Comparing the Safety and Mobility Benefits of Alternative Winter Road Maintenance Standards

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In countries like Canada, driving conditions can be significantly deteriorated by adverse winter weather conditions, such as ice and snow storms. To reduce the negative effects caused by inclement winter weather conditions, winter road maintenance (WRM) services are implemented by transportation agencies to restore road surfaces to bare conditions and provide safer driving conditions. WRM operations are commonly guided by a set of level of service (LOS) standards that specify the minimum level of service to be achieved for the different classes of highways. Higher highway classes receive higher levels of WRM service. However, WRM activities are costly, incurring both significant monetary costs and negative environmental effects.

This research was motivated by the introduction of a new highway class - Urban Freeways (UFW) - in the province of Ontario’s highway classification system for winter road maintenance. UFWs include highways with winter average daily traffic volumes greater than 100,000 vehicle/day; they receive the highest WRM level of service. The substantial direct and indirect costs associated with winter road maintenance have stimulated strong interest in quantifying the safety and mobility benefits of upgrading level of service to the new UFW class.

This research presents the findings from a field study aimed at comparing the winter road maintenance performance of alternative maintenance standards, and their impacts on safety and mobility. The new UFW class was introduced as a pilot study on four highway sections located in Central and Eastern Ontario, in the 2018-2019 winter season. A statistical analysis of the field test data found that bare pavement regain time was reduced by 40%, while salt usage increased by 139%, after implementing the upgraded winter road maintenance standard. A subsequent analysis was conducted to estimate the expected safety and mobility benefits due to the upgrading of the service standard, providing the critical information needed to make a decision on formal adoption of this new standard in future winter seasons. The analysis results conclude that highways with more severe weather conditions are

expected to obtain more safety and mobility benefits. Moreover, traffic exposure is the decisive factor of the safety and mobility benefits gained from implementing the new UFW class when highway sections are having similar weather conditions. The monetized safety and mobility benefits, in combination with the additional costs of implementing the Urban Freeway class, could also be used to determine the optimal winter average traffic volume threshold for the Urban Freeway class. While the findings and conclusions of this thesis are only relevant to the study area where the tests were conducted, the underlying methodology can be applied by other jurisdictions that are facing the same problem.

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Chapter 1
Introduction

1.1 Research Background

Canada has one of the most severe winter climates in the world. During winter season, hazardous weather conditions such as snowstorms result in icy roads and heavy snow accumulation, which reduce road pavement friction and thus lead to poor driving conditions. Moreover, travelers' lives and safety are threatened, since these poor driving conditions increase the risk of traffic accidents. Andrey, Mills, Leahy, & Suggett (2003) concluded that traffic collisions increased by 75% and collision-related injures increased by 45% due to severe weather conditions. Furthermore, inclement winter weather conditions also degrade traffic mobility. Pisano & Goodwin (2002) indicate that adverse weather conditions decrease traffic demand and highway capacity. Traffic congestion happen when the reduction of the highway capacity is higher than the reduction of the traffic demand (Lalit, 2006). In addition, Cambridge Systematics (2005) stated that 15% of the traffic congestion occurs due to inclement weather conditions. Furthermore, Ioannis, Tao & Adel (2013) found that winter weather conditions might significantly impact travel time with light snow resulting in travel time increases of 5.5 – 7.6% in the Greater London area (UK), and heavy snow causing travel time delays from 7.4% to 11.4%.

To reduce the negative effects caused by inclement winter weather events, winter highway maintenance activities such as plowing and salting are used to restore road surfaces to bare conditions and provide safe travel. However, WRM operations have both costs and benefits. Usama (2009) indicates the main benefits of maintaining bare pavement include increased safety, increased roadway capacity, and reduced travel time and delay. On the other hand, Perchanok, Manning and Armstrong (1991) indicate that the direct cost of WRM programs in Ontario is estimated to exceed $100 million annually, which represents 50% of its total annual highway maintenance budget. In addition, indirect costs related to WRM activities lead to negative environmental effects. For instance, about five million tons of salt are applied on Canadian roads (Transport Association of Canada, 2013), which could significantly damage the natural environment, road surfaces, and also vehicles. Furthermore, fatalities and serious injuries caused on winter highways also generate massive indirect costs, as the Transport Association of Canada (2003) estimates that the total cost due to weather-related injuries and property damages is in the range of $1 billion per year in Canada.

WRM operations in most jurisdictions are guided by a set of Levels of services (LOS) standards that specify the minimum level of service to be achieved for the different classes of highways. Generally, each jurisdiction establishes its road classification based on its annual traffic volume, highway type, as well as local climatic conditions. The Ministry of Transportation of Ontario (MTO) has defined five classes of highways based on their winter average daily traffic volumes. In order to enhance highway safety, maintenance activities must be effective during and after storms (Winter highway maintenance, 2015). The ministry also specifying different levels of service for each classification using performance measures such as

- Maximum allowable accumulation of snow: the maximum snow depth during and after the snowstorm;
- Maximum circuit time: the maximum time it should take to plow or spread salt on a measured section of a highway during and after a storm; and
- Maximum bare pavements regain time (BPRT): the maximum time to regain bare pavement status after a storm for a highway It is measured from the snow event ends to when the bare pavement is achieved.

The highways that have higher traffic volumes are designated with higher classes and thus receive higher levels of winter maintenance service (Winter Highway maintenance, 2015). This approach of varying LOS by traffic volume is to achieve a balance between benefits and costs, so as to provide the level of services where benefits to road users exceed the associated costs. Hence, the challenge is to develop the most cost-effective LOS standards for a given highway network.

1.2 Research Problem

In 2016, the MTO introduced a new highway class - Urban Freeway (UFW) - into Ontario's highway classification system for WRM through a pilot program. The UFW highways include those with winter average daily traffic (WADT) volumes greater than 100,000 vehicles/day. As mentioned previously, the winter service levels are aligned with the road classification level. In other words, higher class highways receive higher levels of winter maintenance service. The Urban Freeway class has the highest WRM level of service of all six-highway classes.

Since its pilot implementation, the substantial increase in costs associated with implementing this new class have stimulated significant interest in determining whether or not the new standard is cost-effective. Previous research has tried to quantify the impact of winter driving conditions on traffic safety and mobility, and thus the benefits of varying LOS standards (Usman et all, 2010, 2012; Fu et al. 2014). However, past research is hypothetical in nature with no real-world case study on determining the impacts of upgrading one class (e.g., Class 1) to another (e.g., UFW). In other words, do the safety and mobility benefits from applying the UFW WRM standard to the Class 1 highways justify their introduction? Hence, a research gap exists in terms of the relationship between upgrading highway classes and the associated safety and mobility benefits. This research focuses on evaluating the benefits of alternative level of service standards with the specific objective of quantifying the mobility improvement and safety benefits gained after implementing the new Urban Freeway class.

1.3 Research Objectives and Scope

The main goal of this research is to quantify the impact of alternative winter road maintenance service standards under different weather condition scenarios on traffic safety and mobility. In order to achieve this goal, the following specific objectives are to be completed:

1. Review literature on policies and LOS standards on WRM and various performance measurement methods;
2. Assess the performance of field data from the pilot sites of new introduced WRM class "Urban Freeway";
3. Assess the resource implication and performance outcome in implementing the new LOS standard; and
4. Evaluate the benefit implications of alternative LOS standard.

1.4 Thesis Organization

This thesis consists of five chapters. Chapter 1 provided background and introduced the research problem and objectives. The remaining thesis is organized as follows:

In Chapter 2, a literature review is presented in the area of WRM performance measurement, WRM LOS, and safety and mobility benefits of WRM.

Chapter 3 describes the data sources, study sites, data processing steps, and analysis methods used in this study.

Chapter 4 presents the analysis of field trials and evaluation of benefits.

Chapter 5 concludes major findings and recommend future work.

Chapter 2

Literature Review

During the winter season, highway driving conditions are highly dependent on the amount and intensity of snow events, and other severe weather conditions. The timeliness and thoroughness of winter highway maintenance activities such as snow removal and salting play a significant role in improving highway driving conditions. Adequate winter road maintenance can provide safer highway conditions and therefore reduce the possibility of collisions (Winter Highway Maintenance Special Report, 2015). However, various costs and benefits are incurred while performing winter road maintenance operations. A number of studies have examined both the direct and indirect costs and benefits of winter road maintenance.

This chapter provides a detailed review of these topics in five sections. In the first section, a general introduction to Winter Road Maintenance (WRM) is provided. The second section presents an introduction to WRM performance measurement. In the third section, WRM level of service and practices across different jurisdictions are compared. The fourth section reviews past studies on the effects of winter maintenance on road safety benefits. Finally, the fifth section reviews relevant literature regarding effects of winter road maintenance on mobility benefits.

2.1 Winter Road Maintenance

In the wintertime, harsh weather characterized by low temperatures and heavy snowfall is experienced by northern countries. These storms result in poor road conditions causing increasing travel risks and delays on highways. Governments in cold regions cooperate with transportation agencies to deliver WRM operations, such as plowing, salting and sanding. These activities help to clear snow and control ice on all public roadways, thus reducing the negative effects of winter events on traffic (Ville Hinkka et al., 2015). For example, the Ministry of Transportation of Ontario (MTO) is responsible for ensuring that Ontario highways are kept cleared of winter snow and ice. The MTO has divided Ontario into 21 contracts areas for the purposes of winter maintenance service, and five different contractors are currently contracted and responsible for maintaining the Ontario's provincial highways ("five different contractors," n.d.).

The WRM activities of each contractor are guided by a set of Levels of services (LOS) standards that specify the minimum level of service to be achieved for the different classes of highways. These

LOS standards are established to ensure that consistent services are maintained on all highways over all winter seasons and snow events. For example, the MTO defines five classes of highways based on average 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 recovery time (BPRT).

Therefore, effective WRM performance measures are critical to both government agencies and WRM service contractors (Qiu, 2008). On one hand, by measuring contractors' WRM performance, the government can conduct benchmarks among contractors to ensure sufficient maintenance activities are applied effectively during and after storms. On the other hand, performance measures allow WRM service contractors to make more informed decisions, and comprehensively track the whole process toward specific objectives (TRB, 2011).

2.2 WRM performance measurement

Performance measurement is a deep-rooted concept in the winter road maintenance field. The Federal Highway Administration (FHWA) proposed a conclusive definition of what is considered performance measurement (Shaw, 2003): "Performance measurement is a process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to clients and the extent to which clients are satisfied) and outcomes (the results of a program activity compared to its intended purpose), and the effectiveness of government operations in terms of their specific contributions to program objectives."

In the road sector, Haas et al (2009) outlined that performance can be measured not only to assess current and future road infrastructures conditions, but also to evaluate road agency efficiency in terms of services provided, cost-effectiveness and so on. However, contemporary performance measurements adopted by transport agencies for winter road maintenance operations are not standardized (Karlaftis and Kepaptsoglou 2012; Missouri Department of Transportation 2013; Murphy et al. 2012). To help the assessment of different performance metrics, Karlaftis and Kepaptsoglou (2012) summarized the most important properties of effective performance metrics as follows:

- Relevance: the metric must be relevant to planning and budgeting needs of the agency;
- Clarity: the metric must be clearly defined to avoid misinterpretation;

- Reliability: the measurement process should be standardized to avoid bias or errors from the process or person performing them;
- Precision: the collection of data should be as precise as possible; and
- Availability: the data should be readily available and cost-effectively collectable, and the metric should be useful and up-to-date when the road administrator accesses it.

Since transportation agencies are using different performance measures of WRM operations, it can be difficult to make comparisons among multiple regions. However, performance measures can be classified in the following categories:

• Input measures, indicating the amount of resource used to perform WRM operations (such as types and quantity of material, the number and frequency of plows assigned to each route, labor and equipment assignment, etc.) (Qiu, 2008). In addition, transport agencies keep records of these input measures as pay items if they are using contractors for winter maintenance operations (Bandara et al, 2015);

• Output measures, indicating effectiveness of resources transformed to service (outputs are quantified in terms of lane kilometers per unit of time plowed, material application rates, and other physical accomplishments) (Qiu, 2008);

• Outcome measures, directly reflecting operation impact to road users and society (such as improved accident rate, or lower travel costs to customers) (Qiu, 2008). In addition, outcomes are typically measured through indicators. Table 2.1 shows that bare pavement regain time, friction rate, and user satisfaction are popular measures used for evaluating outcomes (Gang et al. 2017; Blackburn et al. 2004).

Table 2.1: Types of outcome indicators for performance measurements

	Outcome Indicators
Physical Characteristics	Bare pavement regain time Pavement friction rate Duration and frequency of closures
Visual Characteristics	Centerline, wheel path bare Loose snow, packed snow cover Thin ice, thick ice cover

	Road surface conditions: dry, wet, slushy, partly snow covered, snow covered
Customer Satisfaction Characteristics	Reduction of crashes Advanced warning time to customers User satisfaction survey

Input and output measures are important to transportation agencies as they are effective indicators for operational evaluation and budgetary purposes. Nevertheless, a lot of agencies are using outcome measures that more accurately assess if agencies meet their snow and ice control objectives (Gang et al, 2017).

2.3 WRM LOS

In the field of winter road maintenance, level of service is a measure commonly used by transportation agencies as the basis for developing winter highway maintenance guidelines, classifying routes, and coordinating winter maintenance activities (CTC & Associates LLC WisDOT Research & Library Unit, 2009; TRB 2010). The setting of level of service standards is often related to the highway road classification, whereby classes are determined based on the speed limit and average annual daily traffic (AADT) counts (Level of service policy- Township of otonabee-south monaghan, n.d.). Hence, the level of service standards of different jurisdictions are varied, and each highway class is associated with a specific LOS.

2.3.1 Canada

In Canada, 50% of the total road maintenance budget accounts for maintaining winter roads in a safe condition (Buchanan & Gwartz, 2005). Canada classifies its roads based on the priority for WRM. For example, Highways, routes to transit, emergency venues and business areas are treated with priority (Nassiri, Bayat & Salimi, 2014). A review of the province of Ontario and Alberta is provided.

Ontario

The provincial standards of Ontario classify highways into 6 classes. The classification is based on average annual daily traffic and on the posted speed limits. **Table 2.2** shows the classification of highways in Ontario.

Table 2.2: Classification of Highways in the province of Ontario (Minimum Maintenance Standards For Municipal Highways, 2018)

Average Annual Daily Traffic (number of motor vehicles)	Posted or Statutory Speed Limit (kilometers per hour)						
	91 - 100	81 - 90	71 - 80	61 - 70	51 - 60	41 - 50	1 - 40
53,000 or more	1	1	1	1	1	1	1
23,000 - 52,999	1	1	1	2	2	2	2
15,000 - 22,999	1	1	2	2	2	3	3
12,000 - 14,999	1	1	2	2	2	3	3
10,000 - 11,999	1	1	2	2	3	3	3
8,000 - 9,999	1	1	2	3	3	3	3
6,000 - 7,999	1	2	2	3	3	4	4
5,000 - 5,999	1	2	2	3	3	4	4
4,000 - 4,999	1	2	3	3	3	4	4
3,000 - 3,999	1	2	3	3	3	4	4
2,000 - 2,999	1	2	3	3	4	5	5
1,000 - 1,999	1	3	3	3	4	5	5
500 - 999	1	3	4	4	4	5	5
200 - 499	1	3	4	4	5	5	6
50 - 199	1	3	4	5	5	6	6
0 - 49	1	3	6	6	6	6	6

Each class of the highway receives a different level of service as per minimum standards. **Table 2.3** represents the minimum WRM standards and level of service each high class receives.

Table 2.3: Minimum standards of WRM based on the Class of Highway (Minimum Maintenance Standards For Municipal Highways, 2018)

Class of Highway	Patrolling Frequency	Snow accumulation depth (cm)	Time to clear the snow (Hours)	Minimum Time to Treat Icy Highways (Hours)	Level of Service
1	3 times every 7 days	2.5	4	3	bare pavement within 8 hours of storm end or abated
2	2 times every 7 days	5	6	4	bare pavement within 16 hours of storm end or abated
3	once every 7 days	8	12	8	bare pavement within 24 hours of storm end or abated
4	once every 14 days	8	16	12	bare pavement or centre bare condition (the centre 2.5 m) within 24 hours of storm end or abated
5	once every 30 days	10	24	16	Snow pack within 24 hours of after the storm

Alberta:

The snow removal and ice control operations are also based on highway classes in the province of Alberta. **Table 2.4** lists the eight different classes of highways in Alberta and indicates the time in which the snow is to be cleared. “Good Winter Driving Conditions” in **Table 2.4** means the snow and ice has been removed from the road and any remaining snow on the shoulders and centerline of the highways has also been removed; however, it is acceptable to have short sections of packed snow or ice within the driving lanes between the wheel paths or the centerline (Alberta Ministry of Transportation, 2000).

Table 2.4: WRM Standards and Highway Classification of Alberta (Alberta Ministry of Transportation, 2000)

Class of Highway	Average Daily Traffic Volume	Maximum Reaction Time (Hours)	Maximum Time to Good Winter Driving Conditions (Hours)	Typical Reaction Time (Hours)
A	> 15,000	2	6	1
B	7,000 – 15,000	4	6	1
C	5,000 – 7,000	4	8	2
D	2,000 – 5,000	4	8	2
E	1,000 – 2,000	6	12	3
F	500 – 1,000	8	12	3
G	100 – 500	12	18	4
H	< 100	16	24	5

Two large cities in the province of Alberta are reviewed further: Edmonton and Calgary.

Edmonton:

In Edmonton, roads are classified based on the priority types. There are four levels of priority, represented as classes in **Table 2.5**. Each level of priority is expected to be treated with different minimum standards based on how important it is to the city. **Table 2.5** summarizes the deicing and plowing operations' time frame based on the type of the road.

Table 2.5: Summary of Roadway Priority Hierarchy and Level of Service it receives (City of Edmonton, 2015)

Class	Types of Roads	Sanding Standard Frequency (Hours)	Sanding Storm Frequency (Hours)	Plowing Time to Clear Snow
1	Freeways, Arterial roadways, Business Districts & Bus ways	4 to 8	2 to 4	Within 36 Hours After End of Snowfall
2	Collector/Bus Route Roadways, Transit Park and Ride access roads	8 to 12	4 to 8	Within 48 Hours After End of Snowfall
3	Local Industrial Roadways	Sand on as Required Basis	Sand on as Required Basis	Within 5 Days After End of Snowfall
4	Residential Roadways, Alleys	Sand on as Required Basis	Sand on as Required Basis	Snowpack Within 48 hours and complete in 5 days

Calgary:

WRM practice in Calgary is similar to the WRM practices in Edmonton in terms of road classification. However, the time to achieve the similar level of service as in Edmonton is shorter. In Calgary, a Seven Days Snow and Ice Control (SNIC) Plan was organized. **Table 2.6** classifies the roads based on their priority. **Table 2.7** summaries the SNIC plan that is in effect in Calgary.

