How Much Is the Safety and Mobility Benefit of Winter Road Maintenance?

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ABSTRACT: Winter road maintenance activities are intuitively beneficial due to their critical roles in maintaining the safety and mobility of highway networks in winter seasons. There is however no robust methodology currently available for quantifying these benefits, which are needed for comprehensive cost-benefit analyses of all winter road maintenance decisions. This paper introduces a set of collision and mobility prediction models that have the potential to address this need. The models were developed using a unique data set containing detailed hourly records of road weather and surface conditions, traffic counts, and collisions for a number of Ontario highway routes. Several case studies are used to illustrate the applications of these models for evaluating alternative winter maintenance policies and operations, such as changing of bare pavement recovery time, changing maintenance operation deployment time, and changing level of service standards.

1. INTRODUCTION

Safety and mobility becomes the main source of concern for transportation officials during snow storm events. Driving conditions in winter vary dramatically and deteriorate quickly due to snowfall and ice formation. This can cause a significant reduction in pavement friction thereby increasing the risk of accidents and reducing the mobility (***1 – 13***)

Winter road maintenance (WRM) activities such as plowing and salting play an indispensible role in maintaining good road surface conditions and ensuring the mobility and safety of road networks (***1, 8, 14 – 19***).

While essential for keeping roads safe, WRM operations also incur significant monetary costs and negative environmental effects. For example, the direct cost of winter maintenance programs in Ontario is estimated to exceed $100 million annually (***20***). This represents 50% of its total annual highway maintenance budget (21). The total WRM cost is estimated to be $1 billion in Canada, and over $2 billion in the U.S (***22, 23***). These estimates do not include significant indirect costs such as the damage caused to the environment, road side infrastructure, and vehicles due to salt use (***20, 24***). Road salts applied at high levels of concentration could pose a risk to plants, animals and the aquatic environment (***25***).

The substantial direct and indirect costs associated with winter road maintenance have stimulated significant interest in quantifying the safety and mobility benefits of winter road maintenance, such that systematic cost-benefit assessment can be performed. A number of studies have been initiated in the past decade to identify the links between winter road safety or mobility and factors related to weather, road, and maintenance operations. However, most of these studies have focused on the effects of adverse weather on road safety or mobility (***2, 3, 6, 9, 12, 13, 26***). Limited efforts have been devoted to the problem of quantifying the safety and mobility benefits of winter road maintenance under specific weather conditions. Moreover, most of the studies are limited to the investigation of either safety or mobility effects, however without accounting for both safety and mobility, the true benefits associated with WRM are difficult to estimate. Furthermore, most existing studies have taken an aggregate analysis approach, considering roads of all classes and locations together and assuming uniform road weather conditions over the entire day. This aggregate approach may average out some important environmental and operating factors that affect road safety at a micro level (e.g. a roadway section). Therefore, results may not be applicable for assessing decisions at an operational level with an analysis scope of a maintenance yard. Moreover, past studies usually do not control for the effects of traffic and road surface conditions simultaneously. The joint interactions between road driving conditions, traffic and maintenance and their impact on traffic safety and mobility have rarely been studied. In particular, few studies have investigated the link between road safety, mobility and road surface conditions resulting from the mixed effects of weather, traffic and road maintenance during snow storms.

This paper describes a novel approach aimed at addressing the challenge of quantifying the safety and mobility effects of winter road maintenance. The paper first provides a description of the data used in this research followed by introduction of the safety and mobility models that were developed for the evaluation of the safety effects of alternative WRM. The paper then focuses on illustrating the applications of these models in answering some interesting policy questions.

2. METHODOLOGY

2.1. Modelling Approach

The main objective of this research is to develop a quantitative understanding of the relationship between winter road safety & mobility and various factors related to weather, road surface condition, and traffic. The intent is to apply this knowledge to assess the implications of alternative maintenance policies on road safety. A statistical modeling approach is used here to investigate the relationship between winter road safety & mobility and various possible influencing factors. As shown in **Figure 1**, the following steps were followed in the development of these statistical models, including:

1) **Site selection:** this is done based on the availability of weather & road surface, traffic and accident data (winter seasons only).
2) **Data integration:** hourly data from the different sources were obtained and integrated using date, time and location as the common reference.
3) **Event formation:** from the hourly data, snow storm events are extracted at the hourly level first and then subsequently aggregated at the event level. A snow storm event is defined from the start of the precipitation to the time when road surface conditions are restored to some pre-defined condition.
4) **Exploratory data analysis and model development:** a number of alternative modeling techniques available from literature were tested for their power to explain the safety and mobility effects of winter snow storms. For the purpose of this research, however, we have used linear regression, Poisson regression, and Generalized Negative binomial (GNB) regression models.

