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16. Abstract

Winter maintenance of major transportation corridors in northern states presents a persistent challenge, necessitating substantial investment by Departments of Transportation (DOTs). Inefficient snow removal operations contribute to safety hazards, reduced road capacity, and economic losses, particularly for freight transportation. This study develops a mathematical optimization model to assist DOTs in making both long-term planning and short-term operational decisions for winter maintenance, aiming to enhance snowplow efficiency while minimizing capital and operational costs.

The model employs a two-stage stochastic programming approach, integrating priority levels for service regions and stochastic snow event scenarios. The first stage addresses long-term investment decisions, including station locations and fleet acquisition, while the second stage focuses on operational strategies, such as task assignments and de-icing material purchases. The objective function minimizes total costs, including capital investment, operational expenses, and economic losses due to unplowed snow. The solution framework provides optimal station placement, fleet size, resource allocation, and response strategies under varying snow conditions, ensuring robustness against both normal and extreme snow events.

Application of the model to Minnesota's winter maintenance system reveals key insights: as annual snow events increase, operational costs comprise a larger share of total expenses; additional stations become necessary to mitigate transportation costs and economic losses from unplowed snow; for typical conditions with 30 snow events per year, the estimated total cost is $27.5 million, with 43 stations, 87 service regions, and a fleet size of 300; extreme snow events require significantly expanded resources, with 54 stations and a fleet of 475 trucks. Notably, prioritization based on general traffic volume versus heavy-commercial vehicle volume does not yield substantial differences in optimal decisions.

This decision support system offers DOTs a financially efficient tool for winter maintenance planning, reducing costs while improving operational effectiveness. Implementation of the proposed model enhances the safety and efficiency of freight transportation during winter, ultimately benefiting the broader transportation network.

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OPTIMIZATION OF WINTER MAINTENANCE STATIONS FOR SAFE AND EFFICIENT FREIGHT TRANSPORTATION

Final Report

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DISCLAIMER

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1 Executive Summary

In northern states, winter maintenance of major transportation corridors is an ongoing issue. It incurs large investments and costs for Department of Transportation (DOTs). Inefficient snow removal plan also leads to significant traffic safety issue, road capacity reduction, and economic loss for freight transportation. This project aims to is to build a mathematical model that helps DOTs make both long-term planning and short-term operational decisions of winter maintenance, which lead to a much more efficient snowplow system with minimum capital and operation cost.

Using as input identified priority level for service regions and representative stochastic snow events, a two-stage stochastic programming problem was formulated. The two-stage problem naturally emulates the decision-making process of a DOT that first plans for long term investment such as building up snow truck stations and purchasing snow trucks, and then plans for detailed operational strategy such as snow removal task assignment and the purchase of de-icing materials. The objective of the mathematical optimization problem is to minimize the total costs including capital cost and operational costs as well as economic loss due to unplowed snow. The obtained solution determines the optimal geographic locations of stations, optimal fleet-size, task assignment, truck assignment, the amount of de-icing materials, and economic loss due to insufficient snowplow capability. Taking into account the uncertainty of snow events in its intensity and space, the optimal decisions obtained from the developed mathematical model are robust. Plans for both normal snow events and extreme snow events have been developed. The proposed decision support system could benefit DOTs from a financial perspective by reducing winter maintenance operations cost and improving the efficiency in capital investment. The implementation of the decisions obtained from the proposed mathematical model benefits the freight industry by safe and efficient freight transport in winter.

Based on the application on the state of Minnesota, the major findings in this report include:

- With the increase of annual snow events, the operational cost accounts for an increasing portion in the annual total cost for winter maintenance;
- More stations are to be opened when there are more snow events due to the potential benefit of saving on transportation costs and unplowed-snow incurred economic loss;
- Planning for normal snow events, with a typical number of 30 snow events annually, the total cost is estimated to be about 27.5 million dollars. With an average service region to station 2.02, 43 stations are selected to be in charge of 87 service regions. The fleet-size is estimated to be around 300;
- Optimal decisions for VMT-based priority (priority levels for all traffic VMT) and HCVMT-based priority (priority for heavy-commercial vehicle VMT) do not show distinctive differences;
- Planning for extreme snow events, the number of stations and fleet-size is significantly larger than that of the normal case. With an average service region to station 1.59, 54 stations are selected and the fleet-size is estimated to be 475.

2 Problem Background

Snowfall reduces road capacity, increases crash rate and may lead to great economic loss if the snow cannot be efficiently removed from the road network which hinders the travel of freight vehicles. As was introduced before, the closure of two highways in the Washington state resulted in 75 million dollar loss in the winter of 2007-2008. Due to these facts, winter maintenance operations such as snow removal and road de-icing become crucial tasks for state department of transportation (DOTs), who are in charge of maintaining the highway systems to provide a safe and efficient network for people and goods.

In the United States, winter maintenance accounts for approximately 20% of DOT's budgets [1]. For example, the Department of Transportation of Minnesota (MNDOT) spent a total of $106 million for snow and ice control operations in the 2015-2016 fiscal year, and the cost does not include capital investment on snow truck facilities [2]. Winter maintenance operations are time and resource intensive. The operation must be efficient so as to keep the road network in good condition as soon as possible after snow events. The efficiency of the maintenance operation depends on the following several key factors:

1. the geographic locations of snow truck stations where snow-plowing trucks are dispatched from and de-icing materials are stored in;

2. assignment of maintenance tasks to snow truck stations, where the arbitrary or non-optimal assignment can lead to unnecessary truck travel distance and extra deadheading;

3. the number of trucks assigned to service regions and the amount of de-icing materials purchased for each truck station.