Table 2.6 Roads Classification in the City of Calgary (City of Calgary, 2014)

Priority	Types of Roads	Traffic Volume	Level of Service

P1	Major Commuter Roads & Downtown Roads	8,000-20,000 Vehicles/day	Bare Pavement
P2	Feeder Roads Running in & out of communities	5,000- 20,000 Vehicles/day	Bare Pavement
P3	Roads with School & Playground Zones, Hills and intersections	Low Traffic Volume	Snow Packed to 12 cm
P4	Residential Roads	Lowest Traffic Volume	Snow Packed to 12 cm

Table 2.7: Seven Days Snow and Ice Control Plan (City of Calgary, 2017)

Day	**Operation**
1	All P1 routes must be completely plowed, sanded and salted by the end of the day
2	All P2 routes must be completely plowed, sanded and salted by the end of the day
3	Work Begins on P3 & P4 routes in residential areas
4	Work on P3 & P4 routes continues
5	Work on P3 & P4 routes continues
6	Work on P3 & P4 routes continues
7	By the end of the day the plan should be complete and all roads must be cleared

2.3.2 Finland:

The winter season in Finland starts towards the end of November and lasts to approximately mid-March. Average snow depth is around 40 cm and the average cumulative amount of snow fall is about 100 cm. In the city of Helsinki, streets have been divided into three maintenance classes based on their priority. Different classes correspond to specific levels of service. **Table 2.8** presents the action time for clearing the snow for several types of roads (Alatyppö, 2016).

Table 2.8 Helsinki, Finland Best Winter Practices (Alatyppö, 2016)

Maintenance Class	Roadways Type	Action Time at Daytime	Action Time at Night-Time	Action During Continuous Snowfall	Action Limit (Thickness of snow layer/ Slush)
Class I, Highways	Main Streets	3 hours	by 7 AM	Highways to be kept passable	5 cm / 3 cm
Class I, City Roads	Main Streets	4 hours	by 7 AM	N/A	5 cm / 3 cm
Class II, Highways	Collectors Streets	4 hours	by 7 AM	Highways to be kept passable	5 cm / 3 cm
Class II, City Roads	Collectors Streets	4 hours	by 10 AM	N/A	5 cm / 3 cm
Class III, Highways	Residential Streets	3 Weekdays	3 Weekdays	N/A	7 cm / 5 cm
Class III, City Roads	Residential Streets	8 hours	by 12 noon	N/A	5 cm / 5 cm

2.3.3 Iceland:

In the capital city of Iceland, Reykjavík, the winter season starts at the end of October and lasts until the end of April. Average snowfall in the city is approximately 10 mm. Roads in Reykjavík are divided into 4 maintenance classes based on their priority. Similar to other cold regions, each class receives a different level of service in Iceland. Table 2.9 below summarizes the level of service and road classification metrics (Gylfadottir, 2016).

Table 2.9 Reykjavík, Iceland Best Winter Practices (Gylfadottir, 2016)

Road Priority	Roadways Type	Service Time Through	Action Time	Clearing Time	First Action/ Snow	Max Snow Depth	Limited View

		the Day	(Hours)	(Hours)	Thickness (cm)	(cm)	(Days)
1	Main Streets and Important Connection road & Emergency Routes	4 AM - 10 PM	0.5	2	2	5	1
2	Collector Streets & Bus Routes	7 AM - 10 PM	1	3	5	10	1
3	Through Streets	8 AM - 9 PM	1.5	3	7	12	1
4	Local Streets	8 AM - 9 PM	N/A	N/A	N/A	15	N/A

2.3.4 United States of America:

The weather in the United States of America varies among the different states due to the large geographic size of the country. Some states experience sever winter with lots of snowfall and other states experience minimal to no snowfall. Hence, four states which experience a fair amount of snowfall in the winter are compared: North Dakota, Wisconsin, Indiana and New York. **Table 2.10** represents the number of road classes in each state, as well as the level of service each class receives and the time frame in which it is accomplished.

Table 2.10 WRM Standards in the U.S.A (CTC & Associates LLC, 2009)

State	Roads Level	Roadways Types	Time Frame	Level of Service
North Dakota	Level 1	Urban Areas	1-3 Hours	All lanes/ramps interchanges cleared

	Level 2	Rural Interstate	2-6 Hours	All lanes/ramps interchanges cleared
	Level 3	Interregional System	2-8 Hours	All lanes cleared
	Level 4	State Corridor	3-10 Hours	All lanes cleared
	Level 5	District Corridor	6-12 Hours	All lanes cleared
	Level 6	District Collector	8-24 Hours	All lanes cleared
Wisconsin	Category 1	Major Urban Freeways and most highways with six lanes and greater	2.5 Hours	Bare Pavement
	Category 2	High volume four-lane highways ((AADT >= 25,000) and some	2.5 Hours	Bare Pavement
		four-lane highways (AADT < 25,000), and some 6-lane highways		
	Category 3	All other four-lane highways (AADT < 25,000)	2.5 Hours	Bare Pavement
	Category 4	Most high-volume two-lane highways (AADT >= 5,000) and some 2-lanes (AADT <5000)	3 Hours	Bare Pavement
	Category 5	All other two-lane highways	3 Hours	Bare Pavement
Indiana	Class I	AADT over 10,000	Every 2 Hours	Bare Pavement
	Class II	AADT 5,000 - 10,000	Every 2.5	Bare Pavement

			Hours	
	Class III	AADT under 5,000	Every 3 Hours	Partial Bare Pavement
New York	A1	Expressways with low average running speeds	1.5 Hours	Bare Pavement
	A2	Expressways with high average running speeds (500 or more Vehicle/ hour)	2 Hours	Bare Pavement
	B	Major State highways with a one-way design (200 to 500 vehicles / hour)	2 Hours	Bare Pavement
	C	Minor State highways with a one-way design (200 or less vehicles / hour)	2 Hours	Bare Pavement

In general, for each level of service, traffic volume has the greatest impact on the time stipulated for snow clearing. It is also clear from the research summarized above (Tables 2.2 – 2.10), that each country, state, or province formulates its classification based on its annual traffic volume, highway characteristics and the local climatic conditions. These factors led to some jurisdictions having more or less classes than the others. On average, jurisdictions have 3 to 5 classes, and the key level of service measurement is bare pavement regain time.

2.4 Effects of Winter road maintenance on safety benefits

The necessary WRM operations to maintain the aforementioned LOS standards have substantial monetary costs and negative environmental impacts. The average North America highway agency spends about 20 percent of their budget on winter maintenance operations, with a direct cost of $2.3 billion in the U.S and $1 billion in Canada (Transport Association of Canada 2003; FHWA, 2016). On the other hand, WRM results in improved road safety and mobility (Shi & Fu, 2018). Several studies have been conducted to investigate the safety and mobility effects of winter road maintenance in the past three decades.

In order to identify the effectiveness of salting operations on improving road safety, Hanbali and Kuemmel (1992) conducted a statistical analysis of collisions, before and after salt applications, on 570 miles of divided and undivided roads from New York, Minnesota, and Wisconsin. Figure 2.1 presents the collision rates they observed before and after salt spreading, which indicates collisions were reduced after salting operations. The average reduction in collision rates was 87% and 78% for two-lane undivided highways and freeways, respectively. Nonetheless, the statistical analysis employed in their study is overly simplistic. The traffic volumes were estimated based on the historical temporal variation of traffic, which has a discrepancy with observed traffic volumes during the events. Moreover, the study did not consider the confounding effects of weather conditions, such as precipitation, temperature, and visibility. Hence, it is possible to generate misleading benefits of winter road maintenance, if external factors such as highway features, storm characteristics and maintenance treatments are not taken into account (Fu & Usman, 2012).

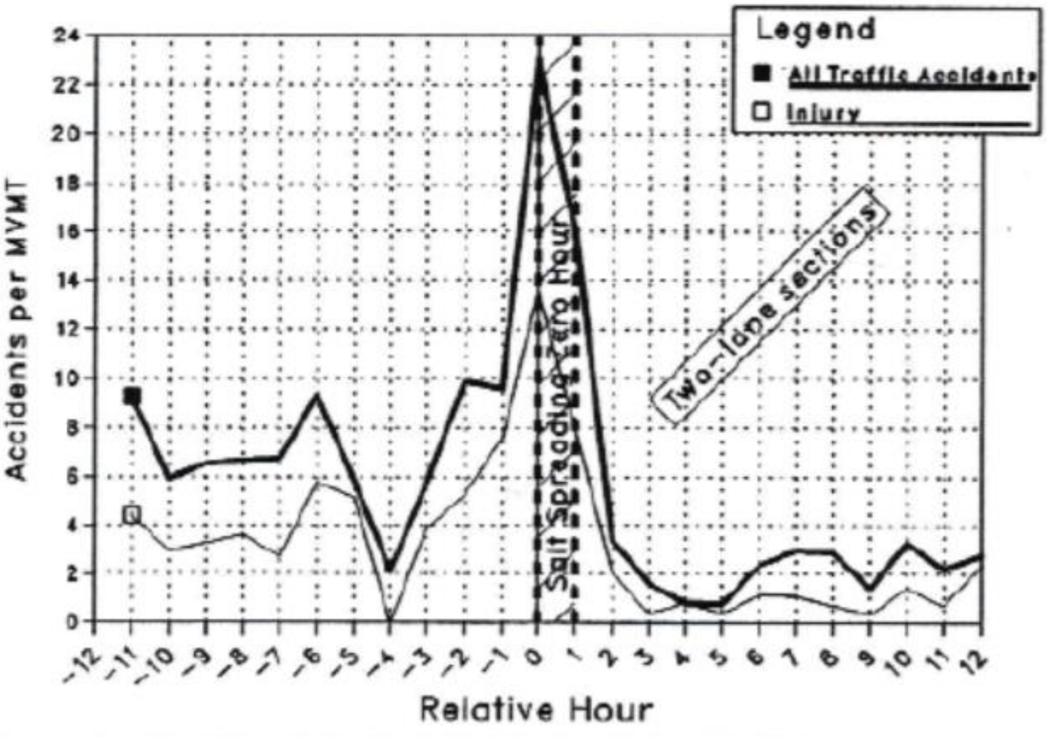


Figure 2.1: Traffic Collision rates Before and After Salting operation (Source: Hanbali and Kuemmel (1992))

Wallman et al. (1997) summarized a comprehensive review of the extensive research that Nordic countries have conducted for winter road maintenance and safety. The review indicates that the collision rate increased 1-1.5 hours before maintenance operations, and the collision rate was reduced by 50 percent a half-hour after the operations were taken. The number of collisions was 6 times higher 6-12 hours before winter road maintenance was performed. They also found the numbers of collisions were 5-14 times and 8 times higher than the collision numbers after salting was carried out in Germany and the U.S., respectively. These findings reveal that winter road maintenance operations are able to improve road conditions and thus reduce collision frequencies. In addition, it also has been observed that preventive salting (anti-icing) was more effective in reducing the collision rate than conventional salting. However, one critical limitation occurs in the most of these studies. In terms of research methodology, most of these studies only applied simple comparative analyses and lacked rigorous statistical modeling. As a consequence, their findings cannot be used to quantify the safety benefits of winter road maintenance.

Norrman et al. (2000) conducted further research to quantify the relationship between road safety, road slipperiness and winter road maintenance activity. In their study, the road condition is classified either as non-slippery or as one out of 10 types of slipperiness, and then compared the accident rates associated with the different road slipperiness classification. They defined collision risk for a specific road surface condition type, as the ratio of the collision rate to the expected number of collisions for each month. The distinguished collision risk was then compared to the percentage of WRM activities performed. Results from their study show that the collision risk was different for different types of road slipperiness: higher collision risks are always associated with greater road slipperiness. Increased maintenance can reduce level of road slipperiness and therefore lessen collisions. Nonetheless, their study has several limitations. First, they conducted an aggregate analysis on roads of all classes and locations together. Accordingly, this approach should consider some significant factors that affect road safety, such as highway geometrical features, road class, and change in traffic as well as local weather conditions. In view of this deficiency, their resulting models may not be appropriate for assessing safety effects of different WRM standards at the level of maintenance yards. Secondly, the categorical method that their approach used to determine crash rates is overly simplistic and may generate significant biases if confounding factors exist, which are likely to be the case for a complex public road condition awareness system. Thirdly, their study did not consider the variety of WRM operations, therefore it cannot be used to compare the effect of different maintenance operations.

Fu et al. (2006) examined the effects of various weather conditions and maintenance factors on road safety. The factors they investigated include air temperature, total precipitation, and different types and amounts of maintenance operations. A generalized linear regression model (Poisson distribution) was used to analyze the effects of different factors on road safety. It was found that anti-icing, prewet salting with plowing, and sanding operations all have statistically significant effects on reducing the number of collisions. However, the safety effect of plowing and salting operations could not be statistically confirmed by their work, possibly because there could be an interdependency between WRM operations and weather conditions. For instance, transportation agencies might dispatch more maintenance operations during more severe snow storms. Their study also has several other limitations. First, they used aggregated daily data and assumed road weather conditions are uniformly distributed over the entire day for each day. Second, their study did not consider some important factors that will also impact road safety, such as traffic exposure and road surface conditions. Last but not the least, the database underlying their analysis is specifically covered in selected sites and winter season and thus their results may not be applicable for quantifying the safety benefits of winter road maintenance of other sites or routes.

Usman et al. (2010) quantified the safety benefits of winter maintenance through a surrogate measure called Road Surface Index (RSI). They examined the relationship between collision frequency during snow events and road surface conditions, visibility, and other influencing factors. By linking the effects of different WRM activities to road safety through RSI, it was found that a 1 percent improvement in RSI would result in a 2 percent reduction in collisions. However, their exploratory analysis indicates that the correlation between maintenance activities and RSI is not statistically significant once road surface conditions are taken into account. Two years later, Usman et al. (2012) conducted a disaggregate approach to examine the relationship between winter road collisions, weather conditions, RSI, traffic exposure, temporal trends by using event based data. They used generalized negative binomial models. Two different models were calibrated for the average event data set and for the hourly event data set. The resulting models are given in **Equation 2-1, 2-2**.

μ-Event based = $Exp^{0.648} * e^{-3.912-0.018T*0.009W-0.044V+0.014\,TP-4.42RSI+M+S}$ **(2-1)**

μ-Hourly based = $Exp^{0.235} * e^{-1.249-0.011T+0.005W-0.039V+0.097\,TP-2.594RSI+M+S+FH}$ **(2-2)**

Where,

μ = Expected number of collisions of a highway

T = Temperature (C)

W = Wind Speed (Km/h)

V = Visibility (Km)

TP = Total Precipitation (cm)

RSI = Road Surface Index (unitless)

Exp = Exposure (equal to total traffic in an event multiplied by length of the road section)

M = Indicator for month of the year (Usman, T.2012)

S = Indicator for site (Usman, T. 2012)

FH = Dummy Variable for the effects of first hour (-0.302 if first hour, 0 otherwise)

They concluded that RSI has a crucial influence on the variation of collisions within and between individual storms and maintenance routes. It was also found that confounding factors such as air temperature, wind speed, visibility, precipitation intensity, event duration, traffic exposure, month of the winter season, have statistically significant effects on winter road safety.

In summary, most studies in this section relied on simple comparative analyses with the exception of Fu et al. (2006) and Usman et al. (2010, 2012). Nonetheless, the findings were generally consistent, indicating that WRM activities improve road surface condition and thus reduce the collision risks. As evidenced by previous studies, the road safety effects of winter road maintenance are not governed by a single factor but a wide variety of confounding factors including highway traffic, storm intensity, and maintenance polices and decisions (Shi & Fu, 2018).

2.5 Effects of winter road maintenance on mobility benefits

Few studies have been conducted on the mobility benefits of winter road maintenance. Mobility benefits consist of two major types, namely, improved travel time and reduced traffic volume impact (Shi & Fu, 2018).

Haber and Limaye (1990) quantified the benefit of reduced delay times between two different maintenance LOS by applying a stochastic simulation. In their approach, random normal variates could be computed to represent the vehicle speeds if the mean and standard deviations of speeds under two alternative levels of service were known. The time saved under a particular maintenance LOS could be computed if an average trip length was also given. Moreover, they converted the saved time to a corresponding dollar value by using functions developed by the Utah DOT. Nonetheless, their study only incorporated the direct benefits of time saving, but neglected other influenced factors such as fuel savings and collision reduction.

Shahdah and Fu (2010) conducted a simulation study to evaluate the mobility benefit of achieving bare pavement on a freeway segment near Toronto, Ontario under different traffic characteristics, weather conditions, and road surface conditions. Six levels of travel demand scenarios were created as an attempt to estimate the mobility benefits of WRM under different congestion levels. The traffic conditions for each scenario of demand and weather conditions was simulated using the INTEGRATION model. It was found that the travel time saving increased with snowfall intensity, and the highest potential reduction in total travel time caused by winter road maintenance could achieve 36 percent. Their research also presents a few limitations. First of all, the mobility benefits generated in this research were estimated based on comparing simulation results of different scenarios, but it is necessary to collect real traffic data under different snow events as a result of maintenance operations. Secondly, the types of weather events considered were limited, thus the mobility benefits estimation model in this study is unlikely to apply on other complex weather scenarios. Furthermore, this study assumed traffic demand under adverse weather conditions was same as that in normal weather conditions, which violates reality - the reasonable change in traffic demand under severe weather conditions should be taken into account for mobility benefit modeling.

Ye et al. (2012) evaluated the mobility benefits of winter road maintenance. In addition to travel time savings, they also consider fuel usage saving. The travel time savings are calculated by the differences in travel speeds over road segments under two maintenance LOS. The function they used to calculate travel time saving for i^{th} vehicle is given in **Equation 2-3:**

$$TTS_i = L/S_{i1} - L/S_{i2} \qquad \textbf{(2-3)}$$

Where:

TTS_i = travel time saving for the i^{th} vehicle during storm events

L = segment length (Km)

S_{i1}= travel speed without winter road maintenance (Km/h)

S_{i2}= travel speed with winter road maintenance (Km/h)

The financial savings can be represented through reductions in vehicle delays and in lost productivity. On the other hand, a comparative analysis between vehicle fuel usage under storm events where winter road maintenance was applied or was not applied were used to estimate fuel usage saving. They found the fuel saving benefit is a function of the fuel consumption rate (mpg) on maintained and non-maintained road. Their fuel usage savings method is given in **Equation 2-4, 2-5 and 2-6**:

For a “no maintenance” condition, fuel usage of passenger vehicles is calculated as:

$$Fuel_{pcNM} = \frac{MVM_{pc}}{MPG_{pc}*0.67} * \frac{Storm_{hrs}}{24} * Cost_{Avg} \quad \textbf{(2-4)}$$

Where:

$Fuel\ pc_{NM}$ = Fuel usage under the no (or typically limited) winter maintenance condition

MVM pc = Million vehicle miles (MVM) traveled for passenger cars during the winter season being examined in the study area

MPGpc = an average passenger vehicle MPG figure

Stormhrs = total storm duration, in hours, per season

$Cost_{Avg}$= average fuel cost for the area (note, a different cost figure should be used for passenger and heavy vehicles, respectively, excluding all taxes (as fuel tax represents a transfer and not a financial benefit).

0.67 = adjustment factor to account for a 33% reduction in vehicle MPG when no winter maintenance is performed. If another reduction factor is selected, it would replace this value.