2.2. Data Description

Thirty-one maintenance patrol routes (sites) were selected from different regions of Ontario, Canada for safety analysis with data available for six winter seasons (2000 – 2006). Out of these thirty-one sites only twenty-one sites and three winter seasons (2003 – 2006) were used for mobility analysis due to unavailability of speed data at all the sites. These sites were selected based on traffic, weather, and road surface condition (RSC) data availability. The selected road sections belong to different highway classes, including low volume rural two lane sections through to high volume multi-lane urban freeways. Data was obtained from different sources such as collision data, road weather information system (RWIS), environment Canada (EC), road condition weather information system (RCWIS), traffic volume and speed data on hourly basis. All these data sets were merged into a single hourly data set using date, time and location as the basis for merging with each site assigned a unique identifier (site-specific variables) to retain its identity. Snow storm events were extracted from this data for safety analysis with two levels of aggregation: hourly event based data with 122,058 observations and average event based data with 10,932 observations. For a detailed description of the sites, data and its processing, readers are referred to Usman, T. (***27***). **Figure 1** shows the process of this data collection, processing, integration and analysis.

For mobility analysis, a new data set was formed from the average event based data but now containing information about directional speed and volume. In the next step matched pairs (controls) were identified a week apart either before or after the event with no precipitation. In case a control period could not be identified for a given event, the event was dropped from the analysis. This resulted in 4822 observations (due to two directions). This data was used for effects of snow storms on speed. Next, another data set was formed from the speed data by adding the directional traffic volume. The data, with 2411 observations, was used for effects of snow storms on traffic volume. **Table 1** gives the summary statistics of the data sets used in this analysis.

2.3. Collision Frequency Models

In road safety literature, the most commonly employed approach for modeling accident frequencies is the generalized linear regression analysis. In particular, the single level Negative Binomial (NB) model and its extensions have been found to be the most suitable distribution structures for road accident frequency (***28 – 34***).

In our recent effort, we have conducted an extensive study based on a large collision data set containing hourly observations of road weather and surface conditions, traffic volume, maintenance operations, and collisions over 31 sites for six winter seasons (2000 – 2006). Two types of models have been developed, namely, event based models for explaining variation of collisions over individuals snow storms and hourly based models for capturing both variations of collisions over event and individual hours within events (***16 – 18***). Different type of generalized linear regression models were evaluated, including Generalized Negative Binomial (GNB), Negative Binomial (NB), Zero Inflated NB and Poisson lognormal (PLN) models. It was found that GNB models performed best, which are given in **Equation 1** and **2**, for event based model (GNB_E) and hourly based model (GNB_H), respectively.

$$\mu_{GNB-E} = Exp^{0.648} e^{-3.912-0.018T+0.009WS-0.044V+0.014TP-4.42RSI+M+S} \quad \textbf{(1)}$$

$$\mu_{GNB-H} = Exp^{0.235} e^{-1.249-0.011T+0.005WS-0.039V+0.097HP-2.594RSI+M+S+FH} \quad \textbf{(2)}$$

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 (***19***)
Exp = Exposure (equal to total traffic in an event / hour multiplied by length of the section for the event based model and hourly based model, respectively)
M = Indicator for month (varies)
S = Indicator for site (varies)
FH = Dummy variable for the effects of first hour (-0.302 if first hour, 0 otherwise).

2.4. Collision Severity Models

Logistic regression models are widely employed for collision severity analysis in literature. Three different approaches can be used for collision severity analysis: a) incorporating severity into the collision frequency models by modeling collisions classified by severity types (***35 – 38***); b) modeling the conditional probability of experiencing each severity level for a given collision (***39 – 42***); and c) establishing aggregate models for the ratios of individual severity levels based on data averaged over given spatial and temporal units (***43***).

Moreover, collision data is hierarchical in nature where individuals or occupants are nested within vehicles and vehicles are nested within collisions. Three different datasets could thus be formed aggregated at different level - collision based records - one level including details on collisions but aggregated info about vehicles and occupants, vehicle based records - two levels including details on both collision and vehicle details but aggregated info about occupants, and occupant based records - three levels including details on collisions, vehicles and occupants. Because of the hierarchical nature of the data, there could be possible correlation at the occupant or vehicle level. Ignoring such correlation (intra class correlation) could result in under estimation of standard errors, thus causing some of the variables to appear falsely significant (***44***).

In our recent research (***45***), we have calibrated and compared a variety of modeling options, including multilevel multinomial logit model (MML), multilevel sequential binary logistic model (MBL) and multilevel ordered logit model (MOL) using six winter seasons of collision data from Ontario, Canada. It was concluded that the occupant based MML model is the best, which is therefore used in our case studies described in the following section. This model for a collision injury severity is shown as follows:

$$P(Fatality + MajorInjury) = \frac{e^{V_1}}{1+e^{V_1}+e^{V_2}}$$

$$P(MinorInjury) = \frac{e^{V_2}}{1+e^{V_1}+e^{V_2}}$$

$$P(PD + MinimalIjury) = \frac{1}{1+e^{V_1}+e^{V_2}} \quad \textbf{(3)}$$

where $V_1 = 0.464 + RT - 0.15NOL + CL + 0.01DA + DC + SB - 0.38Ln(Traffic)$

$V_2 = 0.378 + RT + 0.01SL - 0.07NOL - 0.27RSI + DS + VT + Pos + SB - 0.14Ln(Traffic)$

