SIMULATION OF WINTER STORMS ON A TRANSPORTATION CORRIDOR

Mehdi Nourinejad, Elli Papaioannou, Mathew J. Roorda, Khandker M. Nurul Habib, University of Toronto

1. Introduction

Inclement weather conditions, particularly snow storms, are environmental events that impede urban mobility and require road maintenance to bring the transportation network back to normalcy. Recent storms across the U.S. and Canada have brought the municipal governments over budget. Ottawa spent 70% of its $1.4 million budget for winter road maintenance within the first two months of the winter season (Greg Chandler, 2014). In 2006, Toronto spent a budget of $62.5 million for winter road maintenance operations (City of Toronto, 2001). This budget is expected to exceed $80 million for 2014 (City of Toronto, 2014). The total estimated annual cost for winter road maintenance amounts to $1 billion for Canada and to over $2 billion for the U.S (Usman T. et al., 2012).

Municipal and governmental authorities are searching for new methods and technological advancements to optimize the operations. Automated vehicle location (AVL) and advanced road weather maintenance systems (ARWIS) can be singled out among other improvements. AVL, with the use of global positions systems, allows the locating of the winter maintenance vehicles and creates records of salting and plowing routes (Ontario Ministry of Transportation, 2004). ARWIS provides real time and site specific weather forecasts and pavement conditions. This information is essential for distinguishing among the different winter maintenance operations, which can generally be assorted into salt spreading, snow plowing and snow removal.

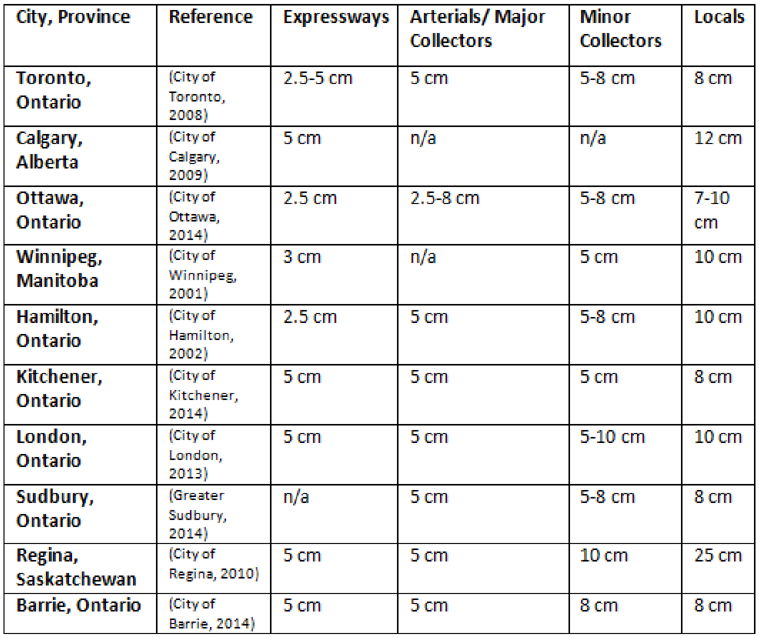
The current implemented policies, however, have not exploited technological advancements to the extent possible. Most North American cities that yearly receive snow, maintain a winter road maintenance plan and a salt management plan. These policies, shown in Table 1 for Canadian cities, are only on the basis of the minimum required accumulation of snow to initiate plowing operations. The winter road maintenance plans also include guidelines about the timeframe to complete the snow clearing based on the traffic volume on streets. Every city categorizes its streets in classes of priority; higher priority streets are treated immediately, once the required snow accumulation is reached. Streets of lower priority have a wider timeframe to be cleared off of snow; in many cases they are not plowed until snow accumulates to 10 cm, and they do not require bare pavement conditions.

Taking all these issues into account, it becomes apparent that winter road maintenance is a matter of concern to the economy, the environment, mobility, and driving safety. The primary objective of this research is to evaluate whether the current “snow-height” based policies are optimal. If not, we seek another tool for policy making that would be better than status quo but just as easily implementable.

