost of road salt parallels the mass of salt used. Recent analyses on the societal cost of traffic congestion in relation to winter conditions (Fu, Taimer...) suggest that it roughly parallels the collision cost and is sensitive to similar factors. The inclusion of these factors would increase the total cost of winter conditions reported in this analysis but would produce a curve of similar characteristics in relation to WADT.

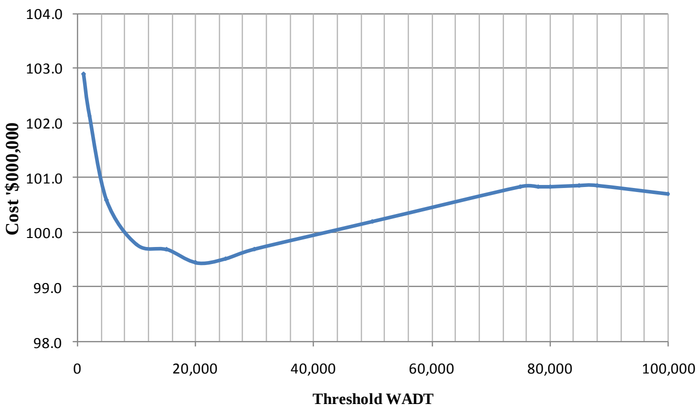
The effect of winter severity on total cost of maintenance was investigated by increasing and decreasing the duration of snow storms by 20%, with other factors held constant. As expected, the total costs associated with winter weather increases with increasing winter severity (Figure 10b) and decreases with decreasing winter severity (Figure 10c). The most cost effective WADT threshold shifts from approximately 12,000 for the test case of winter 2005-06 (Figure 10a) to 4,000 for the more severe winter (Figure 10b) and 20,000 for the less severe winter (Figure 10c). The minimum total cost increases by 17% for the case with 20% longer storms and decreases by 15% for the case with 20% shorter storms. Total costs escalate rapidly with increasing WADT threshold when winter is more severe but are relatively constant when winter is less severe. This trend to cost effectiveness with lower thresholds under more severe conditions, favouring grouping more highways in Class 1 than in Class 2, suggests that the benefit in reduced collisions in Class 1 outweighs the increase in direct maintenance costs under more severe winter conditions.



(a) Base Condition



(b) 20% Increase in Event Duration



(c) 20% Decrease in Event Duration

Figure 10 - Sensitivity of Total Cost (Maintenance and Collision) to Event Duration

7. Conclusions and Recommendations

A methodology has been developed for the analysis of winter maintenance standards from a cost: benefit perspective, including the direct cost of services and the indirect benefits derived by society. The analysis derives salt use and maintenance costs from readily available statistics on winter weather, and uses winter-event based information on weather and road surface conditions to estimate the cost of vehicle collisions as a surrogate for the indirect benefits. The methodology can be expanded to include other indirect factors, such as environmental costs of road salt and the cost of travel delay, where supporting data or models are available.

The model was applied to the case of the public highway network in the Province of Ontario, Canada, to analyse the change in total costs with service level, by varying the threshold between highway Class 1 with an 8 hour BPRT standard and Class 2 with a 16 hour standard. The most cost-effective threshold was WADT 12,000 under base conditions of winter severity. Costs increase at lower thresholds as the cost of providing more intensive services to lower volume highways outweighs the accident reduction benefits, and increase at higher thresholds as the increased accident costs dominate.

This study analysed an optimum threshold between two highway classes. A similar approach can be taken to compare other existing classes, or to subdivide classes that include wide ranges of traffic or other characteristics that affect direct or indirect costs.

Most importantly, the study demonstrates an expansion of the cost:benefit approach that has previously been applied to evaluating specific technologies for highway maintenance, to the analysis and testing of economically sustainable maintenance standards..

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