For the “maintenance” condition, fuel usage of passenger vehicles is calculated as:

$$Fuel_{pcWM} = \frac{MVM_{pc}}{MPG_{pc}} * \frac{Storm_{hrs}}{24} * Cost_{Avg} \quad \textbf{(2-5)}$$

Hence, the fuel savings (ΔFuel) is calculated as:

$$\Delta Fuel = Fuel_{pcNM} - Fuel_{pcWM} \quad \textbf{(2-6)}$$

The results of this study estimated the annual financial savings of travel time savings and fuel usage savings are \$10.9 million and \$41.0 million, respectively. However, this research presents a few limitations. First of all, the researchers did not consider the indirect benefits of winter road maintenance. Secondly, they used general traffic data in the estimation of travel time saving: they converted ADT and AADT data from the month the data was collected to remaining months of the year and did not focus on the traffic volume during the storms. Last but not the least, a further understanding of the changes to fuel use for different types of vehicles on highways with different winter road maintenance level of service is also needed.

Donaher et al. (2012) quantified the beneficial effect of winter road maintenance on traffic volume.

They assumed traffic volume on a highway follows a Poisson distribution and its mean (expected traffic volume) is assumed to be an exponential function of various influencing factors, such as highway characteristics and road weather conditions. On highway h over a given snowstorm k, the relationship between expected traffic volume and the influencing factors is assumed to be obtained by **Equation 2-7**:

$$Q \quad = \bar{Q}_k * \exp\left(-0.264 - 0.004 * WindSpeed + 0.005 * Visibility - 0.007 * Precipitation + 0.265 * RSI\right)$$

(2-7)

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.

RSI = Road Surface Index

exp = Exposure (equal to total traffic in an event multiplied by length of the road section)

A regression analysis was also performed in their research to relate the changes in traffic volume and speed during an event to various contributing factors such as highway type, various weather conditions, and road surface conditions. The resulting model is given in **Equation 2-8:**

V = 69.082 + 0.089* Temperature (ºC) – 0.078 *Wind Speed (km/h) + 0.310 8 Visibility (km) – 1.258 * Hourly Precipitation (cm) + 16.974 * RSI – 4.325 * $\frac{V}{C} + PSL + S$

(2-8)

Where RSI is road surface index (varied between 0 to 1), $\frac{V}{C}$ is average volume to capacity ratio, and PSL is a coefficient of posted speed limit (PSL = 0 if posted speed limit = 80 km/h; 1.951 if 90 km/h; 12.621 if 100 km/h).

Donaher et al. (2012) found that the improvement in RSI would increase traffic volume with a conversion to improved trip-making utility (i.e., if commercial trips are delayed, a loss in productivity and income reasonably exist) and traffic speed. Therefore, mobility benefits of WRM operations that achieved a certain RSI target could be calculated as the increases in the travel speed will lead to an increment in travel time savings (Ye e al., 2012). They conducted a case study to visualise these results using the three winter seasons of snow storms data for the 21 highway segments in Ontario, Canada. The mobility benefit of achieving the target RSI of 0.8 bare pavement condition is shown below in **Figure 2.2**. The dollar value of travel time savings and trip-making utility are $17 and $32 million per winter season, respectively.

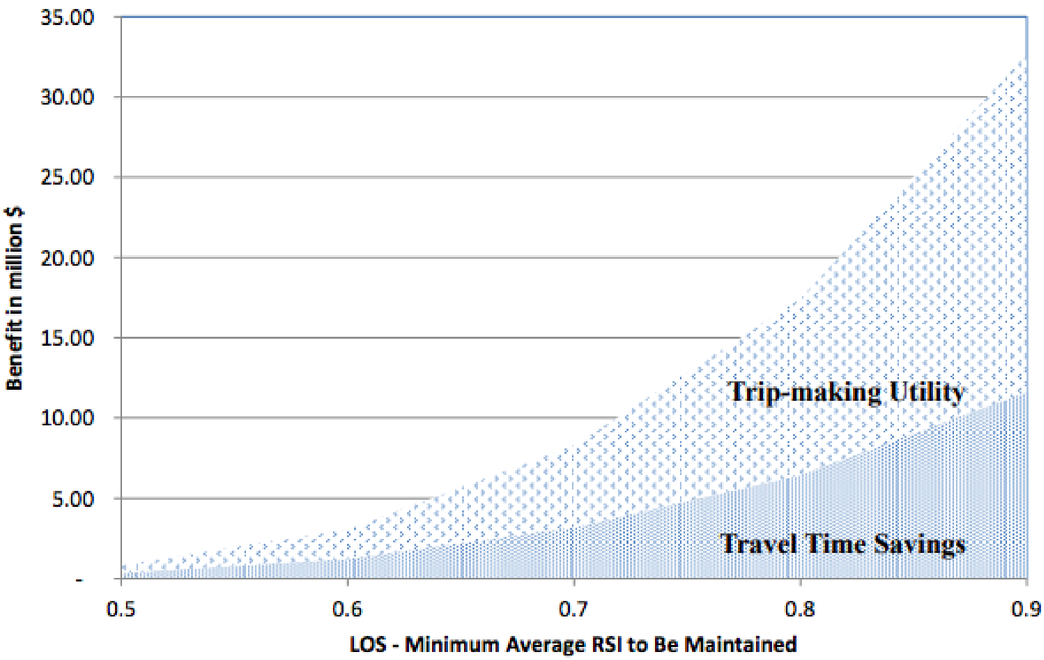


Figure 2.2 Mobility benefit of WRM vs. WRM LOS standard for Ontario Provincial Network. (Source: Donaher, 2012.)

Nevertheless, this research neglected the interaction between variables. For instance, some weather condition variables have intuitive relationships that should be examined to improve the model's estimation power. In addition, the database underlying their analysis is specific for the selected 21 sites and three winter seasons (2003-2006). Consequently, their results may not be applicable for quantifying the mobility benefits of winter road maintenance of other sites or routes.

2.6 Summary

This chapter provided a comprehensive literature review of WRM LOS and practices across worldwide different Jurisdictions. It was found that each country, state, or province establishes its road classification based on its annual traffic volume, highway type as well as local climatic conditions; as a result, some places have more classes than others. On average jurisdictions had 3 to 5 classes and the level of service was to aim for a bare pavement for safer driving conditions. Snow and ice control operations are limited by the resources available for winter maintenance operations, specifically budget, materials, and equipment. Due to these limited resources, the level of service for WRM operations is also associated with the road priorities that have been established by each country, state or province.

This chapter also reviewed the literature on studies related to the safety and mobility benefits of WRM. The findings were generally consistent, indicating that WRM operations improve road surface conditions during the snow events, which leads to a reduction of collision risks, an increase in traffic volume and speed, and thus generates subsequent road mobility and safety benefits. The quantification of the impact of alternative WRM standards on traffic safety and mobility is addressed by this research in the following chapters.

Chapter 3

Methodology and Data sources

The primary objective of this research is to assess the effectiveness of adding a new level of service class (Urban Freeway) to MTO's existing WRM standards. The research was based on data collected from a pilot implementation of the new UFW class at different locations across Ontario. This chapter details (1) methodology; (2) the data sources to be used in this research; and (3) the data processing and integration procedure to create the data set for the subsequent modeling and analysis.

3.1 Methodology

A four steps methodology is applied in this research to achieve the research objectives (**Figure 3.1**):

1. Data Collection and Processing: Event based data of pilot sites are collected from different sources and integrated using event time and location as the common reference.
2. Analysis of Field Performance Data. A qualitative comparative analysis is conducted in this pilot study to analyze and compare the relative WRM performance between the alternative WRM standards in terms of three performance measurements, namely, bare pavement regains time (BPRT), within storm snow coverage, and material usage. The analysis begins with listing and counting three performance measures observed in the data set and is followed by comparing the population means of these three measures of two WRM standards by assuming that there were no systematic differences in environmental factors between two WRM class of each test site.
3. Statistical Analysis: The newly introduced UFW class is stipulated to have a higher requirement of WRM performance (shorter BPRT time). In order to evaluate the benefit implications of shorter BPRT brought by the new LOS standard, a quantitative estimation of the BPRT difference between two alternative LOS standards should be developed. A statistical modeling approach is therefore proposed here to investigate the relationship between the better WRM performance outcome (BPRT difference between alternative LOS standard) and various possible influencing factors.
4. Benefit Estimation: As mentioned in the previous section, highways in Ontario are categorized into five different winter road classes based on winter traffic volume and highway type. Each class is thus specified by a particular level of service (LOS) standard to be maintained during winter snowstorm events. Therefore, the benefits associated with

individual classes of highways vary. For this research, the WRM safety and mobility benefits estimation models developed from past studies are extrapolated to Class 1 and UFW highway sections in the trial sites to estimate the net benefits of upgrading the LOS standard.

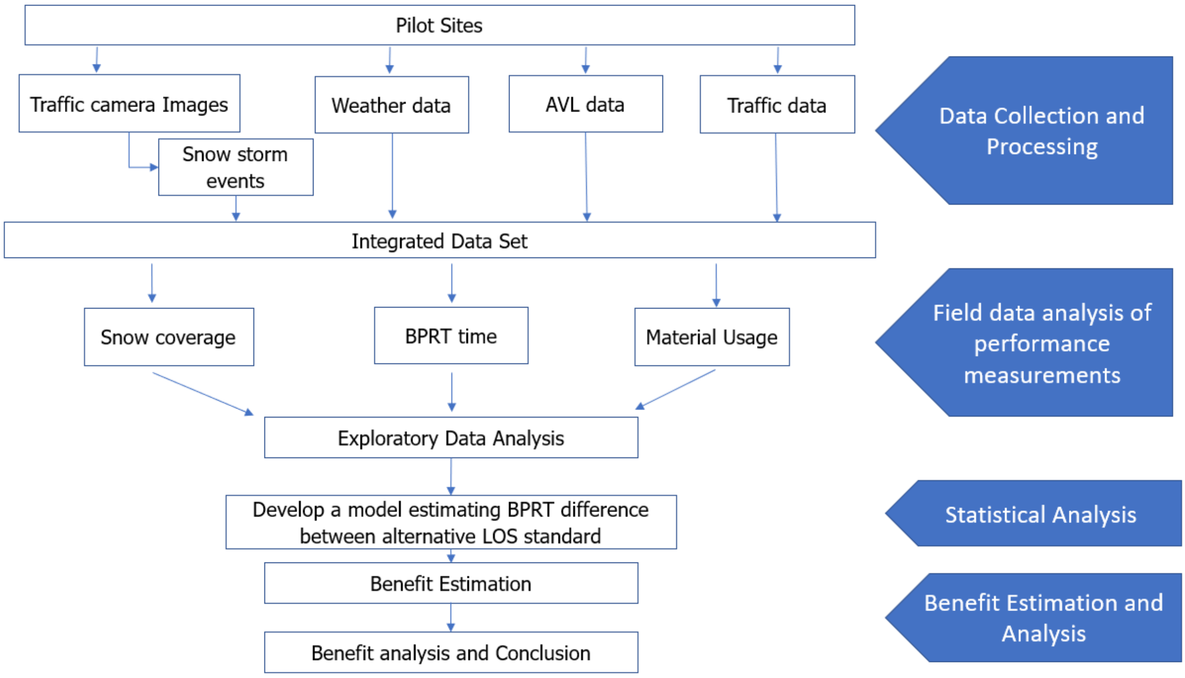


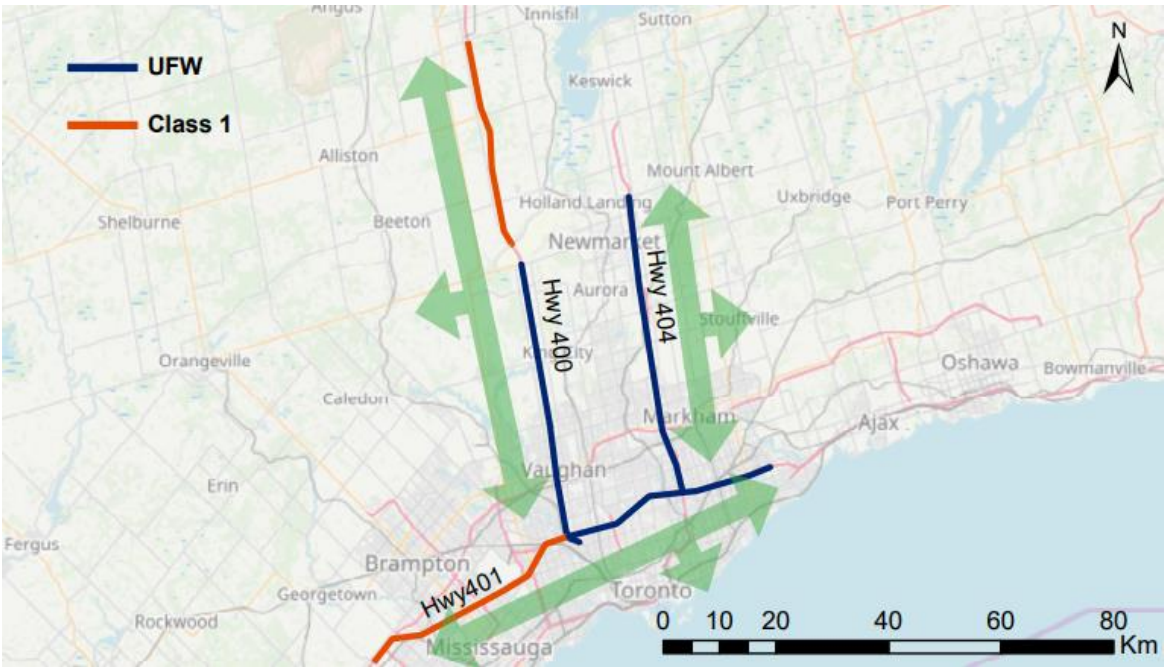
Figure 3.1 Methodology

3.2 Study Sites and Data Sources

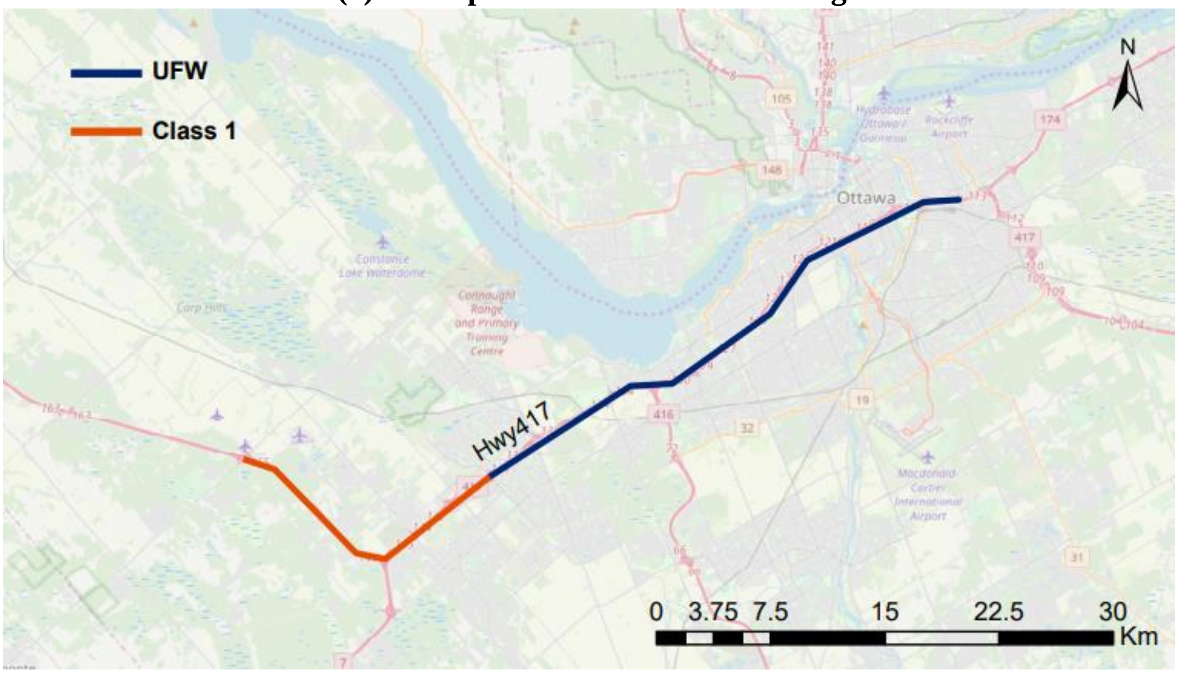
In order to test the effectiveness of the new WRM standard, MTO has piloted several trial sites on different Ontario highways with extremely high winter daily traffic volume as a way to assess their potential impacts in terms of costs and benefits. Data on maintenance operations, performance measures and weather conditions were collected for the comprehensive analysis of the new Urban Freeway (UFW) class of winter road maintenance standard. This section describes selected study sites, various data sources and data measurement samples.

3.2.1 Study Sites

MTO has implemented the UFW standard on four highway sections throughout Ontario: highway (Hwy) 400, 401, 404 and 417. For comparison, the adjacent highway segments that remained as Class 1 highways were selected as control sections. Note the trial site on Hwy 404 shares the same Class 1 section with the trial site in Hwy 400. The distribution of study sites and details of each selected highway section are given in **Figure 3.2** and **Table 3.1**.



(a) UFW pilot sites in the Central region



(b) UFW pilot sites in the Eastern region
Figure 3.2: Selected Study sites

Table 3.1: Selected Study sites

Site	WRM Class	Section Start	Section End	Length (KM)
Hwy400	Class1	Highway 8 (Canal road)	Innisfil Beach Rd	14.6
	UFW	Maple leaf Drive	highway 9	28
Hwy401	Class1	Trafalgar Road	Highway 400	31.5
	UFW	Highway 400	Morningside Ave	28
Hwy 404	UFW	Intersection of 600m south of Hwy 401	Green Lane	36.6
Hwy 417	Class1	Highway 49 (March Rd)	Highway 61 (Terry Fox Dr)	14.6
	Class 1	Highway 61 (Terry Fox Dr)	Highway 26 (St Laurent Blvd)	28

3.2.2 Data Sources

In order to compare the maintenance performance of alternative winter road maintenance standard, five types of data were collected including image data, weather data, Auto Vehicle Locator (AVL) data, traffic data, patrol reports (winter operation records and bare pavement reports). These data were gathered from different sources and managed by different institutions. This section provides a description of these data sources. To be noted, only data during individual snow storm events were collected and compiled in this research. The definition of a snow storm event in this research is given in the following section (3.2.2.1).

3.2.2.1 Image Data

MTO has a number of cameras at the test sites (**Figure 3.3**). Five cameras were used as shown in **Table 3.2**. These cameras record images continuously at approximately 15 min intervals.