2. Method

The method of this paper consists of simulating a transportation network corridor and various snow storms. We keep the same volume of traffic on the road at all stages of analysis. Snow storm profiles are varied both in terms of shape and snowfall intensity. We call each snowfall profile a “scenario”. For each scenario, different plow truck dispatch times are modelled. We call each dispatch time a “case”. By analyzing different cases in each scenario, our objective is to find which case, i.e. what dispatch time, is best in improving mobility on the corridor. We hereby describe the transportation corridor, the snowfall profiles, and dispatch times.

Table 1- Minimum depth of snow for initiation of snow plowing



City, Province	Reference	Expressways	Arterials/ Major Collectors	Minor Collectors	Locals
Toronto, Ontario	(City of Toronto, 2008)	2.5-5 cm	5 cm	5-8 cm	8 cm
Calgary, Alberta	(City of Calgary, 2009)	5 cm	n/a	n/a	12 cm
Ottawa, Ontario	(City of Ottawa, 2014)	2.5 cm	2.5-8 cm	5-8 cm	7-10 cm
Winnipeg, Manitoba	(City of Winnipeg, 2001)	3 cm	n/a	5 cm	10 cm
Hamilton, Ontario	(City of Hamilton, 2002)	2.5 cm	5 cm	5-8 cm	10 cm
Kitchener, Ontario	(City of Kitchener, 2014)	5 cm	5 cm	5 cm	8 cm
London, Ontario	(City of London, 2013)	5 cm	5 cm	5-10 cm	10 cm
Sudbury, Ontario	(Greater Sudbury, 2014)	n/a	5 cm	5-8 cm	8 cm
Regina, Saskatchewan	(City of Regina, 2010)	5 cm	5 cm	10 cm	25 cm
Barrie, Ontario	(City of Barrie, 2014)	5 cm	5 cm	8 cm	8 cm

2.1 Transportation corridor

Roads of most urban cities experience two traffic peaks: a morning peak and an afternoon peak. To account for this a simulation model is developed using the Paramics traffic simulation software (Quadstone Paramics Ltd.), which models vehicles at a microscopic level. The simulation time is large to capture one traffic peak.

2.2 Storm profiles

We use a uniform and a normal distribution function to simulate snowfall profiles (Fig. 1a). These profiles have been applied in the literature by Fu et al. (2009). For the normal distribution, we simulate an early-peak, a mid-peak, and a late-peak of snowfall with respect to traffic peak on the corridor (Fig. 1b). In each peak we consider two different peak intensities leading to a total of 6 scenarios. The uniform distribution, however, does not have a peak. We therefore consider two different intensities leading to 2 scenarios. In total we model 8 different scenarios.

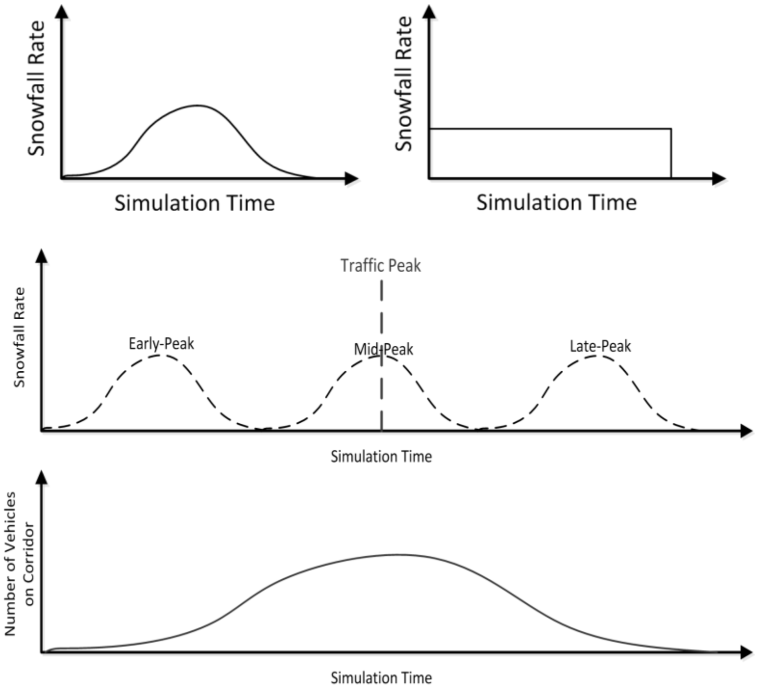


Fig. 1. (a, top) Two snowfall profiles, (b, middle) three peaks of the normal distribution storm profile, and (c, bottom) the traffic peak.