Therefore, an optimization problem involving both planning and operational decisions should be set up for making optimal snow-plow planning and operational decisions. We want to make long-term planning decisions of geographic locations of snow truck stations whose life spans are typically measured in decades. The locations of these facilities affect operation strategies including task assignment and vehicle routing in the long term. The other planning decision to be made is the total number of snow trucks to be purchased. Depending on the predetermined service level, the total number of trucks and the number of trucks at each station vary. At the operational level, assignment of truck stations to operation tasks at different service regions and the amount of de-icing materials such as abrasive and salt at each station needs to be optimized. All the above decisions from the supply side should be determined with a good representation of the demand — snowfall, in this case, while emphasizing its innate stochasticity property. Before setting up the mathematical model for decision support, we first need to ascertain the negative impacts of snow on freight traffic, and identify critical freight corridors that are to be input to the to be developed model.

3 Winter weather effects on freight mobility

The literature on how winter weather, especially for snow and ice conditions, affects freight logistics has been relatively scarce. Whereas, broader and more general studies exploring the impact of adverse weather and climate and whether change on transport have received abundant research attention. Hence, in this chapter, we will provide a literature summary in a broader fashion and try to restrain the emphasis to the relationship between winter weather and freight mobility as much as possible.

Impacts on traffic safety

It is a consensus among people that extreme weather has adverse impacts on road safety. Among various factors such as wind, fog, heat, and precipitation, precipitation is believed to be the most important one that affects the road safety [3]. As is known, two major forms of precipitation are rain and snow. Studies found that, qualitatively speaking, precipitation generally increases the frequency of road accidents [4, 5, 6, 7]. For example, using data from 1975-2010 of 48 states of U.S.A, Eisenberg concluded from a negative binomial model that "an increase of 1 cm of precipitation is associated with a 1.15% increase in the fatal crash rate, and an additional 1 cm of snow corresponds to a 0.9% increase" [5]. Andrea's analysis on the data from Canadian provinces concluded that precipitation is associated with an 75% and 45% increase in vehicle crashes and injuries, respectively [7]. It was also concluded that snowfall's impacts on crashes are more significant than rain's as a whole. Besides, it was also found in both studies that crash severity seems to be slightly dampened in precipitation conditions compared to "normal" conditions, and this was partially attributed to reduced travel speeds for vehicles. Transportation department of the Iowa state had conduced an study on winter weather's impacts on travel mobility and safety [8]. The report pointed out that during severe winter storm events, hourly crash rate increased, whose value varied between 0.021 and 0.223, and this translated to a 942% of increase in percentage. Studies on road safety specific for freight vehicles in winter weather are largely absent, but the negative impacts can be definitely conjectured. An exception is the study by Maze et. al. Similarly, an increase in crash rate and decrease in severity were concluded; the crash rate for commercial vehicles(trucks) was higher than that involving all vehicles due to unlikelihood of diverting trips for commercial vehicles due to winter weather[9].

Impacts on travel speed and travel time

Reduced travel speeds during events of extreme weather is consistently found by a substantial number of studies. The reduction is pronounced in precipitation events [3]. In 1990's, studies on inclement weather's impact on speed had been conducted based on data of cities outside the U.S.A [10, 11]. Ibrahim and Hall showed that heavy snow had larger impacts on free-flow speed reduction than heavy rain, which can result in a speed drop of 24 to 31 mile/hr [10]; Brilon and Ponzlet using data from German obtained a speed reduction of 6-7.5 mile/hr for wet road conditions [11]. Later came some US cities-based studies. A study sponsored by the Federal Highway Administration (FHWA) had a comprehensive analysis on weather impacts of macroscopic traffic flow. In the study, three metropolitan areas including Minneapolis, Baltimore, and Seattle were examined [12]. Two type of speeds—free flow speed and speed at capacity—were tested in different rain and snow conditions. One conclusion drawn from their analysis is that precipitation reduces travel speed, and the speed reduction impacts of snow is generally larger than that of rain. See Table 1 for detailed information[1]. Another study conducted using the data of Twin Cities metropolitan area revealed similar results. It is shown that compared with clear days free-flow speed reductions ranged from 4% to 13% for different snow intensity[9]. The results derived from 7 interstate roads showed that during snowstorm events, a 11% speed reduction was found and speed variability increased as well [8]. In terms of travel time reliability, Tu et al. analyzed 90th and

Table 1: Speed and capacity reduction for precipitation in the snow form

	Free-flow speed	Speed at capacity	Capacity
light snow (<0.01 cm/h)	5% - 16%	5% - 19%	12% - 20%
snow (0.03 cm/h)	5% - 16%	5% - 19%	

10th percentile of travel times and found that adverse weather led to twice travel time variability [13]. Additional studies about the impacts of extreme weather on travel time reliability are for sure needed.

To quantify the welfare loss due to speed reduction (and hence travel time increase), a study conducted using the data from Netherlands gave some insights. Researchers found that the occurrence of snow resulted in about 7% of speed reduction, and using the value of time at the time the welfare loss was estimated to be 22 euro cents for an average-time commuting trip during snow events[14].

Economic analysis for freight logistics disruptions in more severe situations was studied by the Washington State Department of Transportation (WSDOT). There were two storm-related freeway (I-5 and I-90) closures in the winter of December of 2007 and January and February of 2008, respectively. The closure lasted for 8 days in total and 4 days for each. The closure of I-5 tripled the distance from Seattle to Portland from 200 miles to more than 600 miles due to detour for both freight and auto traffic. The closure of I-90 due to extremely heavy snows and avalanche had a even greater impacts—leaving very limited route options for east-west bound freight traffic. The analysis was based on 2,758 surveys received from trucking industry and freight-dependent sectors. A total loss from freight delay due to the closure of the freeways was estimated to be $75 million, and the number was believed to be an underestimation since surveys were only sent to in-state business and not all feedback were received by the time of analysis.

Impacts on traffic volume and road capacity

Traffic volume/flow is directly related to travel demand. Travel demand and road capacity are both impacted by weather conditions. In this section, we summarize key findings on demand and supply of traffic in winter weather in the literature.