Table 3.2 Cameras and Locations

Highway	WRM standard	Camera Location
Hwy417	Class 1	West of Moodie Dr
	UFW	O Connor St
Hwy 400	Class 1	Near Bradfords St
	UFW	Near Langstaff Rd
Hwy 404	UFW	Near Finch Ave

Hwy 401	Class 1	Near Transfer-east of Dixie
	UFW	East of Yonge St

Figure 3.3: Highway traffic cameras

Image data was used as the primary source to identify snowstorm events:

1. Event start time is the time when snow precipitation begins, either observed through camera images that snow is dropping or when snow begins to accumulate on the road surface under the case that the image quality is too bad to capture snow dropping.
2. Precipitation end time is the time when there is no more snow falling in the camera images and snow stops accumulating on the highway road surface.
3. Bare pavement lost time is the time when the road surface lost bare condition and snow accumulation can be visually observed from camera images.
4. Bare pavement regain time is the time from the time when snow precipitation stops to the time when road surface reaches bare condition. In this research, the time at which bare pavement is regained also denotes the event end time.
5. Percent Snow coverage is the fraction of snow coverage on the road surface during the precipitation time; the classification of snow coverage in every five percentage is given in **Appendix A**.

An individual snow event was defined from the beginning of snow falling or accumulation of snow on the road surface to the time when road surface condition was restored to the bare condition, as depicted in **Figure 3.4**. 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. **Table 3.3** describes 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). Once an event is identified, the bare pavement recovery time (BPRT) and the percent of snow coverage are determined. A summary of observed snowstorm events by site for the 2018-2019 season is given in **Figure 3.5.**

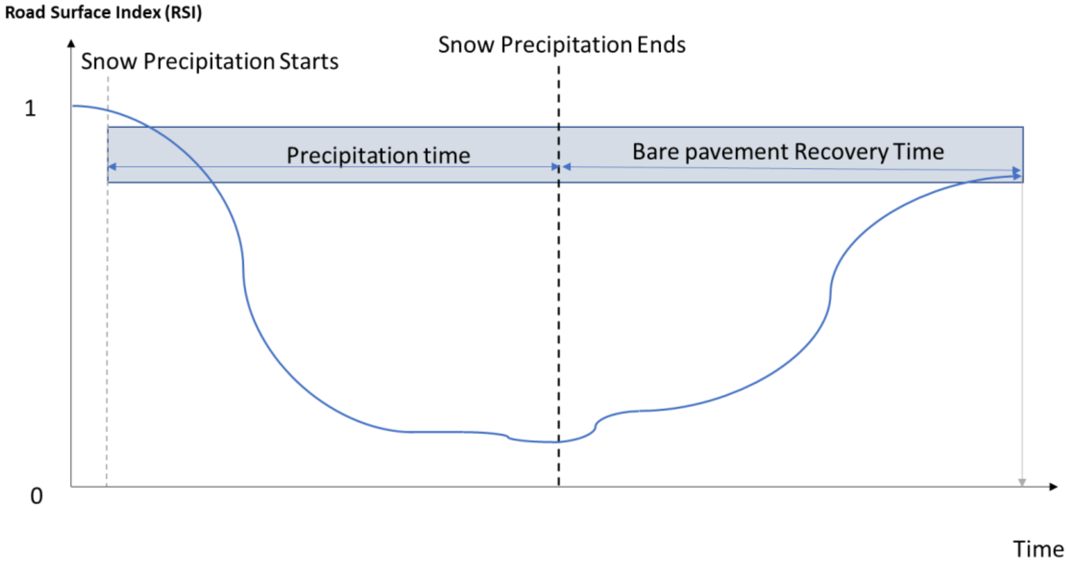


Figure 3.4: Definition of Snowstorm event

Table 3.3 Road Surface Condition Major Classes

Road Surface Condition Major Classes	**Road Surface Index**
Bare and Dry	0.95
Bare and Wet	0.85
Slushy	0.75
Partly Snow Covered	0.6
Snow Covered	0.4
Snow Packed	0.25
Icy	0.125

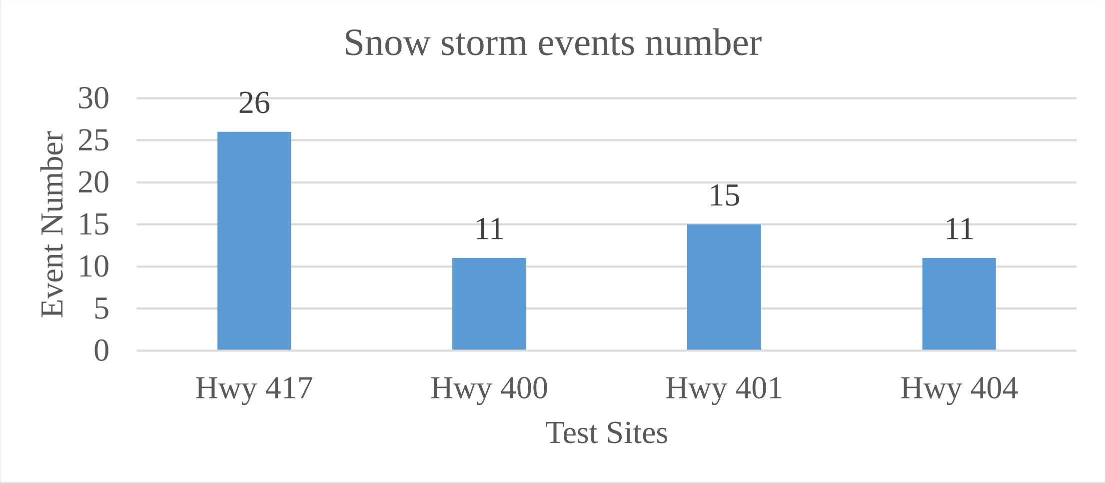


Figure 3.5 Distribution of snowstorm events by sites of 2018-2019 season

3.2.2.2 Weather Data

Weather data was extracted from two sources: Environment Canada (EC) Weather Station (OTTAWA CDA RCS) and the Road Weather Information System (RWIS). Weather data from Environment Canada (EC) includes air temperature (°C), relative humidity (%), wind speed (km/h), visibility (km), wind chill (°C), and precipitation intensity. RWIS contains similar information about temperature, visibility, wind speed, etc., recorded by the RWIS stations near the selected test sites. All data from RWIS are used as a secondary source for filling in the missing data from EC. EC data is available at different time formats, but hourly data was selected for the purpose of this research. However, in terms of the data source for precipitation intensity, only daily type precipitation data is stored by Environment Canada. As a result, precipitation intensity data were derived from the daily type precipitation data by assuming precipitations are uniformly distributed. The EC sites and RWIS stations used in this research are listed in below **Table 3.4**. In **Appendix B**, sample EC and RWIS data are given.

Table 3.4 EC sites and RWIS stations used for each test site

Test Sites	EC sites	RWIS stations
Highway 417	Ottawa International Airport	ER-2 Ashton
Highway 400	Toronto International Airport	CR-16 King City
Highway 404	Toronto North York	CR-23 Hwy404-401
Highway 401	Toronto City	CR-14 Gormley

3.2.2.3 Automatic Vehicle Locator Data

Automatic Vehicle Locator (AVL) is a device that makes use of the Global Positioning System (GPS) to enable maintenance agencies to remotely track the location of their vehicle fleets in real-time (Margaret, 2011). AVL data contains various information including vehicle GPS location, operation timing, material spread amount, material type, and material application rate. Material usage for each site and event could be calculated from AVL data; the processing procedure is explained in **section 3.3.** In **Appendix C**, sample of AVL data is given.

3.2.2.4 Traffic volume Data

Traffic volume data were obtained from the MTO's permanent data count stations (PDCS). PDCS provided both hourly and daily traffic volume data. Unfortunately, traffic volume data were not available for the 2018/2019 winter season under study (Dec 31st, 2018 to Mar 17th, 2019). However, two weeks of traffic volume data for November 2018 at all trial sites were provided by the MTO in both daily and hourly formats. A 12 year (from 1999 to 2010) hourly traffic volume database was therefore used to compute an hourly traffic volume matrix for each site. Every hour's traffic volume data during the study season can be approximated by using that day's daily data multiplied by the corresponding hourly factor. For example, the traffic volume on Wednesdays from 9:00am to 10:00am can be estimated using the daily traffic data for Wednesdays from the sampled traffic volumes multiplied by this hour's volume ratio.

Appendix D illustrates this hourly ratio in 24*7 matrix and corresponded hourly traffic volume for one sample trial site.

3.2.2.5 Winter Operation Records & Bare Pavement Reports

Winter Operations records (WOR) contained the similar information with the vehicle operation data from the AVL system, such as vehicle location, operation time, amount of materials used, traveled distance and maintenance truck number, but have less details. The WOR data was used as a supplementary source of AVL data for verifying if AVL data recorded maintenance operations correctly. The Bare Pavement (BP) reports record start of event time, the time bare pavement was lost, event ending time and bare pavement regain time. It also provides information on the type of the event such as snow, freezing or both. **Appendix E** shows a sample of WOR and BP reports.

3.3 Data Processing

As described previously, there are three main types of data available for each selected study site. Once these data were obtained, they were pre-processed for subsequent merging and integration. After obtaining the data from different sources, the next important step is data integration. Raw data are first extracted and organized to the corresponded trial sites based on the location and event timings. In this stage, three data sets – Snow Coverage, BPRT and Material Usage are constructed for further exploration and processing.

Snow coverage is recorded through highway traffic camera images. Once the event start time was identified, the fraction of snow coverage on the road surface was recorded in percentage for each image until the event stopped, based on the classification of snow coverage given in **Appendix A**. To be noted, snow coverage in this research is measured by the average of all lanes, **Table 3.5** shows how snow coverage is recorded and organized for one sample event, which started on 23:00 2019-01-17 and ended on 5:15 2019-01-18.

Table 3.5 Sample snow coverage in one event

Event ID	Time	Snow Avg
4	2019-01-17 23:00	0%
4	2019-01-17 23:15	0%
4	2019-01-17 23:30	5%
4	2019-01-17 23:45	10%
4	2019-01-18 0:00	5%
4	2019-01-18 0:15	5%
4	2019-01-18 0:30	10%
4	2019-01-18 0:45	10%
4	2019-01-18 1:00	5%
4	2019-01-18 1:15	5%
4	2019-01-18 1:30	10%
4	2019-01-18 1:45	15%
4	2019-01-18 2:00	50%
4	2019-01-18 2:15	40%
4	2019-01-18 2:30	35%
4	2019-01-18 2:45	35%

4	2019-01-18 3:00	30%
4	2019-01-18 3:15	30%
4	2019-01-18 3:30	25%
4	2019-01-18 3:45	25%
4	2019-01-18 4:00	20%
4	2019-01-18 4:15	20%
4	2019-01-18 4:30	15%
4	2019-01-18 4:45	10%
4	2019-01-18 5:00	5%
4	2019-01-18 5:15	0%

BPRT, defined as the time elapsed when precipitation stops to the time when bare pavement is restored, is the most commonly used performance measure in the maintenance sector. In this research, precipitation end times and bare pavement regained times were identified through traffic camera images, and the BPRT times were calculated in unit of hours by using the latter minus the former. Note that for one individual event when the time of bare pavement condition achieved before the time of precipitation stopped, the BPRT time was treated as "0". For a comparative analysis, BPRT of each snow event were summarized for both UFW and Class 1 sections of all trial sites. **Table 3.6** presents one sample BPRT summary (Highway 404 Trial site's UFW section).

Table 3.6 Sample BPRT summary in Highway 404 Trial site's UFW road section

Event ID	**Road Section**	**Precip Start time**	**Precip End time**	**BP lost**	**BP regained**	**BPRT (h)**
1	Hwy404 UFW	2019-01-02 16:15	2019-01-03 6:45	2019-01-02 16:45	2019-01-03 3:45	0.0
2	Hwy404 UFW	2019-01-09 8:00	2019-01-10 8:30	2019-01-09 8:30	2019-01-09 22:15	0.0
3	Hwy404 UFW	2019-01-17 22:30	2019-01-18 16:15	2019-01-18 0:30	2019-01-18 6:00	0.0
4	Hwy404 UFW	2019-01-23 1:30	2019-01-23 11:30	2019-01-23 2:15	2019-01-23 11:30	0.0
5	Hwy404 UFW	2019-01-26 21:45	2019-01-27 6:15	2019-01-27 0:30	2019-01-27 10:45	4.5

6	Hwy404 UFW	2019-02-06 6:15	2019-02-06 15:45	2019-02-06 7:30	2019-02-06 17:30	1.8
7	Hwy404 UFW	2019-02-24 20:00	2019-02-24 22:15	2019-02-24 21:45	2019-02-24 22:00	0.0
8	Hwy404 UFW	2019-02-25 1:00	2019-02-25 5:45	2019-02-25 3:15	2019-02-25 5:30	0.0
9	Hwy404 UFW	2019-02-27 6:30	2019-02-27 23:15	2019-02-27 7:45	2019-02-27 23:45	0.5
10	Hwy404 UFW	2019-03-03 17:15	2019-03-03 20:30	2019-03-03 17:45	2019-03-03 20:00	0.0
11	Hwy404 UFW	2019-03-16 21:15	2019-03-16 23:00	2019-03-16 23:00	2019-03-16 23:30	0.5

It is expected that if higher WRM standards are strictly followed, the UFW section should be covered with a larger sized fleet and use more materials than the Class 1 section. To verify this hypothesis, amount of materials being used or material usage was considered. MTO provided the AVL data of all maintenance vehicles that operated on trial sites, which recorded the material usage of each spreading operation along with application rate and travel distance. Additionally, the GPS technology in the AVL system helped identify all of the AVL records that specifically operated on the trial sites. Furthermore, after the event times were identified in the previous step, the material usage on each test section over each event could be summarized. In addition, for the further comparative analysis, the material usage was normalized in the unit of single lane kilometer. The sample AVL data is shown in **Appendix C**.

3.4 Summary

This chapter provides the methodology applied for this research, introduces the pilot study, and describes the various data sources and data preparation processes utilized in this research. Four trial sites on the 400-series highways in Ontario were selected; these sites experienced different weather conditions and road surface conditions through 2018-2019 winter seasons. Multiple types of data were obtained for each site from various sources, after which image and AVL data were compiled and averaged at the event level for the comparative analysis. For safety and mobility benefit estimation, one single integrated dataset that combined all the data sources on an hourly basis for each trial site was created. The analysis that uses these various data sets is presented in Chapter 4.

Chapter 4
Comparative Analyses

This research aims to quantify the impact of alternative winter road maintenance service standards under different weather conditions on traffic safety and mobility. In order to achieve this goal, field trials were conducted to compare the WRM performance between the alternative WRM standards in terms of three performance measurements, namely, bare pavement regains time (BPRT), within storm snow coverage, and material usage. This Chapter describes (1) the comparative analyses conducted, and the results based on the field trials; (2) the estimation model of BPRT difference between alternative LOS standard developed to associate BPRT difference with a variety of weather condition related variables; and (3) the safety and mobility benefits analyses of implementing the UFW LOS standard.

4.1 Data

Data used in this study was acquired from MTO and Environment Canada, including weather conditions, event information, and AVL data. This data covers the winter season from 31st of Dec 2018 to 17th of Mar 2019, a total of 63 snow events were identified. As described in chapter 3, all the collected data is integrated in the event-based format, and this event -based dataset was obtained by aggregating information for each event. **Table 4.1** shows a snow event summary with their original IDs for all trial sites and **Table 4.2** gives the summary descriptive statistics. **Figure 4.1** presents the weather review of all 63 events.

Table 4.1: Snow events summary for all trial sites.

Event ID	Site name	UFW BPRT (h)	Class1 BPRT (h)	UFW Snow Avg	Class1 Snow Avg	Event Duration (h)	Snow Precip (cm)	Temp (°C)	Wind Spd (km/h)	Visibility (km)	UFW Material Usage (kg per single-lane km)	Class 1 Material Usage (kg per single-lane km)
1	Hwy 400	0.0	0.0	5%	34%	14.00	3.80	-3.15	8.07	14.00	420.42	194.60
2	Hwy 400	0.0	0.0	1%	18%	20.75	0.00	-3.06	24.62	21.74	463.93	510.62
3	Hwy 400	0.0	0.0	6%	8%	14.75	2.20	-3.61	6.73	11.93	311.44	178.91
4	Hwy 400	0.0	0.0	8%	20%	6.25	3.00	-0.72	10.17	7.50	448.06	165.84
5	Hwy 400	3.5	6.0	37%	31%	14.50	10.40	-7.66	12.53	9.21	537.15	121.34
6	Hwy 400	0.0	1.8	36%	10%	11.25	2.00	-4.84	16.45	6.22	658.92	284.45
7	Hwy 400	0.2	0.0	8%	1%	2.00	0.60	-0.53	37.00	12.37	115.08	45.32
8	Hwy 400	0.0	2.0	7%	17%	6.75	1.80	-4.51	30.00	12.44	266.00	190.96
9	Hwy 400	0.2	3.0	27%	16%	19.75	18.40	-12.37	17.05	6.36	898.06	259.13
10	Hwy 400	0.7	1.0	2%	3%	4.25	0.40	-4.50	12.75	11.05	26.01	1.47
11	Hwy 400	1.0	1.0	6%	3%	1.25	0.00	-3.10	15.00	24.10	93.46	0.00
12	Hwy 404	0.0	0.0	9%	34%	11.50	3.80	-3.38	7.55	11.05	695.27	194.60
13	Hwy 404	0.0	0.0	1%	18%	14.25	0.00	-1.92	22.87	22.50	235.31	510.62
14	Hwy 404	0.0	0.0	3%	8%	7.50	2.20	-4.90	4.14	8.09	245.98	178.91
15	Hwy	0.0	0.0	7%	20%	10.00	3.00	-0.17	10.20	7.06	565.91	165.84

	404											
16	Hwy 404	4.5	6.0	44%	31%	13.00	10.40	-7.63	10.92	8.77	821.43	121.34
17	Hwy 404	2.3	1.8	39%	10%	11.25	2.00	-4.84	16.45	6.22	951.35	284.45
18	Hwy 404	0.0	0.0	14%	1%	2.00	0.60	-0.53	37.00	12.37	61.95	45.32
19	Hwy 404	0.0	2.0	9%	17%	4.50	1.80	-4.12	31.20	10.66	277.56	190.96
20	Hwy 404	0.5	3.0	31%	16%	17.25	18.40	-11.98	18.06	4.36	1017.19	259.13
21	Hwy 404	0.0	1.0	6%	3%	2.75	0.40	-4.10	10.50	5.20	142.87	1.47
22	Hwy 404	0.5	0.0	1%	3%	2.25	0.00	-3.20	18.50	24.10	36.11	0.00
23	Hwy 401	2.5	5.3	15%	7%	11.8	3.8	-0.2	13.8	10.9	234.77	215.02
24	Hwy 401	0.0	0.0	0%	1%	1.5	0.0	0.7	36.0	16.1	0.00	0.00
25	Hwy 401	0.0	0.0	1%	3%	10.5	0.4	-0.8	36.3	13.7	83.01	24.36
26	Hwy 401	2.0	1.7	13%	16%	6.2	2.2	-2.1	4.6	9.6	152.68	110.48
27	Hwy 401	0.0	3.3	5%	7%	11.0	3.0	1.2	11.1	11.2	149.39	129.39
28	Hwy 401	0.0	0.0	0%	9%	35.3	1.4	-1.9	28.8	14.0	246.77	45.63
29	Hwy 401	2.0	2.2	51%	54%	15.0	10.4	-5.5	21.7	7.4	448.29	224.74
30	Hwy 401	4.2	4.7	40%	17%	10.7	2.0	-2.3	40.0	8.9	155.04	202.77
31	Hwy 401	0.0	0.5	1%	1%	13.2	0.4	-4.6	48.8	14.7	0.00	10.71
32	Hwy	2.5	5.8	18%	16%	13.3	1.6	-4.1	19.1	13.9	127.20	55.19