PD = Property damage only
RT = Road type (Freeways = 0.055, Multilane Kings = -0.11 for equation 3; Freeways = 0.048, Multilane Kings = 0.082 for equation 4; and 2 Lane Kings is the base category = 0 for both equations)
SL = Speed limit (Km/hr)
NOL = Number of lanes
RSI = Road surface index
CL = Collision location (Intersections = 0.862, Bridges/ Underpasses = 2.162 and straight segment is the base case = 0)
DA = Driver age (years)
DS = Driver sex (Male = -0.36 vs. Female)
DC = Driver condition (Not drinking = -0.42 vs. Drinking)
VT = Vehicle type (Vans = -0.21, Large Trucks = -0.84 and Car/Station Wagon is the base case = 0)
Pos = Position in vehicle (Front = 0.213 vs. Rear)
SB = Seat belt used (Used = -0.69 for equation 3 and -0.77 for equation 4 vs. Not used = 0 in both equations)
Traffic = Hourly traffic volume at the time of collision (Veh/hr)

2.5. Model for Traffic Volume

Traffic volume on highways generally varies over space and time due to the inherent variation in the decisions made by individual travelers. For the same reason, traffic volume also varies randomly, that is: different volumes could be observed by the same time of day, day of week and month and under the external conditions (e.g. weather). The randomness of traffic counts can be reasonably captured by Poisson distribution. Let $Y_{h,k}$ represent the total traffic volume on highway h over a given snow storm k. Assume $Y_{h,k}$ follows a Poisson distribution with its mean, denoted by $Q_{h,k}$, being a function of some independent variables, representing factors such as highway characteristics and road weather conditions. The relationship between $Q_{h,k}$, and the influencing factors is assumed to take the form shown in **Equation 4**.

$$\ln(Q_{h,k}) = \ln(\bar{Q}_{h,k}) + \beta_0 + Site_h + \sum \beta_i x_{k,i} \qquad \textbf{(4)}$$

where

$\bar{Q}_{h,k}$ = an offset term representing the expected total traffic volume for the event period if the event had not occurred. This value is approximated using the observed traffic volume for the same period one week before or after the event day, as discussed previously.
$x_{k,i}$ = attribute related to weather and road conditions
$Site_h$ = constant term that varies by site

Equation 4 can be calibrated using Poisson regression with the data set described in the previous section. The independent variables tested for significance include temperature (°C), wind speed (km/h), visibility (km), total precipitation over the event (cm), RSI (unitless) and site variation indicators (binary variable).

After testing a variety of options, it was found that all variables except temperature were statistically significant in improving the explanatory power of the traffic volume model. The final regression result that was found to best fit the full data set is given in **Equation 5**.

$$\ln\left(Q_{h,k}\right) = \ln(\bar{Q}_{h,k}) - 0.264 - 0.004 * WindSpeed - 0.005 * Visibility - 0.007 * \text{Total } Precipitation + 0.265 * RSI + \mathrm{S} \quad \textbf{(5)}$$

2.6. Model for Traffic Speed

The median speed during a snow event is modeled differently than volume. It is assumed to be a normally distributed random variable with its mean assumed to be a linear function of various influencing factors. Independent variables tested for significance include posted speed (categorical), temperature (°C), wind speed (km/h), visibility (km), hourly precipitation over the event (cm), RSI (unitless), average volume to capacity ratio (unitless) and site variation indicators (binary variable). A standard capacity of 2,200 vehicles per lane per hour is assumed for all highways. The resulting model is given in **Equation 6**.

$$\mathrm{V} = 69.082 + 0.089 * Temperature - 0.078 * WindSpeed - 0.310 * Visibility - 1.258 * \text{Hourly } Precipitation - 16.974 * RSI - 4.325 * \frac{v}{c} + PSL + S \quad \textbf{(6)}$$

where PSL = Coefficient of Posted Speed Limit (PSL = 0 when Posted Speed Limit = 80 km/hr; 1.951 if 90 km/hr and 12.621 if 100 km/hr)

3. Model Application

In this section we first apply the models described in the previous section for assessing the safety effects of three critical maintenance decision variables, including bare pavement (BP) recovery time, maintenance delivery timing, and network wide level-of-service (LOS) goal. The GNB_E model is used for assessing the effects of different maintenance options on a seasonal basis whereas the GNB_H model is for assessing the effects of individual maintenance operations within events. GNB_E and MML models are then used to estimate the network wide safety effects if maintaining a given LOS. Traffic volume and median speed models are used to estimate the network wide mobility effects if maintaining a given LOS.

3.1. Safety Effect of BP Recovery Time

The amount of time that has passed before a highway resumes bare conditions after a storm ends, commonly known as bare pavement (BP) recovery time, is a critical measure of the efficiency of the maintenance program being delivered. A shorter BP recovery time is representative of better maintenance service and means less effects of the snowstorm. As such, BP recovery time has been widely used by transportation agencies as a performance measure and LOS indicator. This section uses a simple case study to show how the benefit of shortening BP recovery time can be quantified.