In terms of general traffic demand, when adverse weather conditions present, people may postpone their departure times, switch to different travel modes, and cancel their trips if possible. Thus, in general, traffic volume on road is smaller during adverse weather time. This has been found consistently in the literature [8, 9, 15, 16, 17]. Knapp et al. found an average of 29% volume reduction at various sites during winter storms [8]. Hourly traffic volumes, however, exhibit both increasing and decreasing patterns. An increase in hourly traffic volume was partially related to the travelers' strategy that they are inclined to leave earlier at the beginning of the event or wait until the end of the event. Hanbali and Kuemmel found

1Results are from [12].

that volume reduction is proportional to snowfall intensity. The reduction percentages ranged from 7 to 53 [17]. See Table 2 for details. A study using Scotland data by Al Hassan and Barker concluded that traffic

Table 2: Traffic volume reduction with snowfall intensity

Snowfall intensity	Traffic volume reduction
<25mm	7-17%
25 -75 mm	11-25%
75-100 mm	18-43%
150-225 mm	35-39%
225-375 mm	41-53%

volume reduced by 10% and 15% during weekdays and weekends when the roads are covered with snow [18]. Maze et al. further concluded that volume reduction is related to visibility and wind speed [19]. Later, a study on I-35 in the state of Iowa, shows that "during snowstorms commercial vehicles became a higher percentage of the traffic stream ... when compared with the percentage during clear weather" [9]. The increase of ratio of commercial vehicles to total traffic can be as high as 70%. This suggests that commercial vehicle drivers are less likely to change their trip plans according to weather conditions. This is agreed by researchers that trip purposes are of relevance to traffic volume during extreme weather conditions [3]. As is pointed out by Koetse and Rietveld, the distinction between work and business trips and recreational trips explains much in the difference of volume change in snowstorms. Therefore, we can conclude that winter weather, especially snowfall, exerts larger impacts on freight vehicles.

On the supply side, road capacity is also found shrunk in extreme weather conditions, especially in snowy days. There are various reasons for the reduction of road capacity. Firstly, when the road is wet or covered with snow or water, deceleration and acceleration performances of vehicles get worse. Secondly, free-flow speed and average speed of vehicles lower because drivers become more cautious and conservative in inclement weather. The report published by FHWA analyzed the Twin Cities data of 2002 and 2004, which includes both rain and snow precipitation. They found that compared with rain, snow impacts on capacity (as well as free-flow speed as mentioned in previous section) are more significant. Snow reduces the road capacity by 12-20% but the roadway capacity is not related to snow intensity [12]. Figure 1 plots the traffic flow fundamental diagram using the data from the Twin Cities metro area with various snow precipitation intensity levels. 2 Using 4 years of data from three different sources, traffic detectors, roadway weather information system, and automated surface observing system, Maze et al. derived the relationship between snowfall intensity levels and roadway capacity reduction and all numbers are statistically significant at the 95% significance level[9]. Their main findings were summarized in Table 3. 3

Evidence from other cities exists. Ibrahim and Hall studied a data set of Hamilton, Canada, and observed that the maximum flow reduced by 48% during heavy snow[10] though the exact capacity measurements were not available. The study in the context of German highway system showed that in expectation, the capacity reduction for a two-lane and three-lane road are 350 vph and 500 vph, respectively[11].

2Results are from [12].

3Results are from [9].

Table 3: Capacity reduction with snow intensity

Snow intensity	Capacity	Capacity reduction
0	2318 veh/h/ln	-
≤ 0.05 in/h	2220 veh/h/ln	4%
0.06 in/h - 0.1 in/h	2117 veh/h/ln	9%
0.11 in/h - 0.5 in/h	2064 veh/h/ln	11%
≥ 0.5 in/h	1801 veh/h/ln	22%

Conclusion

One conclusion that we can draw safely from the summary of weather-related traffic studies is that adverse weather conditions do have negative impacts on travel mobility. In addition, winter snow precipitation has significantly greater impacts as opposed to rain precipitation. This emphasizes the importance of winter road maintenance operations in order to provide traffic facilities that are safe and efficient. The importance of the issue is even pronounced for northern states and cites. In the Twin Cities in Minnesota, for instance, it snows for 10% of days in a year. A well-designed, effective, and efficient winter road maintenance plan and strategy is needed without doubt. Among all factors to be meticulously decided, priority roads heavily used by freight vehicles for maintenance operations and configurations of snow truck stations with respect to their location, type, and capacity will be addressed in this project.