	401											
33	Hwy 401	0.0	1.2	19%	32%	12.5	4.7	-7.6	16.7	5.2	295.85	169.09
34	Hwy 401	1.3	1.7	4%	5%	9.5	2.4	0.6	54.3	12.1	238.68	61.97
35	Hwy 401	3.5	5.8	30%	32%	25.0	18.4	-9.8	21.5	8.1	361.62	288.75
36	Hwy 401	0.0	0.0	1%	4%	7.0	4.0	-1.5	8.0	4.1	14.13	6.78
37	Hwy 401	3.8	10.3	9%	9%	10.8	0.0	-3.6	19.5	16.1	0.00	1.48
38	Hwy 417	0.0	3.3	28.1%	22%	20.00	4.28	-1.2	25.4	10.1	701.23	418.59
39	Hwy 417	1.2	1.2	47.0%	59%	12.50	8.00	-12.4	11.4	7.1	683.44	315.08
40	Hwy 417	5.0	2.7	44.2%	52%	5.00	1.80	-0.9	17.7	14.1	355.83	118.59
41	Hwy 417	4.0	3.7	58.4%	58%	11.25	8.40	-10.0	22.1	7.2	617.18	253.77
42	Hwy 417	0.3	5.0	9.3%	16%	23.25	4.40	-2.8	31.3	11.2	557.06	279.40
43	Hwy 417	0.5	0.3	3.3%	3%	10.75	2.00	-1.8	28.2	15.9	321.47	100.00
44	Hwy 417	0.0	2.7	14.9%	14%	20.00	5.40	-14.5	8.9	7.1	525.15	301.01
45	Hwy 417	0.0	3.0	41.5%	37%	39.75	25.20	-6.0	13.3	5.3	1560.74	746.73
46	Hwy 417	0.0	0.0	7.6%	12%	10.25	0.80	-7.8	18.5	19.7	224.54	102.51
47	Hwy 417	0.5	0.0	35.8%	38%	8.50	3.80	-7.7	27.6	12.2	598.77	154.77
48	Hwy 417	1.2	2.0	26.5%	30%	56.50	14.20	-9.7	11.4	9.3	2639.88	809.05
49	Hwy	5.5	8.8	19.8%	23%	21.25	1.00	-9.3	15.2	10.6	962.25	299.50

	417											
50	Hwy 417	0.0	0.8	0.4%	1%	6.75	0.40	0.2	46.0	24.1	0.00	2.51
51	Hwy 417	0.0	0.0	60.8%	66%	26.25	31.00	-6.7	26.7	7.8	1227.69	250.75
52	Hwy 417	0.0	0.0	17.7%	27%	7.25	3.34	-4.5	22.0	7.9	511.10	124.12
53	Hwy 417	2.0	2.8	4.6%	16%	3.75	0.46	1.1	31.7	24.1	42.94	46.23
54	Hwy 417	5.0	5.3	56.5%	54%	10.00	9.40	-7.4	16.0	6.5	591.32	186.43
55	Hwy 417	0.0	0.3	1.2%	9%	10.25	0.00	-1.2	29.5	7.6	230.06	132.51
56	Hwy 417	1.5	0.0	3.9%	4%	8.25	0.00	-2.1	42.4	16.9	34.36	46.23
57	Hwy 417	1.0	1.5	6.5%	5%	5.50	1.10	-4.7	6.0	7.6	139.27	48.24
58	Hwy 417	2.2	2.0	13.7%	6%	6.75	0.40	-5.9	11.3	14.9	206.02	95.48
59	Hwy 417	2.3	2.3	10.7%	10%	5.25	1.40	-9.1	11.2	13.0	251.48	75.88
60	Hwy 417	1.8	1.3	55.5%	54%	7.25	12.80	-3.5	26.5	2.6	434.91	171.37
61	Hwy 417	4.5	3.0	16.2%	25%	5.50	1.60	-3.9	19.6	15.2	253.43	73.88
62	Hwy 417	1.8	2.3	18.3%	28%	6.00	6.80	-1.0	10.0	10.2	226.21	108.04
63	Hwy 417	0.0	1.5	0.8%	21%	2.75	0.20	-3.6	42.0	24.1	0.00	32.16

Table 4.2: Descriptive Statistics

	UFW BPRT (h)	Class1 BPRT (h)	UFW Snow Avg	Class1 Snow Avg	Event Duration (h)	Snow Precip	Temp (°C)	Wind Spd (km/h)	Visibility (km)	UFW Material Usage (kg per single-lane km)	Class 1 Material Usage (kg per single-lane km)
Minimum	0.00	0.00	0.00	0.01	1.25	0.00	-14.55	4.14	2.60	0.00	0.00
Maximum	5.50	10.25	0.61	0.66	56.50	31.00	1.16	54.30	24.10	2639.88	809.05
Mean	1.20	2.01	0.18	0.19	11.99	4.57	-4.33	21.11	11.67	407.83	170.55
Standard Deviation	1.60	2.27	0.18	0.17	9.50	6.37	3.64	11.79	5.51	433.57	162.76
Count	63	63	63	63	63	63	63	63	63	63	63

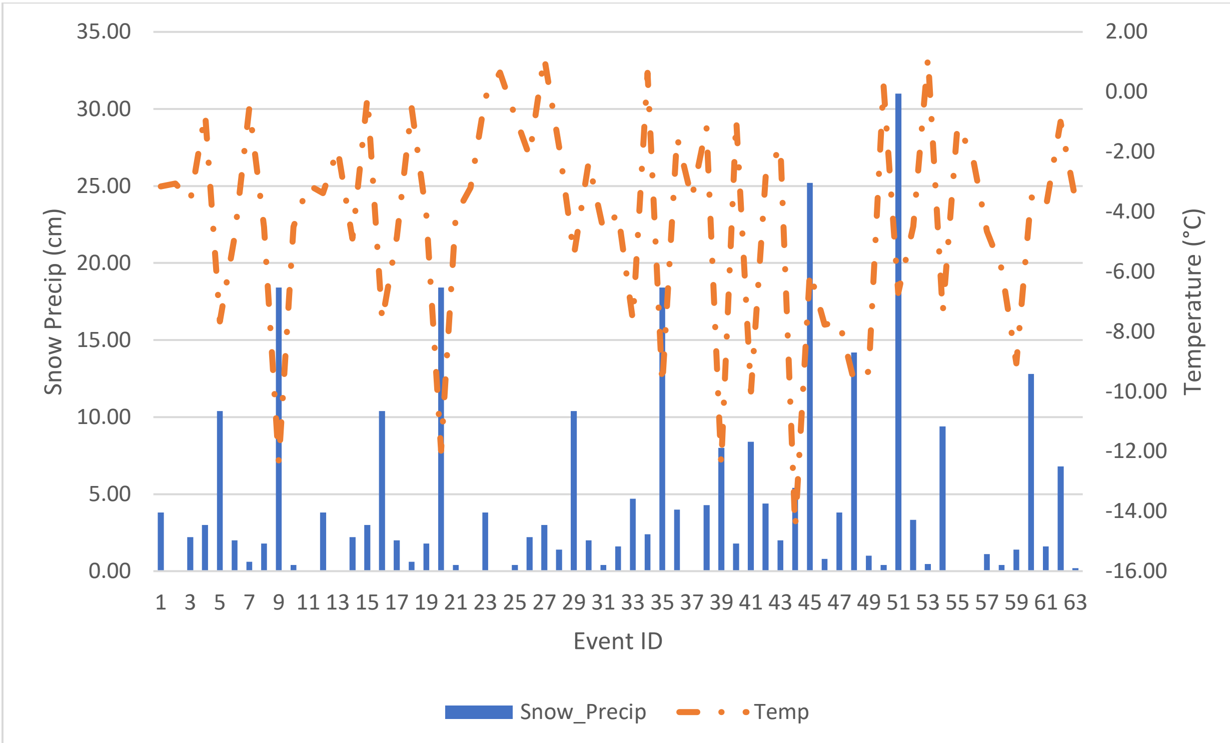


Figure 4.1: Overview of all 63 identified snow events

4.2 Comparative Analysis

4.2.1 BPRT

BPRT, defined as the time elapsed when precipitation stops to the time when bare pavement is restored, is the most commonly used performance measure in the maintenance sector. This section compares the BPRT performance between two alternative LOS standards.

According to MTO's new standards, the target BPRT is four hours for UFW highways and eight hours for Class 1 highways. As discussed previously, the BPRT data were determined manually from camera images. **Figure 4.2** shows a comparison of the average BPRT for all the events. On average, the UFW sections had a lower BPRT as compared to the Class 1 sections. To reduce the effect of any variability present among test sections due to differences in site-specific factors, a paired t-test was conducted. The null hypothesis was that there is no difference in BPRT between the two classes of highways; the alternative hypothesis was that the UFW sections have a lower BPRT than those of the Class 1 section (i.e., single-tailed test). The t-test rejected the null hypothesis, which suggests that the UFW sections had a statistically significant lower BPRT than the Class 1 highways (5% level of significance) (**Table 4.3**). For the 2018/2019 winter season, the average BPRT was 1.20 hours for the UFW sections versus 2.01 hours for the Class 1 sections, showing an improvement of 40%

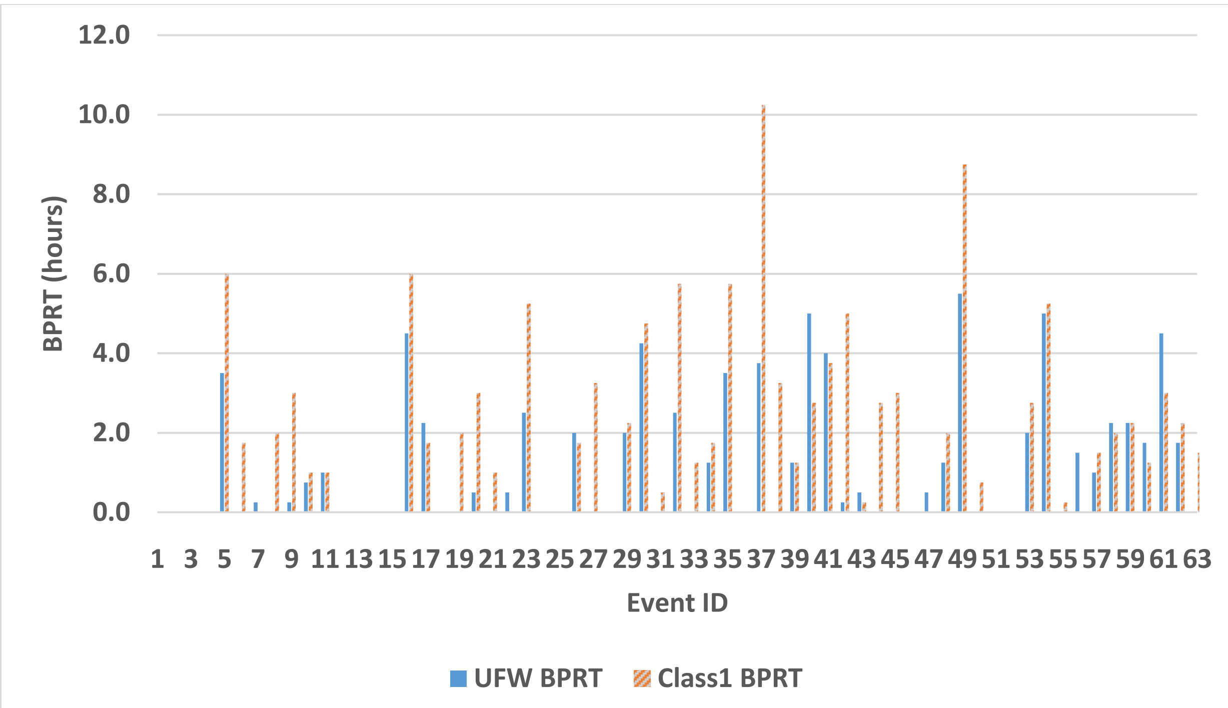


Figure 4.2 BPRT Comparison by events

Table 4.3: Comparison of overall average BPRT between UFW and Class 1 LOS standard

t-Test: Paired Two Sample for Means		
	UFW BPRT	***Class1 BPRT***

Mean	1.20	2.01
Variance	2.57	5.14
Observations	63	63
Pearson Correlation	0.73	
Hypothesized Mean Difference	0	
df	62	
t Stat	-4.17	
P(T<=t) one-tail	0.00005	
t Critical one-tail	1.67	
P(T<=t) two-tail	0.00010	
t Critical two-tail	2.00	
Significant Difference exist in BPRT performance when implement alternative LOS standard		

4.2.2 Within storm snow coverage

Within storm snow coverage was used to measure the maintenance performance over the period of the event. As described in section 3.3, it is manually recorded through highway traffic camera images. The fraction of snow coverage on road surface was determined in percentage for each image from the start of the event to the event end time. **Figure 4.3** shows a comparison of the average snow coverage for all the events. It can be observed that UFW and Class 1 sections had similar within-storm road surface conditions during most events. Overall, the average within-storm condition of the UFW sections were slightly better than that of that of the Class 1 sections (1% less). However, a paired t-test did not provide evidence that the difference is statistically significant (5% level of significance) **(Table 4.4)**. This result is partly expected, since the MTO's current WRM standards do not include any within-storm specific performance requirements.

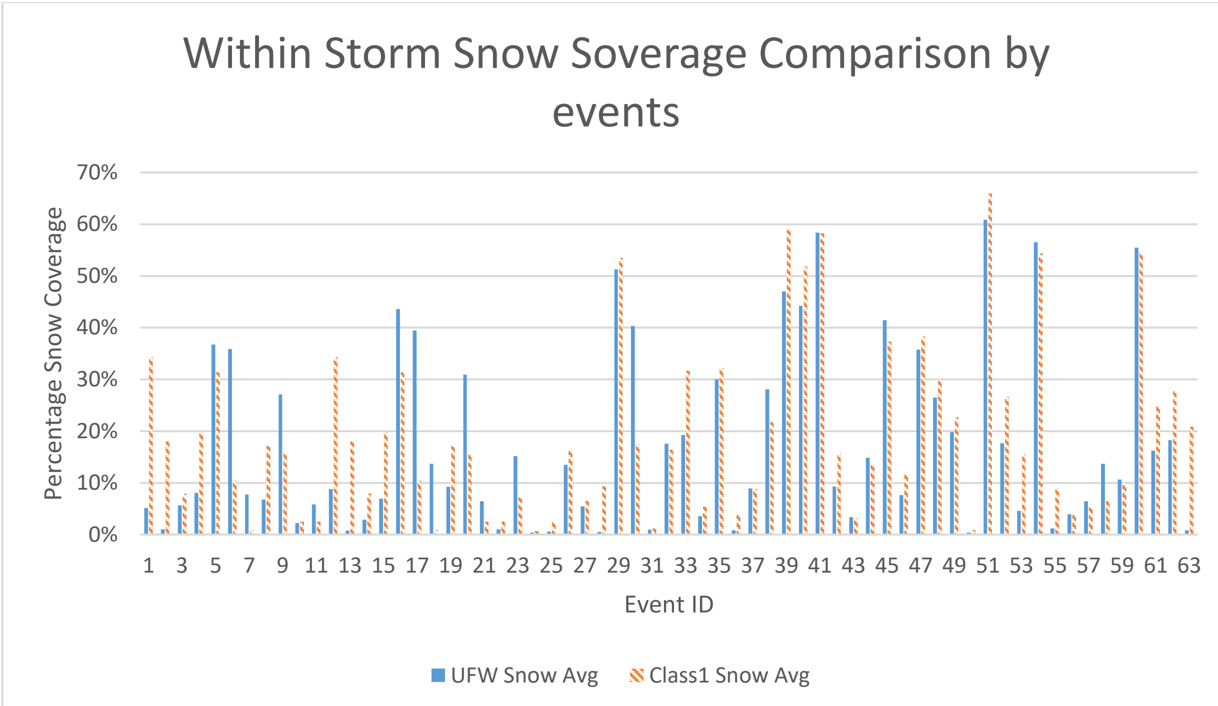


Figure 4.3 Within Storm Snow Coverage Comparison by events

Table 4.4: Comparison of overall average Within Storm Snow Coverage between UFW and Class 1 LOS standard

t-Test: Paired Two Sample for Means		
	UFW Snow Avg	***Class1 Snow Avg***
Mean	**0.18**	**0.19**
Variance	**0.03**	**0.03**
Observations	**63**	**63**
Pearson Correlation	**0.82**	
Hypothesized Mean Difference	**0**	
df	**62**	
t Stat	**-1.28**	
P(T<=t) one-tail	**0.10**	

t Critical one-tail	**1.67**	
P(T<=t) two-tail	**0.20**	
t Critical two-tail	**2.00**	
Significant Difference does not exist in within storm snow coverage performance when implement alternative LOS standard		

4.2.3 Material Usage

According to the MTO's standards, the first salt application rate should be 100 kg/lane-km for UFW sections, whereas it is only 65 kg/lane-km for the first application on Class 1 highways. In the subsequent applications, the same rate of 65 kg/lane-km is adopted for both classes. Furthermore, the maintenance vehicles should be deployed within 20 minutes from the start of precipitation for UFW highways and within 30 minutes for Class 1 highways. Hence, if these standards are strictly followed, the UFW sections should be covered with a larger sized fleet and use more materials than the Class 1 sections. **Figure 4.4** shows a comparison of the amount of materials used during all the events for both seasons. As expected, field data from the trial sites indicate that a greater amount of material was used at the UFW sections as compared to the Class 1 sections. As expected, for most events a higher amount of materials was used at the UFW section as compared to the Class 1 section. To test for statistical significance, a paired t-test was conducted, which supports the empirical observation that a higher amount of material was indeed used for the UFW sections as compared the Class 1 sections (5% level of significance) **(Table 4.5)**. For the 2018/2019 winter season, the average material used for the UFW sections was 407.83 kg/lane-km versus 170.55 kg/lane-km for the Class 1 sections, showing an increase of 139% after implementing the new UFW standard.