Patrol 2, which is a 28km section of Highway 401 from Morningside Avenue to Highway 404, is selected as study route for this analysis. The study route is one of our analysis sites located in the central region (Toronto) of Ontario. It is assumed that a specific snow event has occurred on this highway site, which has the following attributes:

- Event duration = 8 hours
- Total Precipitation = 3.91 (cm)
- Temperature = - 4.31 C
- Wind Speed = 15.75 (Km/hr)
- Visibility = 11.84 (Km)

The total traffic volume on this highway over the storm period is estimated to be 12,000 vehicles. During the event, road surface conditions could vary between completely snow covered and bare pavement. For a complete snow covered condition, the corresponding RSI is assumed to be 0.2 (average condition within the snow storm) while the bare pavement surface is assumed to have a RSI of 0.8. It is also assumed that before the start of the storm, road surface is dry with a RSI of 1.0.

Two scenarios are considered, which have different BP recovery times but same values for all other factors. First, the base scenario is considered by assuming a BP recovery time of 4 hours. The resulting average RSI for this scenario is therefore 0.356 (= (1.0 + 7.0 x 0.2 + 0.8) / 9). The mean number of collisions in this case is estimated using the GNB_E model, which is equal to 1.439.

Second, we consider the alternative scenario of reducing the BP recovery time to three hours. This means reducing the storm duration to seven hours (four hours of precipitation and three hours of BP recovery time). Under the same conditions, the new average RSI is 0.375 (= (1.0 + 6 x 0.2 + 0.8) / 8). The mean number of collisions in this case is 1.214, which represents a 16 % reduction. Note that this reduction in number of collisions represents the benefit of shortening BP recovery time by one hour and can be easily converted into monetary value by using either a unit collision cost or the severity models and unit cost of collisions at each severity level, as shown in the last case study.

3.2. Safety Effect of Maintenance Operation Timing

Maintenance operations have a direct effect on the road surface conditions and thus the safety of a highway. As a result, the timing of maintenance operations is expected to have a significant impact on the safety effect of snowstorms. This section shows how this effect can be quantified by applying the hourly-based model (GNB_H) described previously. The safety benefit of the maintenance operation 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.

The same patrol route and snow storm as those applied in the previous case study are used. Furthermore, the following assumptions are made to represent the effects of the event and the maintenance operation on the road surface conditions of this route:

- 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.
- At the end of the first hour, the road surface becomes "SNOW PACKED WITH ICY" with an RSI value equal to 0.2.
- In the case that no maintenance operations are done, the road surface would remain in this condition (with RSI = 0.2) until the end of the event (i.e., 8 hours).
- For the case with maintenance operations (e.g., a combination of ploughing and salting operations), the road surface condition will be improved to a mixed state of wet and partial snow cover 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.

We consider the scenario that the maintenance operations (ploughing and salting) is deployed and completed at the start of the second hour. **Figure 2** shows the hourly collision frequency predicted using the GNB_H model under the two alternative scenarios of with and without maintenance operations. The shaded area represents the total reduction in the number of collisions that is expected from the maintenance operation at the second hour of the storm event. The mean numbers of collisions over the storm period under the two scenarios are 6.058 (without maintenance) and 3.671 (with maintenance). The benefit of the maintenance operation is therefore a reduction of 2.387 collisions or 39.4%.

3.3. Network-Wide Safety Effect of Maintaining a Given LOS Goal

This section shows how the collision frequency and severity models can be applied to assess the safety implications of different maintenance level-of-service (LOS) goals. The Ontario provincial road network maintained by the Ministry of Transportation Ontario is considered. The network covers proximately 46,000 lane kilometres. The LOS goals are modeled as the minimum average RSI that must be maintained over each storm. For example, if a minimum RSI of 0.6 is used as the LOS target, it means that all highways must be maintained in such a way that the average RSI over each storm during a season must be above 0.6.

To facilitate this analysis, the following assumptions are introduced:

- The 31 patrol routes used in our model calibration, which are about 18.6% of the whole network in terms of total lane kilometres, provide a reasonable representation of the whole Ontario network. As a result, the benefit result from these sample routes can be scaled up to the whole network in proportion. It should be noted that if the AADT is available for all highways, it would make more sense to estimate the network wide benefit based on highway lengths weighted by AATD.
- The snow storms experienced by the 31 sites over six winter seasons (2000-2006) are considered as the basis for analysis.

- The observed RSI for each site under each storm represents the base scenario while the assumed LOS goal, as represented by the minimum RSI to be maintained, represents the alternative scenario. The difference between the two scenarios represents the benefits that could be expected by achieving a target LOS or minimum RSI
- For a given site under a given storm, if the existing RSI is above the target RSI, then the target LOS goal has no effect and thus no additional benefit is to be accounted for. However, the existing RSI is less than the target RSI, a new scenario with a RSI value equal to the target RSI is generated for benefit analysis. The expected number of collisions by each severity level is estimated using the GNB_E and MML models for the base and new scenarios.
- The collision costs by individual severity levels can be estimated on the basis of the nominal unit collision costs provided in **Table 2**.
- The average benefit per season is estimated by dividing the difference of the two cost estimates by six (for the six winter seasons).