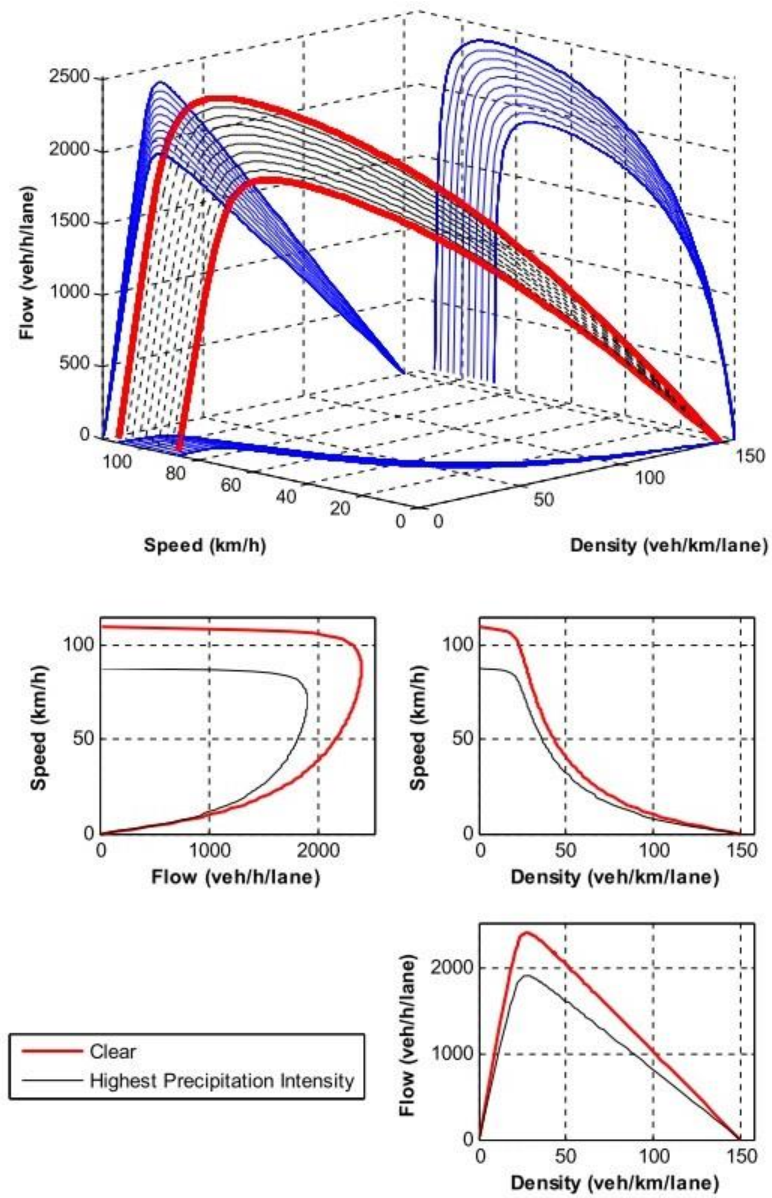

Figure 1: Traffic stream behavior as a result of snow precipitation using the Twin Cities data

4 Critical Corridor Identification

Data of traffic volume and snowfall were employed for analysis purpose. Traffic volume count data including annual average daily traffic (AADT) data and heavy commercial annual average daily traffic (HCAADT) were used to identify road segments that carry heavy traffic and should be prioritized for maintenance; another data set, which is the history snowfall data, were used to identify road segments that are likely to experience heavy snow events and therefore should be plowed with a high priority.

Snowfall data and its predictions

A snowfall data set was obtained from the website of Midwest Regional Climate Center (MRCC) [20]. The data set includes history records of average monthly snowfall amount for both normal conditions and extreme cases from 1981 to 2010. A sample data subset from a station near the Twin Cities metropolitan area is provided in Table 4 and Table 5.

Table 4: Monthly average snowfall sample - Station Forest Lake 5NE

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Snow (in.)	9.1	8.7	9.8	2.9	0.0	0.0	0.0	0.0	0.0	0.5	8.3	11.8	51.1

Table 5: Extreme cases snowfall sample - Station Forest Lake 5NE

Month	1-Day Max (in.)	2-Day Max (in.)	3-Day Max (in.)
Jan	7.7	10.4	12.0
Feb	10.0	10.0	10.0
Mar	12.0	14.0	14.3
Apr	12.3	14.0	10.0
May	0.1	7.0	7.0
Jun	0.0	0.0	0.0
Jul	0.0	0.0	0.0
Aug	0.0	0.0	0.0
Sep	0.0	0.0	0.0
Oct	3.9	4.2	4.2
Nov	16.2	24.4	24.9
Dec	16.0	16.5	17.3

A total number of 26 weather stations in the state of Minnesota and Wisconsin were selected to make predictions of snowfall amount for both normal and extreme cases. Since the snowfall data were collected from a limited number of weather stations that spread across Minnesota, some prediction is needed for snowfall geographic distribution for the entire state so that a maintenance priority based on snowfall amount on road can be obtained. To this end, we adopted an interpolation method—kriging— to estimate the snowfall amount given the geographic location of each weather station and associated history snowfall data. The following section briefly introduces the method of kriging followed by a section summarizing the snowfall prediction results.

Introduction to kriging

Kriging is a statistical method of interpolation that predicts values based on a Gaussian process with prior covariances. It has been widely used in fields such as hydrogeology, environmental science, natural resources, and etc. The method produces "an estimated surface from a scattered set of points with z-values" [21]. In the case of snowfall which has strong geographic correlations, the method of kriging is suitable.

Similar to the inverse distance weight method, kriging weights data points to derive an estimate for unmeasured locations. It assumes that "the distance and direction between sample points reflect a spacial correlation" [21]. The formula for predicting the value for unmeasured location j, $Z(s_j)$, is as follows:

$$Z(s_j) = \sum_{i=1}^{N} \lambda_i Z(s_i), \tag{1}$$

where $Z(s_i)$'s are measured values, and λ_i's are weights for each measured location.

Two main steps of the method are: fitting a model, and making a prediction. To fit a model, an ingredient— a graph of empirical semivariogram which is computed by squaring the difference between paired locations (called semivariance)— is needed for the sake of reflecting spatial correlations. A semivariogram graph has distance as x-values and semivariance as y-values. Then, a model is fitted to the empirical semivariogram. This fitting process is similar to a regression process. See Figure 2 for a fitted model for semivariogram.

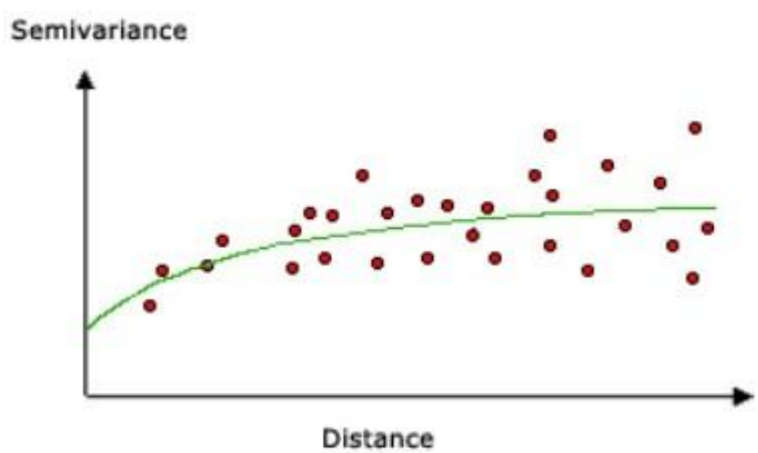

Figure 2: A fitted model to the semivariogram

Having a fitted model, one uncovers the dependence and correlation in the data that takes spacial distribution of data points into consideration. A prediction of unsampled locations can then be made according to the fitted model based on the equation (1), which is a linear estimation. There are various methods for calculating weights, among which the ordinary method and the universal method are most common ones. We leave out the details of these methods and interested readers are referred to the related material [21, 22].