Given the snow profiles, it is important to capture the impact of snow on traffic. Extensive literature is devoted to testing and identifying capacity and speed reductions of roads due to weather conditions. The Federal Highway Administration (FHWA, 1977) provides a classification of pavement conditions (in six categories) and the respective speed reductions. The study shows that severe snow on the ground can lead to more than a 40% reduction in speed, therefore constraining the capacity of freeways. Analogous to FHWA (1977), Chin et al. (2004) define six weather conditions and use loop detector data to link the capacity and speed reductions to changes in weather conditions. Other similar analyses can be found in Martin et al. (2000), and Kyte et al. (2001). These models, whilst insightful, are based on qualitative descriptions of road conditions, and are not suitable for systematic decision-making. As an example, the FHWA (1977) uses the following categories: “Dry”, “Wet”, “Wet and Snowing”, “Wet and Slushy”, “Slushy in Wheel Paths”, “Snowy and Sticking”, and “Snowing and Packed”.

Taking a more quantitative approach, Rakha et al. (2007) formulate a more sophisticated model that accounts for snow intensity and visibility. This is achieved by using a weather adjustment factor that defines more realistic speeds for different weather conditions. Another study, by Wallman et al. (1997) presents free flow speed reductions with respect to height of snow of ground. The study shows that the first 2 cm of snow on bare pavement have the most drastic impact on the speed of vehicles; thereafter the speed is reduced by approximately 3km/h for every additional centimeter of snow. In line with Wallman et al.’s (1997) findings, we use an exponential function to represent the impact of snow height (on ground) on the free flow speed. The function is presented in a solid black line in Fig. 2. The reason for using an exponential function is to capture the higher initial impact on free flow speed at lower heights of snow up to 2 cm. Moreover the exponential function approximately captures the linear speed decrease of 3 km/h for every additional centimeter of snow after 2 cm. The solid line in Fig. 2, with a slope of 3 km/h/cm, is plotted for comparison with exponential function. Finally, the tail of the function is in accordance to FHWA (1977), which shows a lower rate of change in speed as the road conditions become more severe.

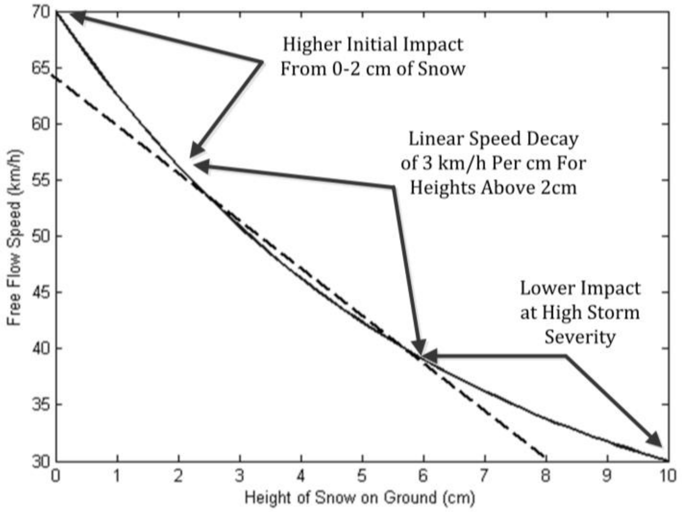


Fig. 2. Impact of snow on free flow speed.

3.2 Dispatch schedules

We use exhaustive enumeration to find the optimal plow dispatching time. Once a plow truck clears the corridor, the height of snow on ground is set to zero. For instance, Fig. 3 presents three different dispatch schedule scenarios. The first line from the left represents the case where no plow truck is dispatched and snow on ground gradually increases to some maximum value. The second (and third) line represent the case when a dispatched vehicle clears the corridor at time t_1 (t_2). At first glance, one may argue that the best dispatch time is as late as possible (which corresponds to the line in the figure at time t_3 or as late as possible) so that the entire amount of snow is cleared. However, we show later on that this is not necessarily the best decision and that a more efficient action would take into account both the profile of snow and the time when snowfall reaches its peak (if a peak actually exists).