Table 2 shows the results of an example case calculation for a target RSI of 0.5. The total additional benefit for the 31 Sites for achieving a target RSI of 0.5 for all storms is $ 0.79 million per season whereas that for the whole Ontario network is $4.22 million. **Figure 3** shows the total network wide benefit as a function of the LOS target (minimum RSI to be maintained). As expected, the total additional benefit is an increasing function of the minimum RSI to be maintained. Approximately, a 0.10 increase in the minimum RSI (e.g., from 0.5 to 0.6) could result in $8.29 million of additional savings in terms of collision reduction.

3.4. Network-Wide Mobility Effect of Maintaining a Given LOS Goal

This section shows an application of the developed mobility impact models for quantifying the mobility implications of alternative WRM policy and programs. As shown in the previous section, a small reduction in highway volume could represent a significant displacement of vehicles and a large impact on mobility of the surrounding community. For example, if work trips are postponed or cancelled, there is an obvious loss of productivity and loss of income. Discretionary trips are likely to be among the most commonly displaced. Loss of these trips represents a loss of the economic activity and social well-being commonly associated with these types of trips. A correlation between RSI and volume indicates that people will make cancellation or rescheduling decisions based on their knowledge of road conditions.

Likewise, a small reduction in speed can dramatically increase travel times. This supports the common knowledge that drivers will slow for poorer road conditions. On a typical 10km highway segment with a posted speed of 90 km/h, a drop to 70km/h translates to an additional 1.9 minutes of delay per vehicle.

A case study is developed to demonstrate these results using the three winter seasons of snow event data for the 21 sites. For the purposes of this case study the level of service (LOS) achieved through WRM activities is described by the average RSI during a snow event. For example, if the WRM goal is to achieve pavement minimum RSI of 0.6, then the average RSI of each highway over each event of a winter season must be greater than 0.6.

Benefits are calculated as increases in speed (travel time savings) and trips not displaced (trip making utility) by achieving a given RSI target as a result of WRM activities. For a given target RSI, all events are examined and their RSIs under the existing WRM program are estimated. If the average RSI during a snow event in the data set is higher than the target value then no benefit is calculated. For those events that have an RSI less than the target RSI, it is assumed that, under the new target LOS goal, additional WRM operations would be provided to improve their RSI to the target value. The improvement in RSI would lead to increase in traffic volume over these events, which can be predicted using **Equation 5**. The increase in traffic volume could then be translated benefit due to improved trip-making utility (i.e., these trips would otherwise be cancelled or shifted to other periods). In addition, the increase in RSI would also improve the average traffic speed, as predicted by **Equation 6**. This will result in reduction in travel time, which can then be translated into dollar value based on value of time. In this research, we assumed a uniform $10 per trip not displaced (for trip making utility) and a value of time of $20 per hour (for travel time savings).

These benefits on a storm by storm basis for all the study sites are aggregated to the total of the three seasons in the data set and averaged to represent a single typical winter season. For the purposes of this case study, the results are scaled to the entire Ontario provincial highway network. This is achieved based on a simple ratio considering the study sites are made up of about 13% of the complete network (in terms of lane-km). It should be noted that the resulting amount represents the additional benefit that could be expected from implementing the new target LOS goal (minimum RSI to be maintained over each storm).

As shown in **Figure4** the mobility benefit of achieving the target RSI of 0.8 bare pavement condition is on the order of 17 to 32 million dollars per winter season on the provincial highway network in Ontario. This figure represents the monetized value of WRM to maintain bare pavement. The WRM policy for the study sites expects bare pavement recovery within 8 hours of bare pavement loss. There is significant benefit that occurs after an event has finished that is currently realized through ongoing WRM activities (but not included in this case study).

4. CONCLUSIONS AND FUTURE WORK

This paper has introduced a methodology for quantifying the safety implications of winter road maintenance. The foundation of this methodology is a set of empirical models that can be used to predict collision frequencies & consequences, traffic volume and median speed based on road weather, traffic and surface conditions. The road surface condition, as represented by a friction-like road surface index, is the primary mechanism to capture the direct effect of maintenance operations. Case studies are used to illustrate the potential applications of these models for quantifying the safety and mobility benefits of winter road maintenance, including, shortening of bare pavement recovery time, changing of maintenance operation deployment time, and increasing in level of service standards. More importantly, this research has shown the feasibility of developing performance based winter road maintenance standards.

In this research we have used fixed effects models. Our future efforts will include investigation of random effect models. In this study only linear regression is considered for the speed model, an obvious extension of this research would be to investigate the possible non-linear relationships. The analysis above considered only first order effects. Interaction between variables, particularly those with intuitive relationships like visibility and precipitation, should be investigated to improve model performance and estimation power.