Snowfall prediction results

According to the kriging method introduced above, we took the data from 26 weather stations and predicted the snowfall amount contours for the entire state of Minnesota. Figure 3 shows the predictions for total snowfall amount in January in normal cases.

Take January as an example, we classified snowfall amount into 10 levels based on history records. A summary of the total road length for each snowfall severity level is provided in Table 6. About 44% of the total road length experience average snowfall amount greater than 10.3 inches. Geographically, these roads are mostly in the northeast part of Minnesota (see Figure 3). Specific to freight traffic, we summarized road length and total heavy vehicle volume on trunk highways and interstate highways for each snowfall level. In Table 7, it is found that 46% of trunk highways and interstate highways experience more than 10.3 inches of snowfall in January, while in terms of total HCAADT on these roads, it only accounts for less than 19% of the total HCAADT. In other words, there are more trips of heavy commercial vehicles on roads with lighter snowfall severity.

Table 6: Road length summary by snowfall severity

Snowfall amount (in.)	Road length (km)	Snowfall amount (in.)	Road length (km)
≤ 8.8	3439.86	8.8 - 9.4	9257.03
9.4 - 9.7	11509.22	9.7 - 9.9	14179.44
9.9 - 10.3	16347.83	10.3 - 10.8	17310.20
10.8 - 11.7	8343.45	11.7 - 13.2	6825.04
13.2 - 15.6	9696.95	15.6- 19.4	335.95

Table 7: Interstate and trunk highway length summary and volume summary by snowfall severity

Snowfall amount (in.)	Total road length (km)	Total HCAADT	Snowfall amount (in.)	Total road length (km)	Total HCAADT
≤ 8.8	656.03	48011	8.8 - 9.4	1797.36	179118
9.4 - 9.7	2240.91	301513	9.7 - 9.9	2532.25	1328100
9.9 - 10.3	2956.85	1578977	10.3 - 10.8	3362.13.20	402364
10.8 - 11.7	1783.57	173010	11.7 - 13.2	1594.49	70938
13.2 - 15.6	1906.71	131193	15.6- 19.4	68.39	3280

Traffic volume analysis and critical corridor identification

In this section, traffic volume data including AADT and HCAADT obtained from Minnesota Department of Transportation's website[23] were analyzed for identifying roads that need prioritized winter maintenance. Apart from the traffic volume data, road hierarchy was also used for aiding the identification process.

In the state of Minnesota, the total length of road system is estimated to be more than 97,300 kilometers, which includes interstate highways, trunk highways (TH), county roads(CR), County State-Aid Highways (CSAH), Municipal State-Aid Street (MSAS), and other types of roads. Among these, interstate and trunk highway systems are the major corridors that carry significant amount of traffic for long and short trips. Interstate highway and trunk highway systems in Minnesota have more than 18,900 kilometres of road network, which account for about 20% of total road mileage.

Figure 9 shows AADT by road segment for interstate highway and trunk highway systems. The highest AADT amounts to 216,000 by road segment, which is on I-35W, and other segments with heavy traffic volume are on I-35E, I-494, I-94, I-694, I- 394, TH 62, Th 212, and TH 10. In terms of freight traffic volume, the highest HCAADT road segment is on I-694 with 13,000 heavy commercial vehicles per day, followed by others on I-94, I-35, I-494, I-35W, TH 10, TH 12 and I-35E.

Critical corridor for freight logistics identification is mainly based off traffic volume and road hierarchy. For example, in Figure 4, based on HCAADT, we clustered interstate and trunk highway road segments into 3 priority levels with each level having roughly equal number of road segments. The greener the color is shaded for a segment, the higher the priority is required during snow removal tasks.

Conclusion

Employing history snowfall data from scattered weather stations, a continuous snowfall amount prediction for the entire road network system is carried out whose results will be used as stochastic demand input to the optimization problem. Analyzing the data set of AADT and HCAADT, critical corridors for traffic were identified where road hierarchy was taken into consideration as well. The priority results of maintenance operation will be given as input to the optimization problem for making optimal operation decisions in the optimization problem to be presented in the following chapters.