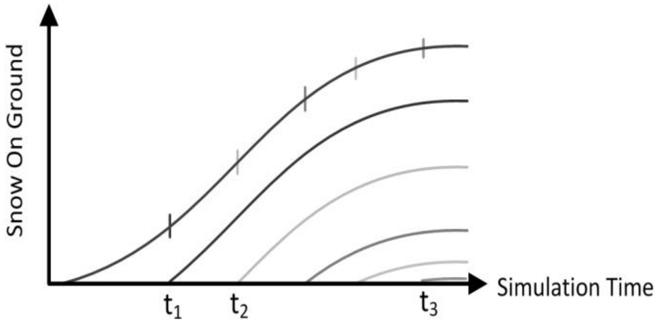


Fig. 3. Impact of dispatch time on the height of snow on ground.

Given that we are simulating plow trucks, we assume that no vehicle passes the truck. This assumption is coded in the simulation and is valid both in reality and the literature (Salazar-Auilar et al., 2012).

3. Results

We simulate a 5 km corridor, with no exit or entrance ramps, with three lanes and free flow speed of 70 km/hr. The simulation time is 5 hours and a demand of 3700 vehicles per hour is loaded onto the network so that the traffic peak would occur in the middle of the simulation at 2.5 hours (Fig. 1c). Results of each scenario are provided below. The first six scenarios pertain to the normal distribution and the last two to the uniform distribution snowfall profile. Table 2 presents the details of the scenarios. For each scenario we simulate 10 different truck dispatch cases equally spaced in time. The maximum plow speed is set to 30 km/hr. The measure of effectiveness that we use in this study is total network travel time, which is equal to the area under the curves of figures 4 to 7 provided below. In some cases where the total network travel time changes substantially from one dispatch time to the next, we simulate more than 10 cases. This helps find a dispatch time with a lower total network travel time.

Table 2. Details of the 8 scenarios

Scenario	Snowfall Profile	Storm Peak	Total Snow	Storm Duration
1	Normal	Early	10 cm	2 hr
2		Mid	10 cm	2 hr
3		Late	10 cm	2 hr
4		Early	15 cm	2 hr
5		Mid	15 cm	2 hr
6		Late	15 cm	2 hr
7	Uniform	-	10 cm	5 hr
8		-	15 cm	5 hr

3.1 Scenario 1: Normal profile, Early Peak, Total Snow 10 cm

The storm profile for this scenario has an early peak located at the 60th minute of the simulation. Fig. 4 presents the total number of vehicles on the corridor at each minute of the simulation for different dispatch times. The area under each curve represents the total network travel time. The D=NA curve is the case where no vehicle is dispatched. As the figure shows, dispatching a plow truck at the 60th minute, right at the peak of the storm, has the lowest total network travel time. The figure also shows that dispatching earlier than the 60th minute (e.g., D= 25, where D denotes dispatch time) has a more adverse impact compared to cases when plow trucks are dispatched after the 60th minute (e.g., D= 75 and D= 100).

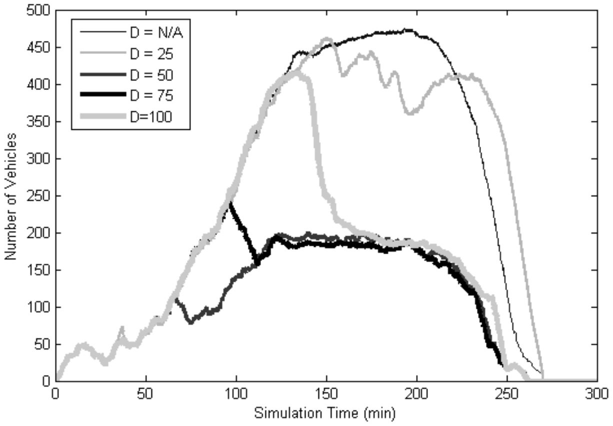


Fig. 4. Number of vehicles on the corridor for Scenario 1.

3.2 Scenario 2: Normal profile, Mid Peak, Total Snow 10 cm

The storm profile for this scenario has a mid-peak located at the 150th minute of the simulation. Similar to Scenario 1, the same curves are plotted for Scenario 2 but for different dispatch times. As Fig. 5 shows, the optimal dispatch time is again right at the peak of the storm at 150th minute. The two spikes of the cases D=100 and D=125 occur because vehicles are jammed behind the plow truck until it clears the corridor. Compared to Scenario 1, Fig. 5 shows that the mid peak scenario is much more sensitive to dispatch time.