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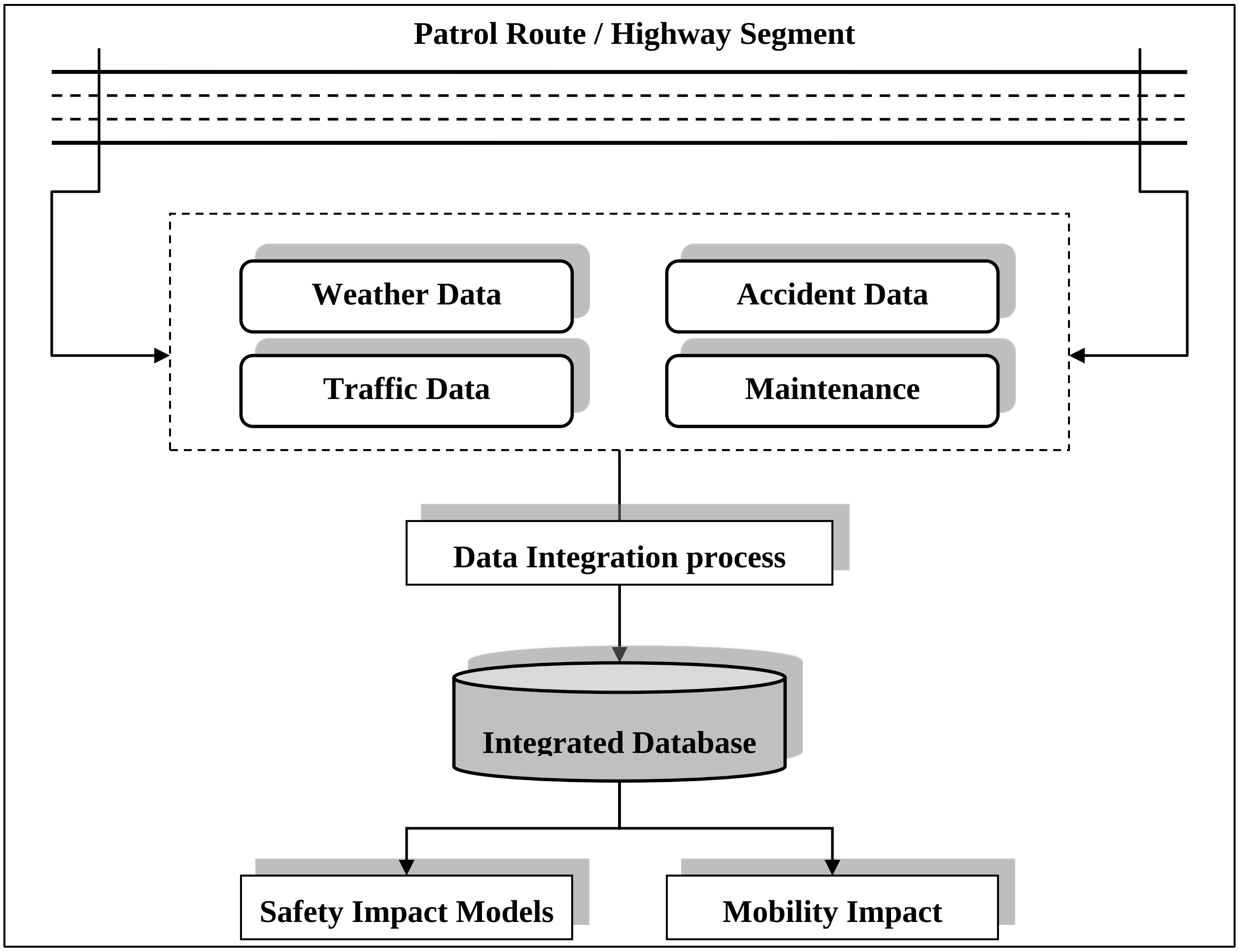