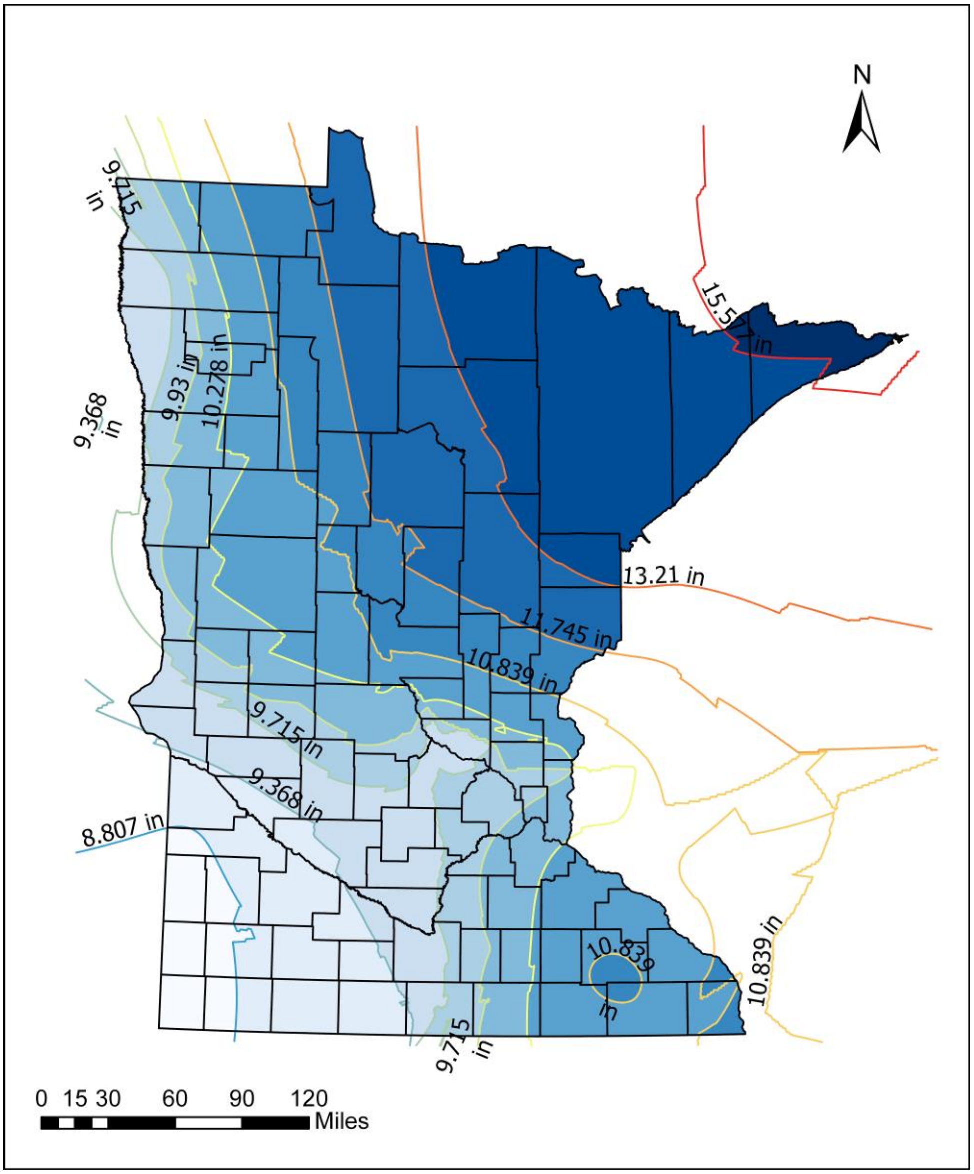

Figure 3: Average snowfall prediction for normal cases - January

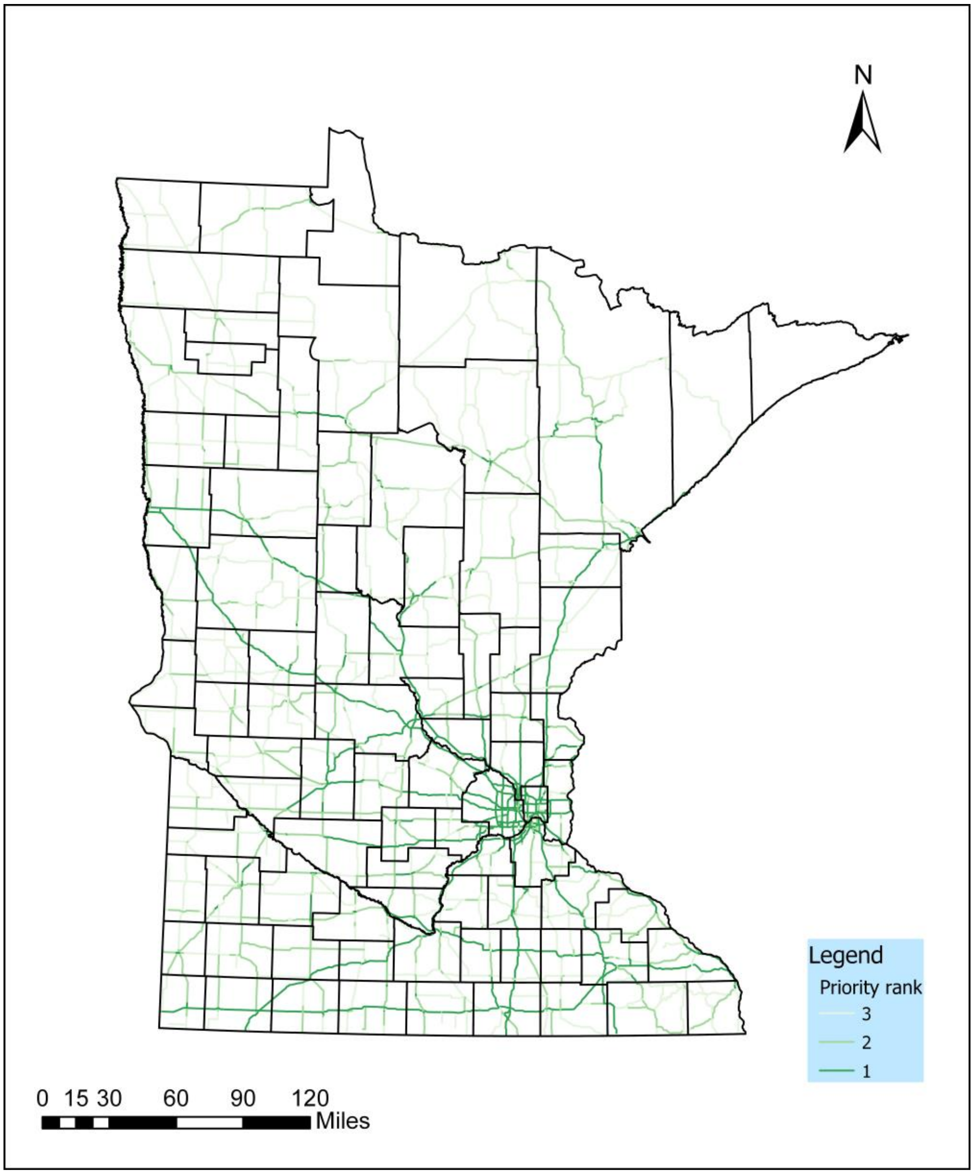

Figure 4: Priority map for interstate highway and trunk highway systems

5 Optimization Model

We introduce the optimization model developed for the winter maintenance problem in this chapter. The problem is formulated as a two-stage stochastic program.