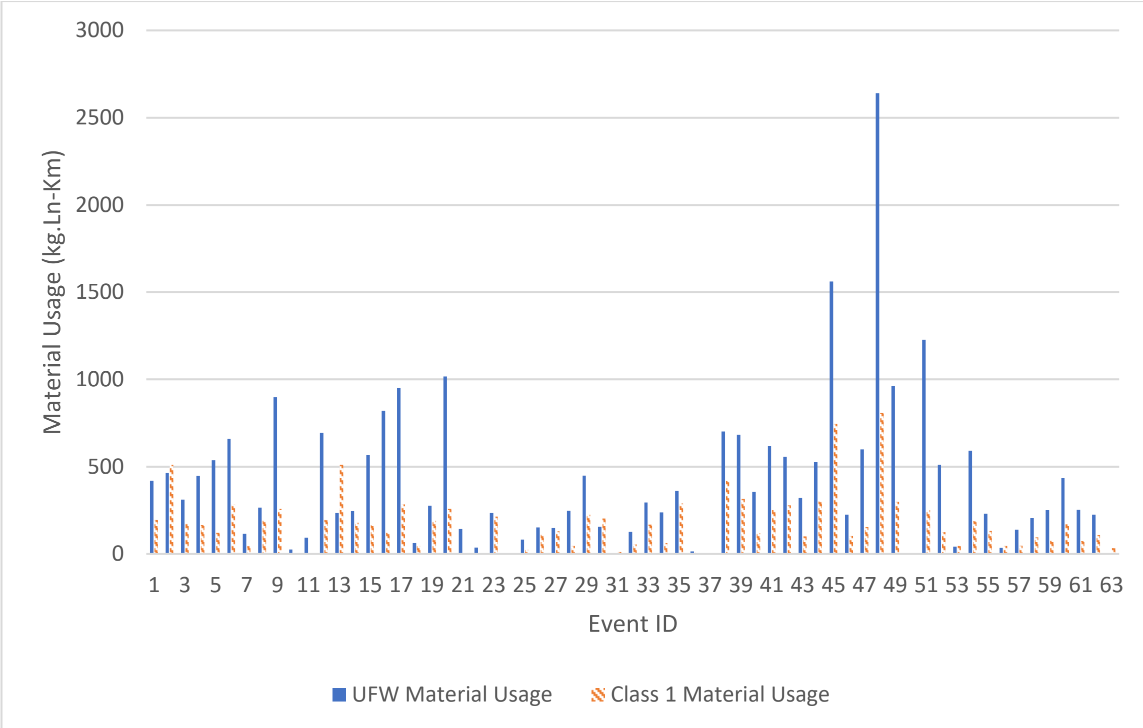


Figure 4.4 Material Usage Comparison by events

Table 4.5: Comparison of overall average Material Usage between UFW and Class 1 LOS standard

t-Test: Paired Two Sample for Means		
	UFW Material Usage	***Class 1 Material Usage***
Mean	**407.83**	**170.55**
Variance	**187982**	**26491**
Observations	**63**	**63**
Pearson Correlation	**1**	
Hypothesized Mean Difference	**0**	

df	**62**	
t Stat	**6**	
P(T<=t) one-tail	**7E-08**	
t Critical one-tail	**2**	
P(T<=t) two-tail	**1E-07**	
t Critical two-tail	**2**	
Significant Difference exist in Material Usage performance when implement alternative LOS standard		

4.3 Analysis of Factors Contributing to the WRM Performance Differences

The comparative analysis of field data summarized in Section 4.1 shows the highway sections treated as UFW had better average performance than those of Class 1, as measured by BPRT. However, the comparative analysis does not explain which factors contributed to individual differences. A linear regression analysis was first conducted to identify the possible contributing factors related to weather conditions. To evaluate the relative performance of UFW versus Class 1, models were developed for the difference between BPRT (ΔBPRT) as a function of a number of variables.

4.3.1 Linear Regression Analysis

Multiple linear regression was employed for modelling the relationship between performance indicator (BPRT difference) and various potential influencing factors, which can be written as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_n + \varepsilon$$

Where y represents the ΔBPRT between two WRM standard in this research; $x_1, x_2, \dots, x_n$ represent the various weather variables considered in this study; $\beta_0, \beta_1, \beta_2, \dots \beta_n$ are the coefficients to be estimated; and ε is a random error term.

The SPSS software package was used to calibrate the model in this research. Because of the small number of observed events from each site (63 in total), the data from all sites were pooled together to develop a single model. Five weather factors were considered in the selection of potential independent variables: Snow Precipitation (cm), Event Duration (hours), Temperature (°C), Wind Speed (km/h), Visibility(km). A Pearson correlation coefficient was used to investigate the correlation between these weather factors and ΔBPRT. A pearson correlation coefficient is a measure of the linear correlation between two variables; its value can range from -1 to +1, where a value of 1 represents total positive linear correlation, 0 is no linear correlation, and a value of −1 indicates a total negative linear correlation between two investigated variables. **Table 4.6** shows the Pearson correlation coefficient results.

Table 4.6 Pearson Correlation Matrix

	ΔBPRT	Snow Precip	Event Duration	Temperature	Wind Speed	Visibility
ΔBPRT	1					
Snow Precip	0.18	1				
Event Duration	0.29	0.58	1			
Temperature	-0.19	-0.51	-0.39	1		
Wind Speed	-0.05	-0.18	-0.12	0.35	1	
Visibility	-0.12	-0.50	-0.24	0.38	0.39	1

The absolute values of all the correlation coefficients between ΔBPRT and other weather factors are less than 0.35, which indicates the correlations are weak. A simple linear regression model was estimated to investigate the relationship between ΔBPRT and each of the five weather factors. Forward selection was implemented, where variables were added to the model specification in the order of absolute values of correlation coefficients. **Table 4.7** shows the simple linear regression results in term of the BPRT difference between UFW and Class1 WRM standard. “Multiple R” value indicates that Event Duration, Snow Precipitation and Temperature have a relatively strong linear relationship with the BPRT difference. However, the *p* values indicate that apart from Event Duration, all the other simple linear regression models are not significant.

Table 4.7 Simple linear regression results of the difference of BPRT

	Event Duration	**Snow Precipitation**	**Temperature**	**Wind Speed**	**Visibility**
Multiple R	0.295	0.184	0.188	0.047	0.119
R Square	0.087	0.034	0.035	0.002	0.014
T statistic	2.410	1.458	-1.493	-0.365	-0.936
P Value	0.019	0.150	0.141	0.717	0.353
Coefficients	0.043	0.040	-0.072	-0.006	-0.030
Intercept	0.423	0.760	0.633	1.061	1.297

4.3.2 Cross-Categorical Analysis

The exploratory simple linear regression analyses described in the previous section indicated some non-linear and interaction effects of certain weather variables on the BPRT difference. As a result, a cross-classification model was developed to determine the difference in BPRT (ΔBPRT) at the UFW and Class 1 sections, as a function of some weather variables. Two independent variables that were found to have the strongest correlation with ΔBPRT: Event Duration and Temperature were selected to create the cross-classification table.

The first step in cross-classification analysis is to define categories (bins) for each independent variable. Therefore, the histograms of the two independent variables were plotted as shown in **Figure 4.5** and **Figure 4.6**. **Figure 4.5** shows that the event durations of last season's event are left-skewed; most of the sample values are less than 15 hours and clustered on the left side of the histogram. On the contrary, **Figure 4.6** indicates that more than half of the last season's temperature data are larger than 5°C and clustered on the right side of the histogram. For both event duration and temperature, three categories were defined with a relatively equal number of observations in each category. The resulting cross-classification table is shown in the **Table 4.8**. It can be seen from **Table 4.8** that as event duration increases, ΔBPRT increases. In other words, the adoption of the UFW standard over the Class 1 standard has a greater improvement on BPRT for longer events. For shorter events, the improvement in BPRT is lesser.

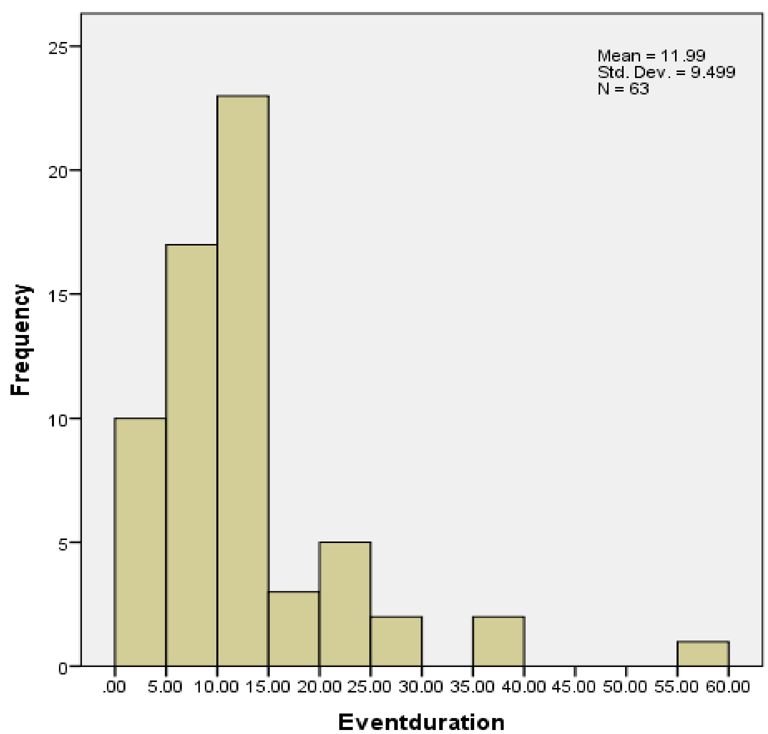


Figure 4.5 Histogram of Event Duration

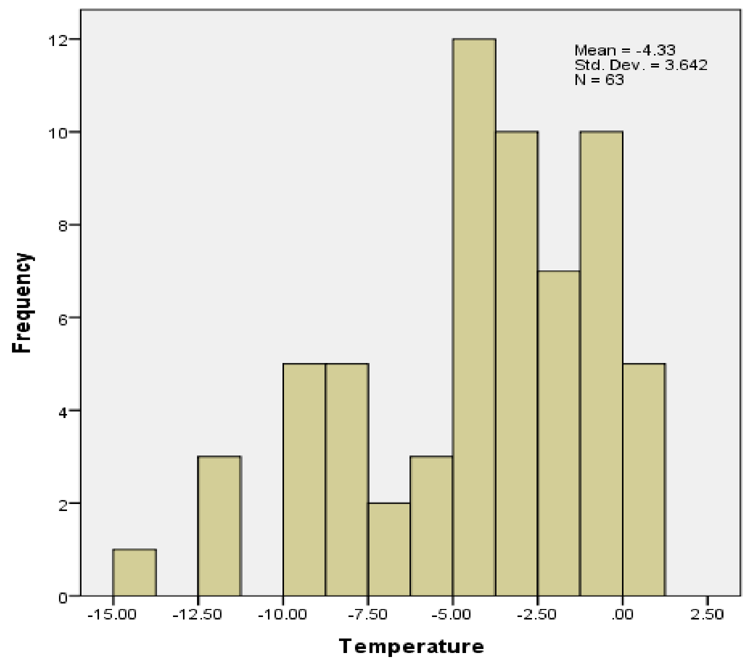


Figure 4.6 Histogram of Temperature

Table 4.8 Cross-Classification

		Temperature class			No. of Observations
Event Duration Class		<-5 °C	-5°C to -2.5°C	>-2.5°C	
0-7 hours	Avg ΔBPRT	0.00	0.81	0.20	21
	Std. Deviation	0.00	0.80	0.31	
	N	2	9	10	
7-12 hours	Avg ΔBPRT	0.06	1.18	0.81	20
	Std. Deviation	0.11	2.25	1.19	
	N	4	7	9	
>12 hours	Avg ΔBPRT	1.75	1.42	1.08	22
	Std. Deviation	1.14	1.89	1.53	
	N	13	6	3	
No. of Observations		19	22	22	63

The relationship between temperature and ΔBPRT is less straightforward (**Figure 4.7**). For long events (> 12 hours), as temperature decreases, ΔBPRT increases. In other words, the adoption of the UFW standard over the Class 1 standard has a greater improvement on BPRT for colder events. For long events with warmer temperatures, the improvement in BPRT is lesser. However, for shorter events (< 12 hours), there seems to be little to no improvement in BPRT if the temperature is cold (< -5°C). Note that for events with a duration of less than 12 hours, the greatest improvement in BPRT occurs when the temperature is between -5°C and -2.5°C, with lesser improvement as the temperature rises (>-2.5°C). This non-linear effect for shorter events could be due to the decreased effectiveness of salt at cold temperatures (< -5°C), where only in longer events (> 12 hours) do the WRM providers take on additional activities for UFWs to ensure BPRT is minimized; for shorter events, contractors may forgo salting due to its ineffectiveness at cold temperatures. This hypothesis requires further data for validation. In any case, this non-linear relationship is also the rationale behind developing a cross-classification model (as opposed to a linear regression model).

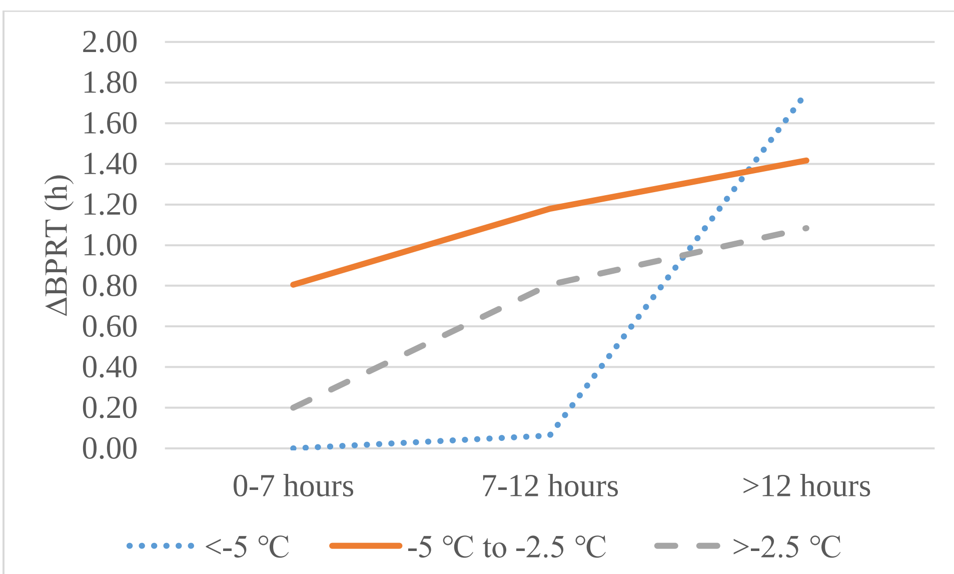


Figure 4.7 ΔBPRT in Cross-Classification

4.3.3 Goodness of fit test

In order to test how likely it is that the observed distribution in the categorical model described in the last section is due to chance, the Chi-square test was performed. In other words, it tests the null hypothesis that the variables are independent. The test compares the observed data to a model that distributes the data according to the expectation that the variables are independent. Wherever the observed data doesn't fit the model, the likelihood that the variables are dependent becomes stronger, thus proving the null hypothesis incorrect.

The chi-square statistic for each cell is calculated by following below **Equation 4-1**:

$$x^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \qquad \textbf{(4-1)}$$

Where n represents the number of cells in the table, O_i represents the observed frequency of type *i* (for *i* = 1,2,…,n) , and E_i stands for the expected frequency of type *i* (for *i* = 1,2,…,n). The first step in computing the Chi-square statistic in the contingency table is the computation of the expected cell frequency for each cell. The estimation for this is the total for its row multiplied by the total for its column, then divided by the total for the table: (Row Total*Column Total)/Grid Total. The next step is to subtract the expected cell frequency from the observed cell frequency for each cell. This value gives the amount of deviation or error for each cell. Following this, the difference computed in the last step is squared, represented as $(O_i - E_i)^2$, and each of the squared differences is then divided by the expected cell frequency for each cell, represented as $\frac{(O_i - E_i)^2}{E_i}$. The Chi-square statistic is computed by summing the x^2 value of each cell. Moreover, the degrees of freedom can tell how many numbers in the gird are independent, which is equal to the number of rows minus one times the number of columns minus one. In this case, the degrees of independence are therefore (3-1) * (3-1), or 4. **Table 4.9** provides the Chi-square results in the form of contingency table, where values in the parentheses represent the expected values for each cell, and values in the square brackets represent the Chi-square statistic for each cell. The Chi-square statistic for this contingency table is 14.9, which is equal to the summation of each cell’s Chi-square statistic, and P -value is 0.005. The result is significant at 5% significant level, which indicates that the rows and columns of the contingency table are independent. The interpretation of the cell frequencies is therefore warranted, differences in cell frequencies could not be explained by chance. In this case it means that ΔBPRT is not distributed similarly across the different levels of weather conditions (event duration and temperature).

Table 4.9 Chi square contingency table

	<-5 ℃	-5℃ to -2.5℃	>-2.5℃	Row Totals
0-7 hours	2 (6.33) [2.96]	9 (7.33) [0.38]	10 (7.33) [0.97]	21
7-12 hours	4 (6.03) [0.68]	7 (6.98) [0.00]	9 (6.98) [0.58]	20
>12 hours	13 (6.63) [6.11]	6 (7.68) [0.37]	3 (7.68) [2.85]	22
Column Totals	19	22	22	

4.4 Analysis of Safety and Mobility Benefits

4.4.1 2018/2019 Season

In order to evaluate the potential benefits from improvements in BPRT due to the introduction of UFW class, an analysis was first performed on the 2018/2019 winter season’s event history for the four UFW sections. The categorical model described in the previous section was used to estimate the ΔBPRT for each event. The ΔBPRT is representative of the additional time to bare pavement conditions had the UFW standard not been adopted (i.e., the highway sections remained Class 1 for 2018/2019).

A road section with better driving conditions is expected to have fewer car accidents. Therefore, the safety benefit of implementing the UFW standard is defined as the difference in the expected total number of collisions between the conditions with the UFW standard and with the Class 1 standard over the event period. An hourly based Generalized Negative

Binomial (GNB) described in Chapter 2 was previously developed for estimating the number of collisions over each hour within an event to estimate the average expected total number of collisions of each event for each highway section (Usman et al, 2010). The model is shown **in Equation 4-2**:

$$\mu = Exp^{0.235} * e^{-1.249-0.011T+0.005WS-0.039V+0.097\,TP-2.594RSI+M+S+FH} \quad \textbf{(4-2)}$$

where μ is the expected number of collisions of a highway, Exp is exposure (equal to total traffic in given time multiplied by length of the road section), T is temperature (℃), WS is wind speed (Km/h), V is visibility (Km), TP is total precipitation (cm), RSI is road surface index (unitless), M is indicator for month (unitless), S is indicator for site (unitless), and FH is dummy variable for the effects of being the first hour (-0.302 if first hour; 0 otherwise).

Similarly, the mobility benefit of the application of UFW standard is defined as the difference in the travel time between two alternative WRM standards. A small reduction in travel speed can sharply increase travel times, as drivers proceed more cautiously for worse road conditions. A speed estimation model described in Chapter 2 was previously developed considering various influencing factors, as shown in **Equation 4-3** (Usama, 2009):

$$V = 69.082 + 0.089 * T - 0.078 * WS + 0.310\,VIS - 1.258 * HP + 16.974 * RSI - 4.325 * \frac{V}{C} + PSL + S \quad \textbf{(4-3)}$$

where V is the estimated travel speed, T is temperature (℃), W is wind speed (Km/h), VIS is visibility (Km), HP is hourly precipitation (cm), RSI is road surface index (unitless), M is indicator for month (unitless), S is indicator for site (unitless),V/C is average volume to capacity ratio, and PSL is a coefficient of posted speed limit (PSL = 0 if posted speed limit = 80 km/h; 1.951 if 90 km/h; 12.621 if 100 km/h).