Figure 1: Data Integration and Analysis

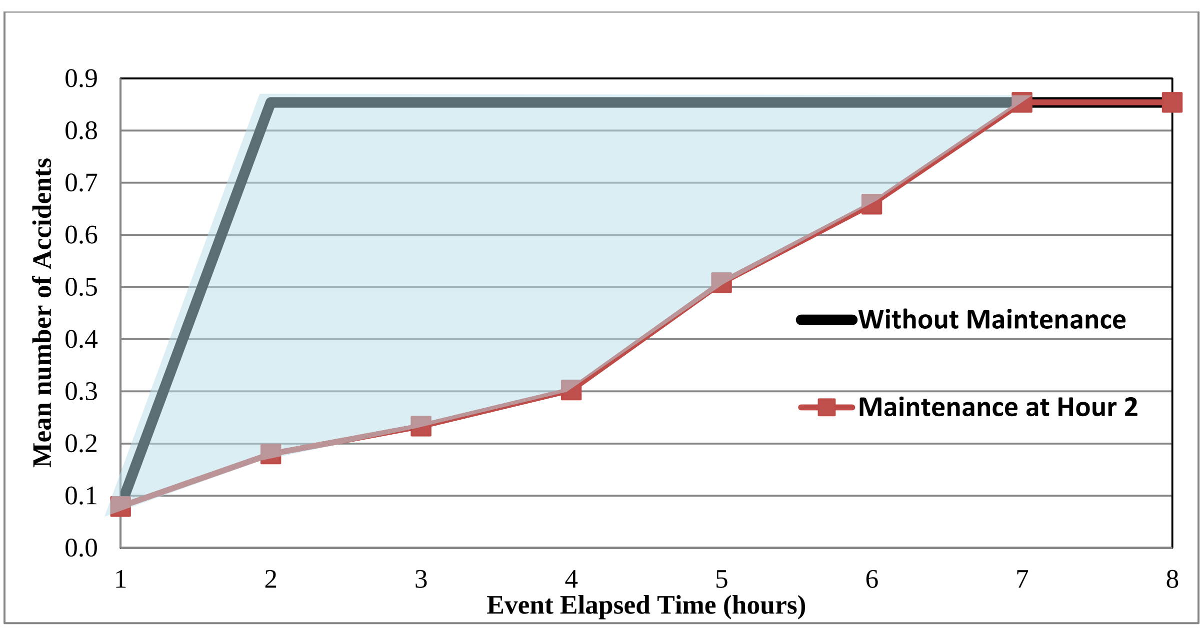

Figure 2: Safety Benefit vs. Maintenance Timing

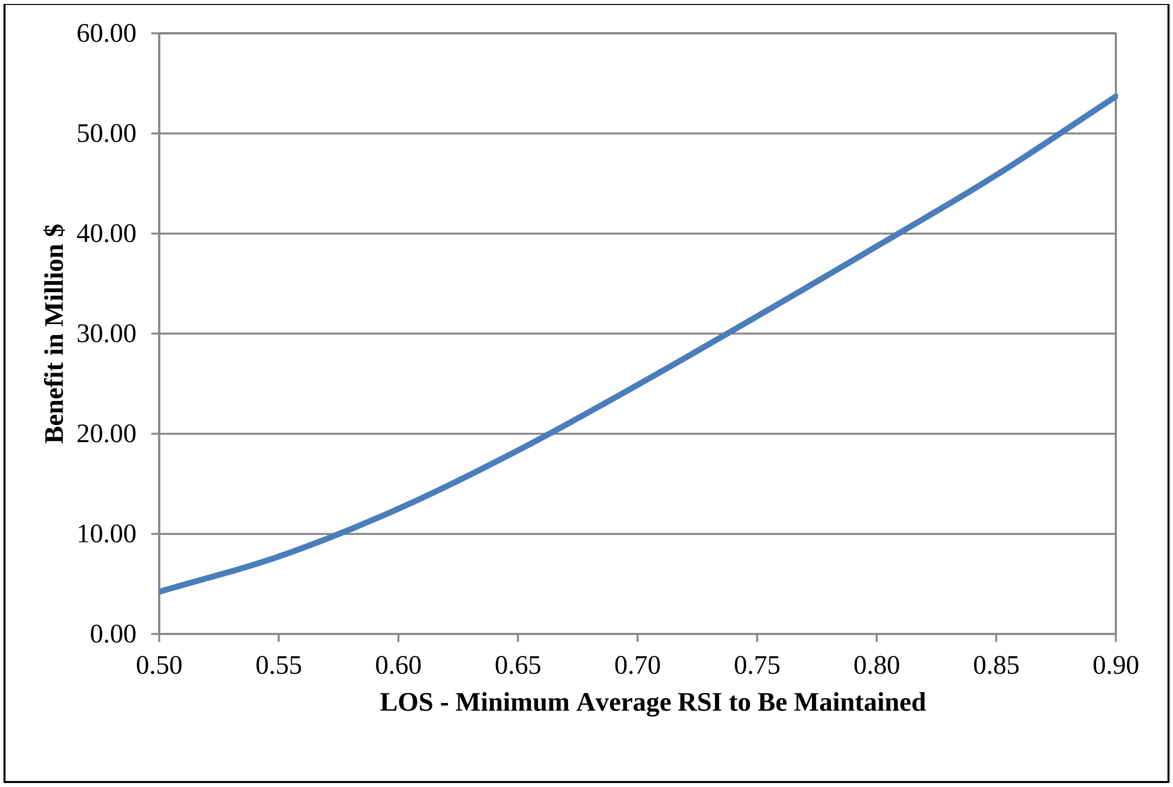

Figure 3: Additional Safety Benefit for Achieving a Given LOS Target

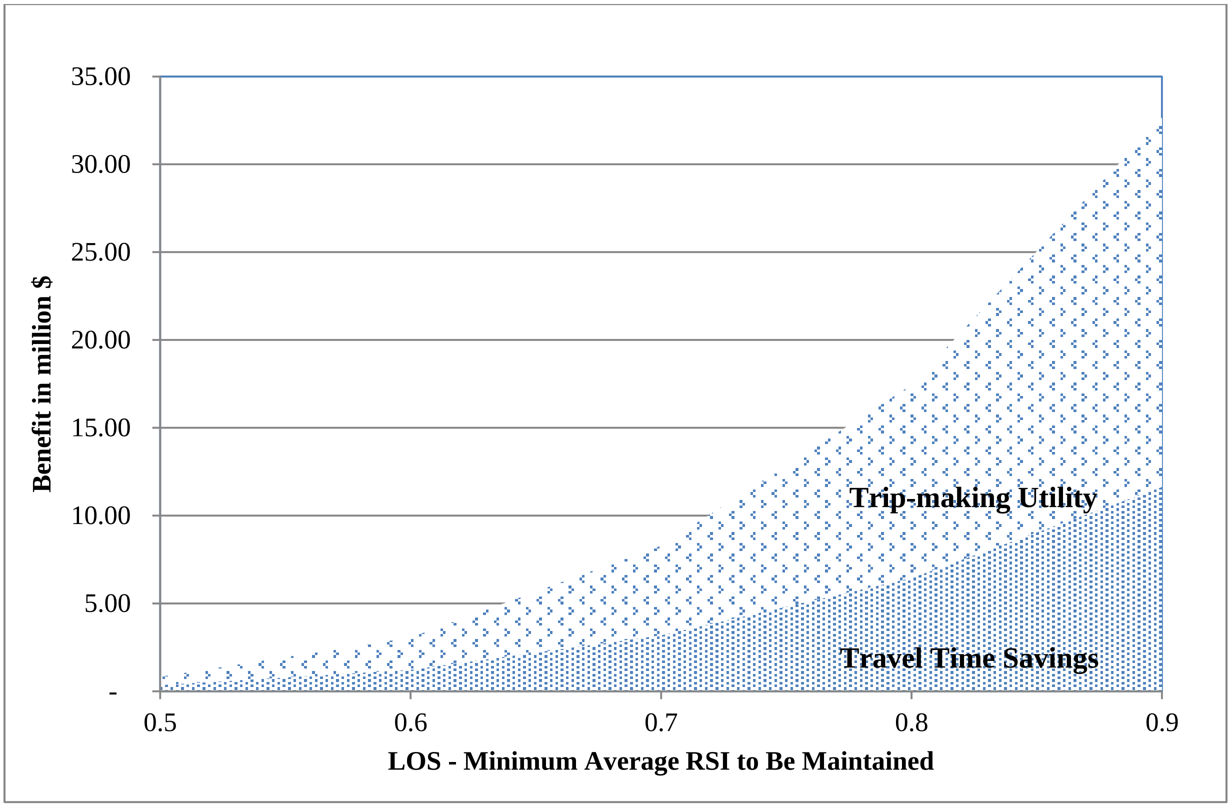

Figure 4: Mobility Benefit of WRM versus WRM LOS Standard (Ontario Provincial Network)

Table 1: Descriptive Statistics for Data Used in Safety Analysis

Average Event Based Data - Safety Analysis					
Variables	Min	Max	Average	St.Dev	N
Temperature (°C)	-29.87	4.98	-4.31	5.06	10932
Wind Speed (km/h)	0	60.5	15.75	8.8	10932
Visibility (km)	0	40.2	11.84	6.23	10932
Total Precipitation (cm)	0.02	189.9	3.91	6.82	10932
Hourly Precipitation (cm)	0.01	13.8	0.36	0.54	10932
Accidents	0	21	0.28	1	10932
RSI	0.2477	0.99	0.8017	0.14	10932
Event Duration (hour)	2	47	11.17	9.61	10932
Total Traffic	3	453626	18295	35162	10932
Hourly Event Based Data - Safety Analysis					
Temperature (°C)	-33.55	28	-5.12	5.56	122058
Wind Speed (km/h)	0	69	16.28	9.62	122058
Visibility (km)	0	40.2	11.16	7.91	122058
Hourly Precipitation (cm)	0	13.8	0.24	0.37	122058