For a system design problem with both long-term decisions and short-term decisions, and especially when there is the uncertainty of input, it is well suited to formulate a two-stage stochastic optimization problem. The two-state stochastic optimization problem, as its name suggests, has two decision-making stages, where the first stage problem is related to planning decisions while the second stage problem is related to operational decisions. In the context of the winter maintenance problem, the first stage problem involves decisions on facility locations and capital investment on snow trucks, and the operational decisions are mostly included in the second stage problem. Long-term decisions are made before any stochastic events are realized, then operational decisions are made in response to different realizations of stochastic events and the value of the first-stage decisions in the future is obtained.

Formulation development

Consider a set $\mathbf{I}$ of candidate snow truck stations and a set of service region $\mathbf{J}$. A selection of snow truck stations $i \in \mathbf{I}$ are to be set up such that $y_i = 1$ indicates the open of a station at location i. An opened station i can be assigned to service region j for winter maintenance operations. The variable x_{ij} takes the value of 1 if such an assignment is confirmed and otherwise 0. The number of trucks to be purchased for each opened station is denoted as n_i, which is an integer variable, and the amount of de-icing materials to be stored at each station is denoted as z_i. Note that constrained by the availability of land, each station i has its associated capacities for both snow trucks c_i and de-icing materials c^m_i, respectively. Parameters related to the first stage problem are the capital cost for setting up a truck station at location i, e_i, which varies from location to location; unit cost for purchasing a snow truck f_i, which is assumed to be equal for simplicity; unit cost for purchasing de-icing materials h_i, which is also assumed to be equal across stations.

First-stage Problem

The overall two-stage stochastic problem is as follows.

$$\textbf{[P]} \quad \text{minimize} \quad \sum_{i\in\mathrm{I}} e_i y_i + \sum_{i\in\mathrm{I}} f n_i + \mathrm{Q}(\mathbf{x}, \mathbf{y}, \mathbf{n}) \tag{2}$$

$$\text{subject to} \quad \sum_{i\in\mathrm{I}} x_{ij} = 1, \qquad \forall j \in \mathrm{J} \tag{2a}$$

$$x_{ij} \le y_i, \qquad \forall i \in \mathrm{I}, \forall j \in \mathrm{J} \tag{2b}$$

$$n_i \le c_i y_i, \qquad \forall i \in \mathrm{I} \tag{2c}$$

$$x_{ij} \in \{0, 1\}, \qquad \forall i \in \mathrm{I}, \forall j \in \mathrm{J} \tag{2d}$$

$$y_i \in \{0, 1\}, \qquad \forall i \in \mathrm{I} \tag{2e}$$

$$n_i \in \mathrm{Z}_+, \qquad \forall i \in \mathrm{I} \tag{2f}$$

The objective function minimizes the sum of three terms where the first term and second term computes the capital cost for setting up truck stations and purchasing snow trucks, respectively. The third term, $Q(\mathbf{x}, \mathbf{y}, \mathbf{n})$, computes the operational costs for given values of first stage decision variables (in boldface representing their vector forms). Note that the natural cost parameters such as e_i, f_i, and other operational costs in the second stage come in different analysis time horizons, we need to scale them into the same analysis time horizon to make them comparable and additive. Therefore, the objective minimizes the total amortized planning and operational costs.

Constraints (2a) guarantee that each service region j has to be assigned to some snow truck station i. Constraints (2b) stipulate that an active service assignment for station i can happen only when the station i is opened. Capacity constraints for snow trucks are captured in constraints (2c), and the rest are variable definition constraints.

Second-stage problem

The second stage sub-problem computes the operational costs for stochastic snowfalls given the solution of the first stage problem. In the framework of the two-stage stochastic program, the uncertainty of input and/or parameters is represented with a series of scenarios each representing a realization of one snow event. Here, we index a scenario by k. A snow event k results in total snowfall D^k_j, but restrained by the limited resources and the underlying benefits against cost, an operation strategy may leave some lane-miles $\bar{l}^k_j$ for each region j unplowed. In the following we compact the notation with $\mathbf{D}$ and $\bar{\mathbf{l}}$ representing the vector form of the above two variables for all regions and may omit the scenario index k for brevity.

For a scenario k, the second stage sub-problem takes the following form:

$$Q(\mathbf{x}, \mathbf{y}, \mathbf{n}, \mathbf{D}) = \min_{\mathbf{x},\mathbf{n},\mathbf{z},\bar{\mathbf{D}}} \left\{ \sum_{i \in I} \sum_{j \in J} s_{ij} + \sum_{i \in I} h_i z_i + \rho \mathbf{V}^t \bar{\mathbf{l}} : \quad (\mathbf{s}, \mathbf{z}, \bar{\mathbf{l}}) \in Y(\mathbf{x}, \mathbf{y}, \mathbf{n}, \mathbf{D}) \right\}.$$

Given the first stage's solution, the second stage problem minimizes a weighted sum of travel distance, de-icing materials, and unplowed snow incurred costs. The first term in the objective function involves travel cost variable s_{ij} that computes the costs for dispatching vehicles to service regions and aggregated cost for routing trucks. The second term is the cost of purchasing deicing materials. The last term is the penalty cost related to unplowed lane miles, which can be weighted differently with the zone-specific parameter V_i ($\mathbf{V}$ is its vector form) and a uniform weighing parameter ρ for cost analysis consistency. The zone-specific parameter can relate to vehicle miles traveled (VMT) for freight vehicles to capture costs such as economic loss due to road capacity reduction and etc that are resulted from unplowed snow remains on the road network. The set $Y(\mathbf{x}, \mathbf{y}, \mathbf{n}, \mathbf{D})$ represents the feasible region of $(\mathbf{s}, \mathbf{z}, \bar{\mathbf{l}})$, which will be presented later.