Considering a specific highway section under a specific event, the total travel time saving over the ΔBPRT time can be estimated using **Equation 4-4** (Ye et al, 2012).

$$TTS = Q_h\,(L/S_{i1} - L/S_{i2}) \quad \textbf{(4-4)}$$

where TTS is total travel time saving during storm events (hour), Q_h is total traffic volume over the ΔBPRT time, L is segment length (km), Si1 is average traffic speed of the road section in the ΔBPRT under Class 1 WRM standard, km/h, and Si2 is average traffic speed of the road section in the ΔBPRT under UFW WRM standard, km/h

The four pilot UFW sites described previously are considered. Two scenarios are assumed: one representing the case that UFW is implemented, while the other assumes they are Class 1 highways. Under both scenarios, the same events observed over the season are considered.

Furthermore, the following assumptions were made for the safety and mobility analysis:

- The base scenario is considered with the UFW standard at the trial sites, while the alternative scenario is considered by applying the previously used Class 1 standard. Within the ΔBPRT period, the road sections maintained with the UFW standard have already achieved bare conditions, whereas if they were maintained as Class 1 highways, they would still be in the partly snow-covered condition. Therefore, the corresponding RSI of base scenarios during BPRT period is assumed to be 0.85 (bare and wet condition), whereas the Class 1 section's corresponding RSI is assumed to be 0.6 (partly snow-covered condition).
- A standard capacity of 2,200 vehicles per lane per hour is assumed for all highways.
- The posted speed limit is assumed to be 100 km/h for all highways.
- The expected number of collisions and travel time savings can be converted into equivalent monetary costs. The unit collision cost is $77,035 and the value of travel time per hour is $20 (Transport Canada, 2007; Fu et al, 2012).

All of 63 events observed in 2018/19 season were grouped into different categories by using the previously defined bins in the categorical model (Table 4.6). The categorical model was then used to find the corresponding ΔBPRTs for each event. Safety and mobility estimation models described in this section were then applied to estimate the benefits for each event based on the estimated ΔBPRT. The estimated monetary value of safety and mobility benefits are shown in **Figure 4.8** and **Figure 4.9**, respectively.

In term of the safety benefits, the medians in **Figure 4.8** indicate that the Hwy 417 site has the highest safety benefits, obtained \$4533 per lane-km estimated benefits over the season, followed by the Hwy 404, Hwy 400 and Hwy 401 sites. Moreover, a 95 percent confidence interval was established by standard deviation of ΔBPRTs of bins in the categorical model. However, given the much larger difference of 95 percent interval for the Hwy 417 site, ranging from \$2001 to \$4615 per lane-km, it can be deduced that safety benefits gained by implementing UFW standard vary the most at the Hwy 417 site. In contrast, the other three trial sites have a relatively similar pattern of benefits, with a range from \$271 to \$1266 per lane-km.

Figure 4.9 reveals that the estimated mobility benefits for all four trial sites have the same trend as **Figure 4.8**, with a much smaller range from \$13 to \$1156 per lane-km. The Hwy 417 site obtains the highest benefit because it experiences a much larger number of snow events than the other sites. Similarly, the benefits at the remaining three sites following their relative traffic exposures, as shown in **Table 4.8**. Note that an increase in traffic exposure leads to an increase in the total number of accidents that would be expected to occur on the route over the ΔBPRT period.

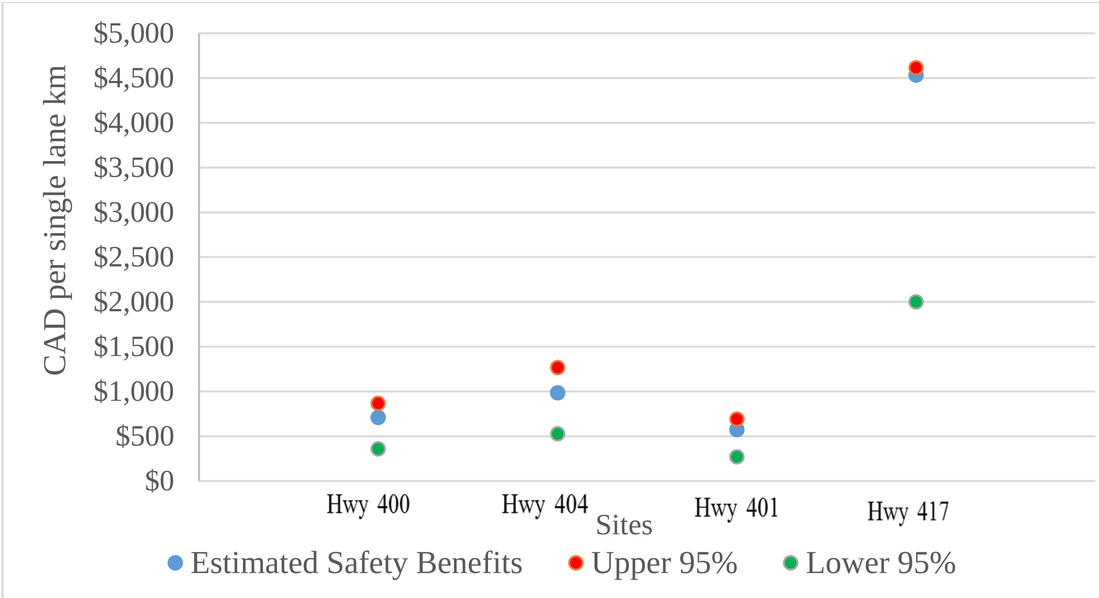


Figure 4.8 Safety Benefits

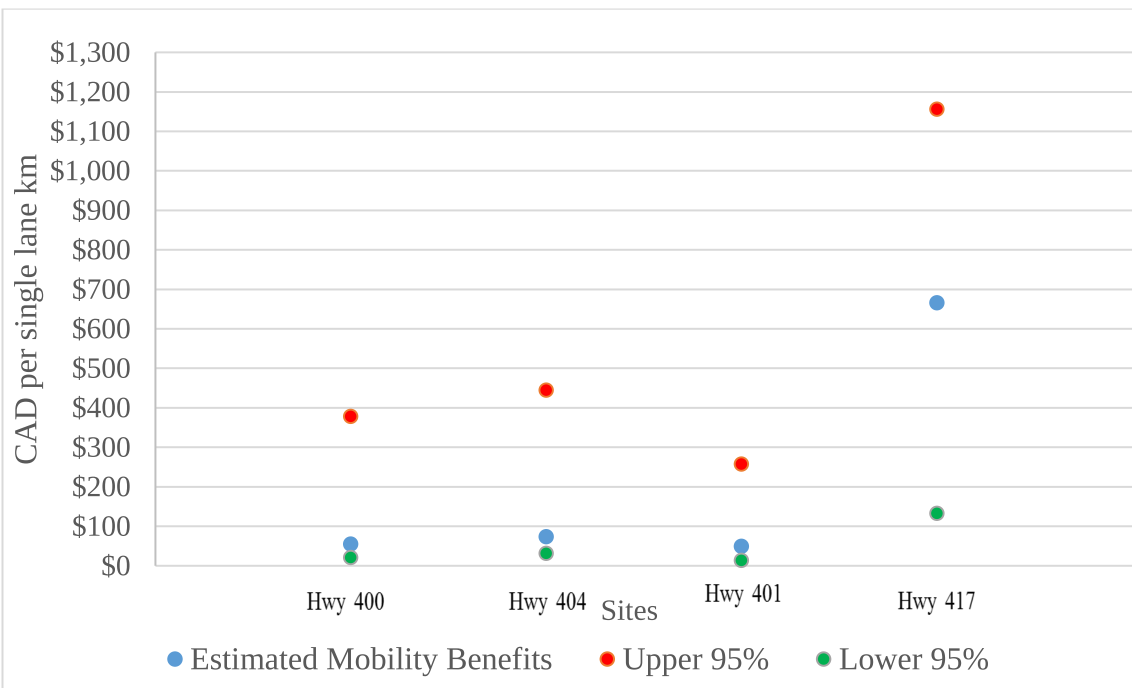


Figure 4.9 Mobility Benefits

Table 4.10 Traffic exposure

	Avg Hourly Traffic Volume	Section Length (km)	No. of Lanes	Traffic exposure (Millions vehicle kilometer/lane)
Hwy400	6330	35.4	6	37347
Hwy401	6901	28.0	14	13802
Hwy404	6994	36.6	6	42663

4.4.2 Past seasons

In order to investigate the sensitivity of benefits to seasonal weather variations, the same benefit analysis was conducted for the winter seasons (2000-2010), over which the data required for the analysis are available. The time-series dataset contains the same data previously described for the 2018-2019 winter season and has a total of 2,983 weather event observations. As **Figure 4.10** shows, the total benefits per event follows the same site ranking as the 2018/19 winter season: Hwy 417 experiences the most benefits, followed by Hwy 404, Hwy 400, and Hwy 401. Moreover, the positive linear trend reveals that the total benefits per event increase at all four trial sites as the WADT rises. **Figure 4.10** can be used to help decision makers determine the appropriate WADT thresholds of the Urban Freeway Class, if the additional maintenance cost per event (over the Class 1 standard) is known. For example, if the WRM cost per event of implementing UFW standard is $40 per lane-km, then it might not be worthwhile to set the minimum WADT requirement for the UFW standard at 100,000 for Hwy 401, since the benefit per event was always less than $40 per lane-km during the past ten years. Unfortunately, cost data were not available for this study, so definitive recommendations on the adoption of the UFW class on the studied highways in Ontario can not be made publicly.

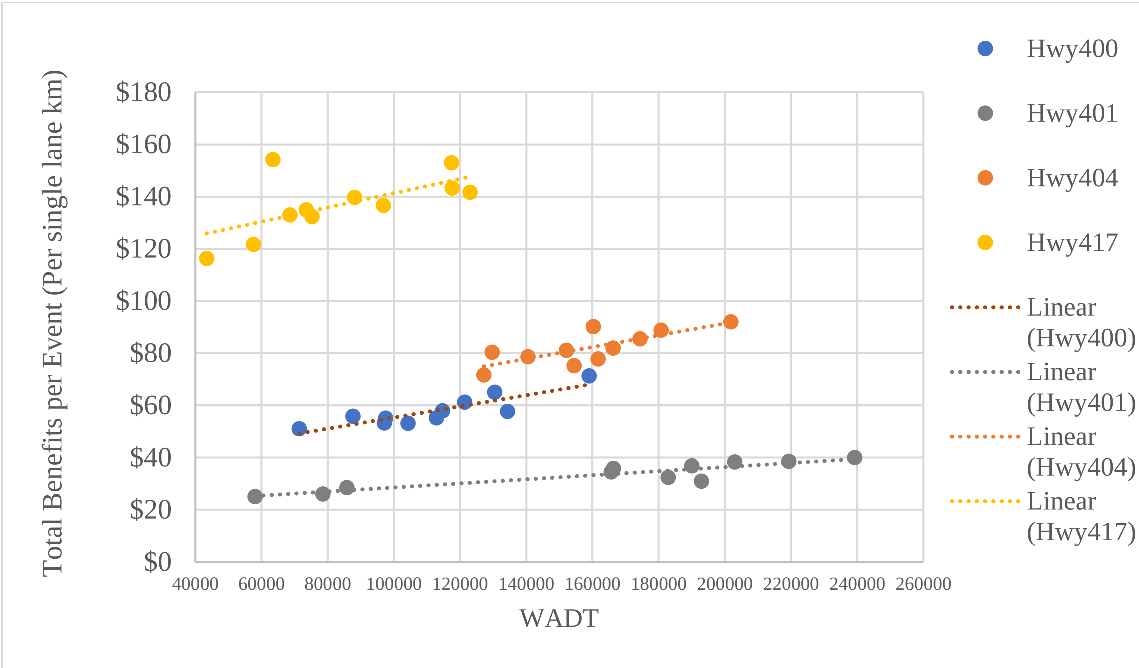


Figure 4.10 Total benefit per event VS WAD

Chapter 5
Conclusion and Future Work

In the field of winter road maintenance (WRM), a number of past efforts were dedicated to improving the understanding of the safety and mobility implications of winter weather and road maintenance activities. However, few studies have considered the impact of implementing different WRM level of service (LOS) standards. This study has attempted to evaluate the safety and mobility benefits of alternative LOS standards, particularly focusing on quantifying the mobility and safety improvements of implementing the new LOS standard (UFW class).

In order to assess the performance and benefits of the newly introduced UFW class, a field study was conducted to compare the WRM performance of two alternative LOS standards – Class 1 versus UFW. Three performance measurements were considered: bare pavement regain time (BPRT), within storm snow coverage, and material usage. Second, a statistical model was developed to quantify the relationship between the performance difference (ΔBPRT) between two alternative standards and various possible contributing factors, which is the core factor that contributes to the potential road safety and mobility benefits. Third, the safety and mobility estimation models developed in previous studies were applied to evaluate the safety and mobility benefits of upgrading Class 1 highways to the UFW class. This chapter highlights the main findings of this research. Future research is also recommended based on the limitations of this research.

5.1 Findings

The primary objective of the comparative analysis was to determine whether or not the newly introduced UFW class results in better WRM performance. Image and AVL data for the 2019 winter season were used to assess four trial sites. Test results indicate that the UFW standard has led to better WRM performance and the following findings were statistically validated:

- The level of service in terms of BPRT for the UFW highway section was significantly improved as compared to Class 1 highway section. The average BPRT was 1.20 and 2.01 for the UFW and Class 1 sections, respectively, for the 2019 winter season, representing a 40% improvement.

- There was no statistically significant difference found between the two classes of highway sections in terms of within-storm level of service as measured by the average snow coverage.
- The unit salt usage on the UFW highway section was 407.83 Kg/Ln-km as compared to 170.55 Kg/Ln-km for the Class 1 section for the study covered winter season, which indicates that 139% more material was applied on the UFW sections.

Furthermore, this study has estimated the expected safety and mobility benefits that could be obtained by upgrading the Class 1 highway standard to the UFW standard based on the expected differences in BPRT. The estimated benefit results led to the following main findings:

- Highways in the northern areas with more severe weather conditions are expected to have more gains in safety and mobility benefits than those in areas that experience fewer and less severe snow events;
- For highway sections that have similar weather conditions, traffic exposure is the largest determinant of the safety and mobility benefits from the new standard;
- Had the UFW standard been applied in the past ten winter seasons (2000-2010), it would have brought both safety and mobility benefits, in accordance with the first two findings.

5.2 Future Work

Moving forward, further research is needed to support decisions related to the new WRM standards. First, in the pilot study, the road sections under different WRM LOS standards of each test site are actually maintained by different area maintenance contractors (AMCs). While each maintenance contractor is expected to maintain each highway according its required LOS standards, differences in maintenance practices between AMCs such as equipment composition, operations management, and crew experience, likely exist. These differences could skew the performance differences resulting from the different LOS. Selecting two trial road sections with different LOS standards but maintained by the same

WRM agency will help to give more accurate comparative results of WRM performance. Second, only one season of WRM performance has been observed for the UFW standard. Collecting additional data at the trial sites in future winter seasons will allow for more robust estimation of UFW benefits (e.g., more observations for the cross-classification model). Third, a comprehensive cost-benefit analysis should be carried out to help decision makers determine the appropriate criteria (i.e., WADT threshold) for the UFW class. Fourth, a similar study could also be conducted on the remaining classes (1 through 5) to develop the most cost-effective winter road maintenance service standards supported by an evidence-based cost-benefit analysis.

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Appendix A

Image samples:

Image of 5% Snow Coverage:

Image of 10% Snow Coverage:

Image of 15% Snow Coverage:

Image of 20% Snow Coverage:

Image of 25% Snow Coverage:

Image of 30% Snow Coverage:

Image of 35% Snow Coverage:

Image of 40% Snow Coverage:

Image of 45% Snow Coverage:

Image of 50% Snow Coverage:

Image of 55% Snow Coverage:

Image of 60% Snow Coverage:

Image of 65% Snow Coverage:

Image of 70% Snow Coverage:

Image of 75% Snow Coverage:

Image of 80% Snow Coverage:

Image of 85% Snow Coverage:

Image of 90% Snow Coverage:

Image of 95% Snow Coverage:

Image of 100% Snow Coverage:

Appendix B

Sample Environment Canada (EC) data:

Station Name	OTTAWA INTL A												
Province	ONTARIO												
Current Station Operator	NAV Canada												
Latitude	45.32												
Longitude	-75.67												
Elevation	114.9												
Climate Identifier	6106001												
WMO Identifier	71628												
TC Identifier	YOW												
Legend													
E	Estimated												
M	Missing												
NA	Not Available												
Date/Time	Year	Month	Day	Time	Temp (°C)	Dew Point Temp (°C)	Rel Hum (%)	Wind Dir (10s deg)	Wind Spd (km/h)	Visibility (km)	Stn Press (kPa)	Wind Chill	Weather
2019-01-01 0:00	2019	1	1	0:00	-1.5	-2	96	7	22	2.4	98.63	-7	Freezing Rain,Fog
2019-01-01 1:00	2019	1	1	1:00	-0.8	-1.3	97	3	29	2.4	98.42	-7	Freezing Rain,Fog
2019-01-01 2:00	2019	1	1	2:00	-0.1	-0.6	97	5	26	6.4	98.17	-6	Freezing Rain,Fog
2019-01-01 3:00	2019	1	1	3:00	0.2	-0.3	97	3	27	6.4	98.11		Rain,Fog
2019-01-01 4:00	2019	1	1	4:00	0	-0.5	97	36	25	3.2	98.03	-6	Freezing Rain,Fog
2019-01-01 5:00	2019	1	1	5:00	-0.4	-1	96	32	32	3.2	98.19	-7	Snow
2019-01-01 6:00	2019	1	1	6:00	-0.5	-1.6	92	30	29	16.1	98.44	-7	Snow
2019-01-01 7:00	2019	1	1	7:00	-0.5	-2.2	88	30	26	24.1	98.84	-7	Mostly Cloudy
2019-01-01 8:00	2019	1	1	8:00	-0.2	-2.3	86	31	36	24.1	99.23	-7	NA
2019-01-01 9:00	2019	1	1	9:00	-0.8	-3.4	83	31	32	24.1	99.5	-8	NA
2019-01-01 10:00	2019	1	1	10:00	-1.8	-4.2	84	30	35	24.1	99.74	-9	Cloudy
2019-01-01 11:00	2019	1	1	11:00	-3.3	-6	82	31	34	24.1	100	-11	NA
2019-01-01 12:00	2019	1	1	12:00	-4.4	-8.1	76	30	32	24.1	100.17	-12	NA
2019-01-01 13:00	2019	1	1	13:00	-5.4	-9.3	74	31	30	24.1	100.19	-14	Mainly Clear
2019-01-01 14:00	2019	1	1	14:00	-5.9	-10.6	70	33	26	24.1	100.31	-14	NA
2019-01-01 15:00	2019	1	1	15:00	-6.4	-11.5	67	31	26	24.1	100.53	-14	NA
2019-01-01 16:00	2019	1	1	16:00	-7.5	-13.2	64	31	23	24.1	100.75	-15	Mainly Clear
2019-01-01 17:00	2019	1	1	17:00	-9.3	-13.8	70	28	18	24.1	100.89	-17	NA
2019-01-01 18:00	2019	1	1	18:00	-10.6	-14.3	74	28	17	24.1	100.93	-18	NA
2019-01-01 19:00	2019	1	1	19:00	-11.1	-15.3	71	31	21	24.1	101.06	-19	Mainly Clear
2019-01-01 20:00	2019	1	1	20:00	-12.2	-16.4	71	30	18	24.1	101.11	-20	NA
2019-01-01 21:00	2019	1	1	21:00	-13	-17.6	69	33	16	24.1	101.13	-21	NA