Accidents	0	7	0.020	0.18	122058
RSI	0.05	1	0.7457	0.20	122058
Total Traffic	1	49710	1639	2555	122058
Dataset for Traffic Volume Analysis					
Temperature (°C)	-29.99	5	-4.52	4.89	2411
Wind Speed (km/h)	0	60.5	12.85	8.88	2411
Visibility (km)	0	26.82	10.48	6.94	2411
Total Precipitation (cm)	0	40	2.34	3.16	2411
RSI	0.12	1	0.761	0.16	2411
Dataset for Median Speed Analysis					
Temperature (°C)	-29.99	5	-4.46	4.88	4822
Wind Speed (km/h)	0	60.5	12.99	8.86	4822
Visibility (km)	0	26.82	10.49	6.94	4822
Hourly Precipitation (cm)	0	13.8	0.50	0.76	4822
RSI	0.12	1	0.763	0.16	4822
V/C	0.00023	0.35	0.046	0.06	4822

Table 2: Benefit Calculation for Target RSI

	Under Existing Conditions	For Target RSI	Unit Cost of an Injury Level*	Associated Cost (base case)	Associated Cost (Target
Expected Collision Frequency	3240	3032			
Number of Occupants	8524	7977			
PD + Minimal Injury	7178	6713	249	1,787,395	1,671,596
Minor Injury	1296	1216	4,674	6,059,265	5,684,603
Fatal + Major Injury	49	47	2,036,638	100,707,253	96,485,250
			Total	108,553,913	103,841,450

*Source: Transport Canada (***46***)