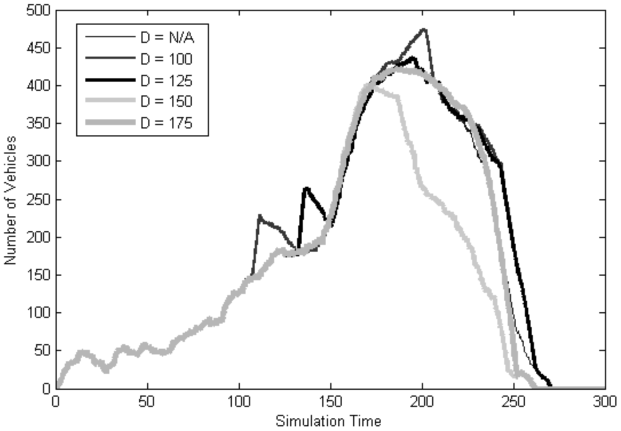


Fig. 5. Number of vehicles on the corridor for Scenario 2.

3.3 Scenario 3: Normal profile, Late Peak, Total Snow 10 cm

The storm profile for this scenario has a late-peak located at the 240th minute of the simulation. Fig. 6 is plotted for this scenario. Similar to Scenarios 1 and 2, the optimal dispatch time for Scenario 3 is again the peak of the storm at the 240th minute of the simulation. Dispatching slightly before the peak also provides a low total network travel time. Fig. 6 shows that the curves for not dispatching a plow truck (D = NA) or dispatching it at $D \geq 240$ overlap. This means that depending on when a truck is dispatched, the total network travel time cannot get any lower than the case of doing nothing. The curves for Scenarios 4, 5, and 6, provided in Appendix A, are very similar to Scenarios 1, 2 and 3, respectively.

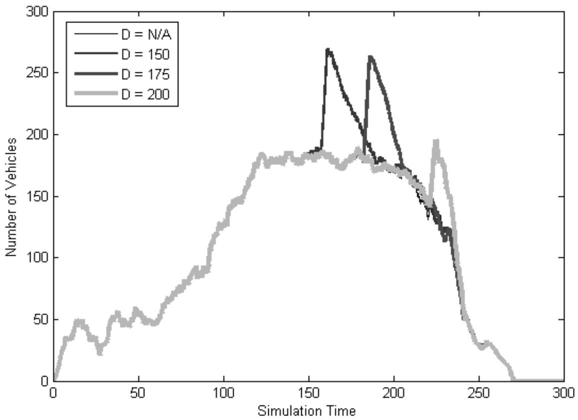


Fig. 6. Number of vehicles on the corridor for Scenario 3.

3.4 Scenario 7: Uniform profile, low intensity, Total Snow 10 cm

The storm profile for Scenario 7 is a uniform distribution with a snowfall intensity of 0.03 cm/min reaching a total of 10 cm at the end of the 300 minute simulation. Results are provided in Fig 7 which show that the optimal time of dispatching a plow truck is before the traffic peak at D = 100. The same decision can be made for Scenario 8 at a higher snowfall intensity of 0.05 cm/min which amounts to 15 cm of snow at the end of the simulation. Curves of Scenario 8 are provided in Appendix A.

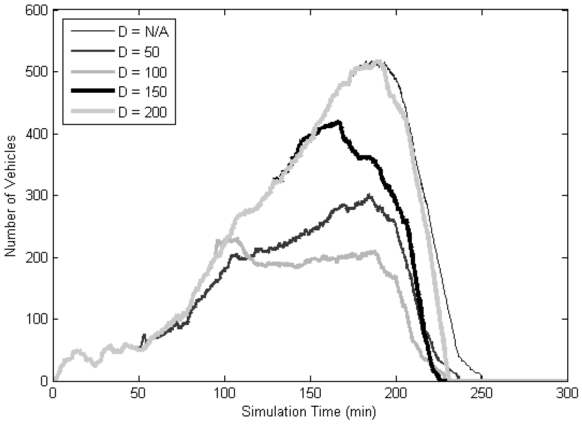


Fig. 7. Number of vehicles on the corridor for Scenario 7.