2019-01-01 22:00	2019	1	1	22:00	-14.2	-18.4	70	33	16	24.1	101.13	-22	Mainly Clear
2019-01-01 23:00	2019	1	1	23:00	-15.2	-19.8	68	33	20	24.1	101.22	-24	NA

Sample RWIS data:

Valid Date EDT	Issue Date EDT	Air Temp (°C)	Dew Point (°C)	Relative Humidity (%)	Visibility (km)	Pressure (kPa)	Liquid Precipitation Rate (1 hour) (mm)	Solid Precipitation Rate (1 hour) (cm)	Liquid Precipitation Rate (3 hour) (mm)	Solid Precipitation Rate (3 hour) (cm)	Total Cloud Cover (%)	Precipitation Probability (%)	Wind Speed (km/h)	Wind Direction	Wind Gusts (km/h)	Surface Temperature (°C)	Road Conditions
2019-01-01 23:00	2019-01-01 20:00	-10.5	-16.6	61	15	102.6	0	0	0	0	50	10	29	NNW	50	-9	N.A.
2019-01-01 22:00	2019-01-01 20:00	-10.3	-16.2	62	15	102.6	0	0	0	0	40	0	32	NNW	58	-8.4	N.A.
2019-01-01 21:00	2019-01-01 20:00	-9.8	-15.4	63	15	102.6	0	0	0	0	40	0	36	NNW	61	-7.5	N.A.
2019-01-01 20:00	2019-01-01 20:00	-8.9	-14.5	64	15	102.6	0	0	0	0	40	0	40	NNW	68	-5.1	N.A.
2019-01-01 19:00	2019-01-01 20:00	-8	-13.5	64	15	102.6	0	0	0	0	40	0	47	NNW	79	-5	N.A.
2019-01-01 18:00	2019-01-01 14:00	-7.4	-12.6	66	15	102.5	0	0	0	0	40	0	58	NNW	97	-6	N.A.
2019-01-01 17:00	2019-01-01 14:00	-6.7	-11.8	67	15	102.4	0	0	0	0	40	0	72	NNW	122	-4.7	N.A.
2019-01-01 16:00	2019-01-01 14:00	-6	-11.1	67	15	102.3	0	0	0	0	50	10	83	NNW	140	-2.3	N.A.
2019-01-01 15:00	2019-01-01 14:00	-5.4	-10.5	67	15	102.2	0	0	0	0	50	10	86	NNW	144	1.2	N.A.
2019-01-01 14:00	2019-01-01 14:00	-4.9	-10	67	15	102.2	0	0	0	0	50	10	86	NNW	144	1	N.A.
2019-01-01 13:00	2019-01-01 14:00	-4.4	-9.6	67	15	102.1	0	0	0	0	60	20	83	NW	140	1.1	N.A.
2019-01-01 12:00	2019-01-01 8:00	-4.2	-8.3	82	15	102.1	0	0	0	0	100	20	97	NW	162	0.1	N.A.
2019-01-01 11:00	2019-01-01 8:00	-3.8	-8	81	15	102	0	0	0	0	100	20	104	NW	173	-0.1	N.A.
2019-01-01 10:00	2019-01-01 8:00	-3.3	-7.5	82	15	101.9	0	0	0	0	100	20	112	NW	184	-0.4	N.A.
2019-01-01 9:00	2019-01-01 8:00	-2.5	-6.6	82	15	101.7	0	0	0	0	100	20	115	NW	191	-0.6	N.A.

2019-01-01 8:00	2019-01-01 8:00	-1.6	-5.4	83	15	101.5	0	0	0	0	100	20	119	NW	194	0	N.A.
2019-01-01 7:00	2019-01-01 8:00	-0.6	-4	85	15	101.2	0	0	0	0	100	20	119	NW	194	0.2	N.A.
2019-01-01 6:00	2019-01-01 2:00	0.5	-1.3	88	15	100.6	0	0.1	0	0	100	40	122	NW	184	0.2	Snow Moderate
2019-01-01 5:00	2019-01-01 2:00	2.6	0.9	89	15	100.2	0	0	0	0	100	40	108	WNW	162	1.4	Snow Moderate
2019-01-01 4:00	2019-01-01 2:00	4.3	2.8	90	15	99.8	0	0	0	0	100	40	90	W	137	2.1	Rain Light
2019-01-01 3:00	2019-01-01 2:00	5	3.9	93	15	99.6	0	0	0	0	100	40	65	WSW	97	2.1	Rain Light
2019-01-01 2:00	2019-01-01 2:00	5.2	4.5	95	15	99.5	0.1	0	0	0	100	40	40	SW	61	2.2	Rain Light
2019-01-01 1:00	2019-01-01 2:00	4.9	4.6	98	15	99.5	0.7	0	0.9	0	100	80	29	SSW	43	2.9	Rain Moderate

Appendix C

Sample AVL data:

Start_Date	Distance km	Speed km/h	Spreading Dry	Spreading Liquid	Prewet	N/A	Extra Input	Angle Dry	Angle Liquid	Rate Dry	Rate Liquid	Rate Prewet	Blast	Amount Dry kg	Latitude	Longitude	Heading	Direction
2018-12-31 20:04:08	10905.1	0.0	False	False	False	False	False	0	0	170.0	0.0	0.0	False	1648600.0	45.305722	-75.915757	42	NorthEast
2018-12-31 20:14:58	10905.1	47.0	False	False	False	False	False	0	0	170.0	0.0	0.0	False	1648600.0	45.304195	-75.915866	237	SouthWest
2018-12-31 20:15:41	10905.1	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1648600.0	45.301805	-75.921773	240	SouthWest
2018-12-31 20:17:14	10906.1	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1648800.0	45.296752	-75.932832	225	SouthWest
2018-12-31 20:18:40	10907.1	42.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1648900.0	45.290730	-75.942323	225	SouthWest
2018-12-31 20:20:14	10908.2	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1649100.0	45.284486	-75.952154	228	SouthWest
2018-12-31 20:21:48	10909.2	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1649300.0	45.278282	-75.961939	225	SouthWest
2018-12-31 20:23:17	10910.2	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1649500.0	45.272666	-75.971949	246	SouthWest
2018-12-31 20:24:51	10911.3	36.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1649600.0	45.272803	-75.984659	279	West
2018-12-31 20:26:25	10912.3	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1649800.0	45.277478	-75.995290	318	NorthWest
2018-12-31 20:27:59	10913.3	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650000.0	45.284435	-76.003974	318	NorthWest
2018-12-31 20:29:33	10914.4	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650200.0	45.291424	-76.012742	315	NorthWest
2018-12-31 20:31:10	10915.4	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650300.0	45.297178	-76.023264	303	NorthWest
2018-12-31 20:32:44	10916.4	37.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650500.0	45.303632	-76.032301	318	NorthWest
2018-12-31 20:34:22	10917.5	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650700.0	45.310077	-76.041664	297	NorthWest
2018-12-31 20:36:04	10918.5	29.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650900.0	45.313872	-76.053434	315	NorthWest
2018-12-31 20:36:36	10918.6	0.0	False	False	False	False	False	0	0	170.0	0.0	0.0	False	1650900.0	45.314538	-76.054278	312	NorthWest
2018-12-31 20:37:41	10918.6	34.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1650900.0	45.313066	-76.056826	228	SouthWest
2018-12-31 20:39:40	10919.7	33.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651100.0	45.312038	-76.052499	102	East
2018-12-31 20:41:19	10920.7	37.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651200.0	45.308957	-76.040179	126	SouthEast
2018-12-31 20:42:54	10921.7	37.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651400.0	45.302330	-76.031469	138	SouthEast
2018-12-31 20:44:33	10922.7	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651600.0	45.296077	-76.021843	123	SouthEast

2018-12-31 20:46:12	10923.8	36.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651800.0	45.290202	-76.011968	135	SouthEast
2018-12-31 20:47:54	10924.8	36.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1651900.0	45.283190	-76.003194	138	SouthEast
2018-12-31 20:49:33	10925.8	35.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1652100.0	45.276272	-75.994349	138	SouthEast
2018-12-31 20:51:12	10926.9	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1652300.0	45.272198	-75.983162	99	East
2018-12-31 20:52:47	10927.9	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1652500.0	45.272746	-75.970362	60	NorthEast
2018-12-31 20:54:22	10928.9	39.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1652600.0	45.278624	-75.960736	45	NorthEast
2018-12-31 20:55:52	10929.9	40.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1652800.0	45.284755	-75.951066	48	NorthEast
2018-12-31 20:57:27	10931.0	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653000.0	45.290944	-75.941267	45	NorthEast
2018-12-31 20:59:02	10932.0	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653200.0	45.297037	-75.931680	48	NorthEast
2018-12-31 21:00:37	10933.0	37.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653300.0	45.301907	-75.920595	60	NorthEast
2018-12-31 21:02:11	10934.0	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653500.0	45.306688	-75.909299	48	NorthEast
2018-12-31 21:03:42	10935.1	38.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653700.0	45.312682	-75.899283	48	NorthEast
2018-12-31 21:04:11	10935.4	42.0	False	False	False	False	False	0	0	170.0	0.0	0.0	False	1653700.0	45.314493	-75.896186	48	NorthEast
2018-12-31 21:05:52	10935.4	13.0	False	False	False	False	False	0	0	170.0	0.0	0.0	False	1653700.0	45.318413	-75.885210	81	East
2018-12-31 21:08:05	10935.4	35.0	True	False	False	False	False	0	0	170.0	0.0	0.0	False	1653700.0	45.320502	-75.886221	234	SouthWest

Appendix D

Hourly ratio of traffic volume for sample trial site (Hwy 417 UFW section):

	Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday	
Hour	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**	**Ratio**	**Traffic volume**
0	0.01	2057	0.01	2026	0.01	2074	0.01	2046	0.02	2142	0.02	2664	0.03	2581
1	0.01	1777	0.01	1730	0.01	1740	0.01	1729	0.01	1789	0.02	2132	0.02	2081
2	0.01	1700	0.01	1654	0.01	1660	0.01	1644	0.01	1689	0.02	1919	0.02	1838
3	0.01	1723	0.01	1685	0.01	1683	0.01	1657	0.01	1677	0.01	1743	0.02	1640
4	0.02	2144	0.02	2122	0.02	2121	0.01	2090	0.01	2016	0.01	1731	0.02	1557
5	0.03	4049	0.03	4132	0.03	4118	0.03	4076	0.03	3742	0.02	2078	0.02	1728
6	0.05	7476	0.06	7757	0.06	7743	0.05	7611	0.05	7138	0.02	2945	0.02	2199
7	0.06	8456	0.06	8681	0.06	8720	0.06	8600	0.06	8375	0.03	4037	0.03	2687
8	0.06	8171	0.06	8401	0.06	8407	0.06	8295	0.06	8112	0.05	5595	0.04	3602
9	0.05	7383	0.05	7561	0.05	7586	0.05	7552	0.05	7486	0.05	6680	0.05	4824
10	0.05	6957	0.05	6967	0.05	7030	0.05	7074	0.05	7225	0.06	7194	0.06	5718
11	0.05	7273	0.05	7264	0.05	7334	0.05	7389	0.05	7725	0.06	7826	0.06	6361
12	0.05	7453	0.05	7370	0.05	7424	0.05	7495	0.06	7867	0.07	8241	0.07	7048
13	0.06	7623	0.05	7550	0.05	7580	0.05	7691	0.06	8043	0.07	8219	0.07	7273
14	0.06	8427	0.06	8389	0.06	8439	0.06	8490	0.06	8729	0.07	8212	0.07	7228
15	0.07	9452	0.07	9479	0.07	9472	0.07	9409	0.07	9311	0.07	8173	0.07	7159
16	0.07	9510	0.07	9574	0.07	9506	0.07	9430	0.07	9222	0.06	7976	0.07	6821
17	0.06	8888	0.06	9006	0.06	8960	0.06	8940	0.06	8772	0.06	7418	0.06	5997
18	0.05	7130	0.05	7308	0.05	7413	0.05	7464	0.05	7550	0.05	6494	0.05	5194
19	0.04	5525	0.04	5610	0.04	5770	0.04	5872	0.04	5965	0.04	5180	0.05	4657
20	0.03	4794	0.03	4868	0.04	5028	0.04	5086	0.04	5050	0.04	4636	0.04	4205
21	0.03	4263	0.03	4501	0.03	4529	0.03	4765	0.03	4687	0.04	4749	0.04	3633
22	0.03	3463	0.03	3749	0.03	3597	0.03	4128	0.03	4076	0.04	4457	0.03	3012
23	0.02	2643	0.02	2739	0.02	2710	0.02	2899	0.02	3320	0.03	3502	0.02	2345
Total		138336		140122		140645		141431		141708		123799		101386

Appendix E

Sample WOR:

Winter Operation Record Page 1 of 2

Date:	February 24, 2019	**Activity:**	Winter Maintenance
Checker:	ccaverly	**Contractor:**	Miller Maintenance
		Contract Number:	2013-22
Continued To (Date):		**Location:**	Toronto-York
Continued From (Date):		**Patrol Yard:**	Gormley

Requested By	Request Time	Operator Time:	Start Time	Finish Time	Unit Hours	Route #	Route Description	Truck #	Operator Name	Tow Plow 7706	Spreading 7702	Plowing Only 7701	Combo 7700	Anti-Icing 7703	Distance (km)	Combo Hours 7700	Spreading Hours 7702	Plow Hours 7701	Anti-Icing Hours 7703	Salt (Tonnes)	Sand (Tonnes)	Liquid (Litres)	Application Rate
James Douglas	16:04	Arrival 16:05	16:22	17:29	1:08	GS1		144525-G2	Paul Brethour		X				53.0	1:07				10.47			200.0
		Dismissal 18:00							Paul Brethour														
James Douglas	16:04	Arrival 16:05	16:22	17:37	1:16	GS4		154519-G7	Ramdath Marshall		X				63.2	1:15				5.18			200.0
		Dismissal 18:00							Ramdath Marshall														
James Douglas	16:04	Arrival 16:05	16:22	17:39	1:17	GS5		154523-G12	Matt Leyenson		X				68.2	1:16				3.62			200.0
		Dismissal 18:00							Matt Leyenson														
Fred MacNeill	21:07	Arrival 21:00	21:17	21:50	0:33		Salt mainline Major Mackenzie to Steeles and return	134508-G10	Jesse Hillis		X				27.0	0:33				5.8			300.0
Fred MacNeill	21:07	Arrival 21:00	21:17	21:45	0:28		Salt mainline Major Mackenzie to Steeles and return	144526-G3	Brandon Binns		X				18.1	0:28				4.63			300.0
Fred MacNeill	21:07	Arrival 21:00	21:17	22:20	1:02		Salt circle ramps Major Mackenzie to Steeles and return	104563-G5	Richard Leandro				X		34.2	1:02				3.56			200.0
Fred MacNeill	21:07	Arrival 21:00	21:17	22:15	0:57		Salt long legs Major Mackenzie to Steeles and return	154532-G6	Slobodan Jakovljevic				X		35.0	0:57				3.48			200.0
Fred MacNeill	21:35	Arrival 21:30	21:47	22:49	1:02		Salt long legs Major Mackenzie to Aurora Rd and return	154519-G7	Ramdath Marshall				X		43.3	1:01				3.47			200.0
Fred MacNeill	21:35	Arrival 21:30	21:47	22:49	1:01		Salt circle ramps Major Mackenzie to Aurora Rd and return	154523-G12	Matt Leyenson				X		48.3	1:01				2.84			200.0
Fred MacNeill	21:35	Arrival 21:30	21:47	22:58	1:11	GS1		144525-G2	Paul Brethour		X				53.0	1:10				10.6			200.0
Fred MacNeill	22:10		22:27	23:09	0:42	GS2		134508-G10	Jesse Hillis		X				35.4	0:42				8.6			300.0

Comments:

Reviewed By ________

Approved By Supervisor ________

Sample BP report:

Region: Torono/York Area/Contract: 2013-22 Patrol: 41 Report Period From: Feb 25 2019 To: Mar 10 2019

BARE PAVEMENT DATA COLLECTION SHEET

HWY #	Event Beginning (1)		Bare Pavement Lost (2)		Event Ending (3)		Bare Pavement Regained (4)		Event Type (5)	BP Regained Time N/A	Continuous Entry	Comments	MMIS Event Number (6)	Name (7) Please print
	Date YYYY-MM-DD	Time HH:MM	Date YYYY-MM-DD	Time HH:MM	Date YYYY-MM-DD	Time HH:MM	Date YYYY-MM-DD	Time HH:MM						
404	2019-02-25	22:53	2019-02-25	22:53	2019-02-26	1:00	2019-02-26	1:35	S					Fred MacNeil
404	2019-02-27	8:15	2019-02-27	8:15	2019-02-28	1:56	2019-02-28	3:27	S					Rick Tilling
404	2019-03-02	11:10	2019-03-02	11:10	2019-03-02	19:40	2019-03-02	21:24	S					Rick Tilling
404	2019-03-03	17:55	2019-03-03	17:55	2019-03-03	20:28	2019-03-03	20:46	S					Mike Gommer
404	2019-03-06	0:03	2019-03-06	0:03	2019-03-06	3:25	2019-03-06	6:55	S					James Douglas
404	2019-03-07	3:40	2019-03-07	3:40	2019-03-07	3:50	2019-03-07	4:40	S					James Douglas
404	2019-03-10	0:13	2019-03-10	0:13	2019-03=10	1:22	2019-03-10	6:15	S					Mike Gommer
404	2019-03-10	20:50	2019-03-10	20:50	2019-03-10	22:54	2019-03-10	23:37	B					Mike Gommer

1) Event Beginning – Means the time when snow or freezing rain starts falling on any portion of a route, where accumulation begins, or when drifting snow begins to accumulate on the driving surface of the road, or when frost creates a slippery condition.
2) Bare Pavement Lost – Means as soon as a winter event occurs.
3) End of Event – Means the time when snow or freezing rain stops falling and accumulating on any portion of a route, when drifting ceases to cause accumulation on the road surface of the road or when frost is no longer creating a slippery condition.
4) Bare Pavement Regained – Means achieved when 95% of the driving surface (edge line to edge line) is free of snow, slush, and/or ice.
5) Event type : S – Snow FR – Freezing Rain B - Both

Kevin [illegible]
Supervisors Name

Supervisors Signature