4. Conclusions

Inclement weather conditions affect the regular operation of road networks. Winter events, in particular snow storms, affect roadway mobility, impede the smooth operation on main and local streets, and result in speed reductions, capacity restrictions and consequently traffic delays. Most Canadian and United States cities have winter road maintenance policies to face this multidimensional challenge but require better planning and a more sophisticated, yet easily applicable, decision support system for the time frame of the operations and for more efficient resource allocation.

In this study, we show the total network travel time during snow storms is dependent on (i) the profile of the storm and (ii) the peak of the traffic. In cases where the storm has a peak, it is best to dispatch a plow truck right at the peak of the storm. In other cases when the storm has no peak, it is best to dispatch the plow truck right before the traffic peak. Simulating for two different storm intensities we show that the height of snow on ground, which is the current policy tool implemented in most Canadian cities, is not necessarily the best criterion for determining plow deployment.

Changing policies from the basis of “snow on ground” to “relative peaks of the storm and traffic” is not farfetched as current technological advancements such as AWIS have increased the accuracy of predicting weather conditions. Furthermore, municipalities have somewhat accurate estimates of the peak hours in the transportation network. Coupled together, the winter maintenance operations can be more efficient for the system in terms of minimizing the total network travel time.

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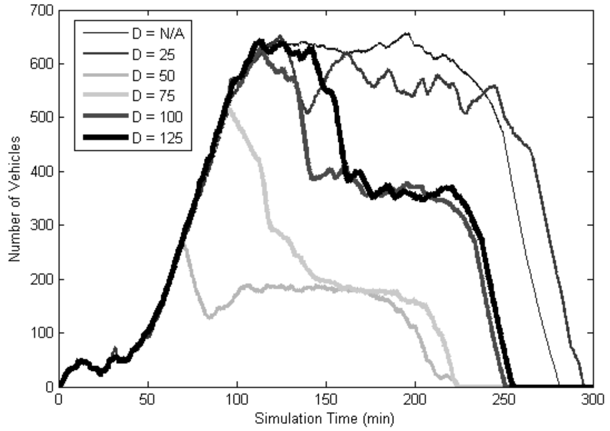
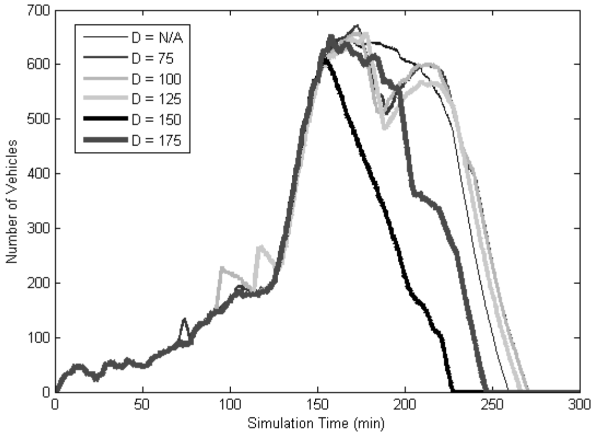
APPENDIX

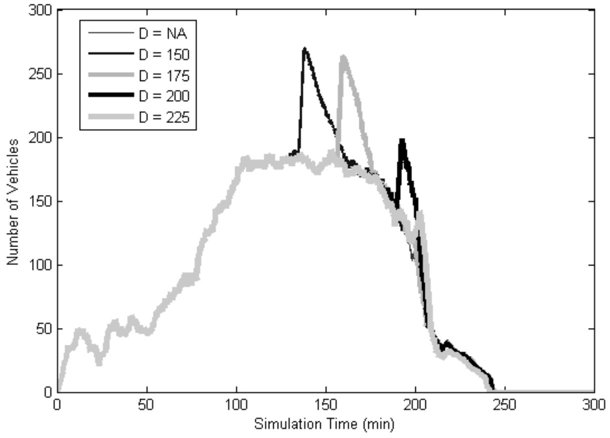
Scenario 4: Normal profile, Early Peak, Total Snow 15 cm



Scenario 5: Normal profile, Mid Peak, Total Snow 15 cm



Scenario 6: Normal profile, Late Peak, Total Snow 15 cm



Scenario 8: Uniform profile, high intensity, Total Snow 15 cm