It is impractical to enumerate all the possible scenarios in solving the problem, therefore, we consider a sample average approximation of the operational costs. It is assumed that a few representative realizations of snow events from historical data can provide a good estimation of the weather condition in the region, and each realization has an associated probability q^k such that $q^k \geq 0$ and $\sum_{k \in K} q^k = 1$, where K is the scenario set. Now, we consider the expected cost

$$Q(\mathbf{x}, \mathbf{y}, \mathbf{n}) = \mathbb{E}\left[Q(\mathbf{x}, \mathbf{y}, \mathbf{n}, \mathbf{D})\right]. \tag{3}$$

Then, the objective function of the second stage problem can be stated as the following with i.i.d. samples of snow events.

$$Q(\mathbf{x}, \mathbf{y}, \mathbf{n}) = \sum_{k\in K} q^k \sum_{i\in I}\sum_{j\in J} s^k_{ij} + \sum_{k\in K} q^k h \sum_{i\in I} z_i + \rho \sum_{k\in K} q^k \mathbf{V}^{\mathbf{t}}\bar{\mathbf{l}}^{\mathbf{k}} \tag{4}$$

The complete second stage sub-problem is as follows.

$$\textbf{[SP]} \quad \text{minimize} \quad \sum_{k\in K} q^k \sum_{i\in I}\sum_{j\in J} s^k_{ij} + \sum_{k\in K} q^k \sum_{i\in I} h_i z_i + \rho \sum_{k\in K} q^k \mathbf{V}^{\mathbf{t}}\bar{\mathbf{l}}^{\mathbf{k}} \tag{5}$$

subject to

$$n_{ij} \le Q x_{ij}, \qquad \forall i \in I, \forall j \in J \tag{5a}$$

$$\sum_{j\in J} n_{ij} \le n_i \qquad \forall i \in I \tag{5b}$$

$$\sum_{j\in J} z_{ij} \le z_i \qquad \forall i \in I \tag{5c}$$

$$s_{ij} \ge \gamma o_{ij} n_{ij} + \gamma l_j x_{ij}, \qquad \forall i \in I, \forall j \in J \tag{5d}$$

$$\sum_{i\in I} x_{ij} l_j D_j - \sum_{i\in I} q n_{ij} \le D_j \bar{l}_j, \qquad \forall j \in J \tag{5e}$$

$$z_{ij} \ge u(l_j - \bar{l}_j) x_{ij}, \qquad \forall i \in I, \forall j \in J \tag{5f}$$

$$z_i \le c^m y_i \qquad \forall i \in I \tag{5g}$$

$$n_{ij} \in \mathbb{Z}_+, \qquad \forall i \in I, \forall j \in J \tag{5h}$$

$$z_{ij} \in \mathbb{R}_+, \qquad \forall i \in I, \forall j \in J \tag{5i}$$

$$z_i \in \mathbb{R}_+, \qquad \forall i \in I \tag{5j}$$

Constraints (5a) ensure that only when there is an active assignment between station i and region j that snow trucks can be dispatched to its assigned region, where Q is a parameter taking a relatively large integer value. Constraints (5b) and (5c) ensure that the sum of station-to-region trucks (de-icing materials) should not exceed the total number(amount) of trucks(de-icing materials). Travel costs for each assignment are computed in constraints (5d), where o_{ij} represents the distance from the station i to the centroid of service region j, and l_j is the aggregate measure of the freight road length in region j. The travel distance is converted to travel cost including fuel cost and vehicle depreciation cost by the parameter γ. Constraints (5e) computes the unplowed snow in each service region, that is, the difference between the total demand (road lane-mile l_j multiplied by snowfall in inch (D_j)) and the snow removal capacity allocated to region j is the unplowed snow amount (the RHS of the equation). The parameter q represents the snow removal capability of a snow truck in the unit of lane-mile-inch. Constraints (5f) ensure that the de-icing materials allocated to service region j are enough for melting and de-icing operations, which is in practice mostly determined by the lane-mile covered by the snow trucks. The parameter u converts the lane-mile to the amount of deicing materials. Station capacity for materials is enforced in constraints (5g). The rest constraints are variable definitions. The objective function computes the sum of three terms: transportation cost, cost for purchasing deicing material, and penalty cost for unplowed lane-miles, with each of them multiplied by the probability mass q^k for the corresponding scenario. Therefore, the second-stage problem is to minimize the total operation cost.

Note there are two problems need to be addressed in the above formulation. Firstly, in the second-stage optimization problem the computed total cost is amortized to one snowfall event. In order to align with the first-stage's capital cost, we will introduce a variable parameter m that denotes the snowfall events that could happen in a year. Sensitivity analysis on the parameter is carried out in the result section. Secondly, (5f) in the second-stage problem contains a multiplication of two decisions variables, which need to be linearized. We propose to linearize the corresponding constraint as follows by introducing a big-M type parameter:

$$z_{ij} \geq u(l_j - \bar{l}_j) - (1 - x_{ij})M, \qquad \forall i \in \mathbf{I}, \forall j \in \mathbf{J}.$$

If the task of plowing snow in region j is assigned to a snow trucks station i, x_{ij} takes the value of 1 which makes the RHS of the above equation $u(l_j - \bar{l}_j)$; otherwise, z_{ij} takes the value of zero due to its non-negativity constraint.

The two-stage stochastic formulated problem can be solved using the Benders Decomposition method typically adopted in the literature for solving the this class of problem. For this particular case, since the complete problem is MILP we can directly combine the two stages into one complete problem, which is presented in the following subsection and can directly solve it with the help of optimization solvers.

Optimization Problem

The complete optimization model is presented as follow, which is the main problem we deal with. The results return the optimal locations of snow trucks stations, the number of snow-plow trucks to be assigned to each station and their service zone assignment, and the number of de-icing materials to be purchased for each snow truck station.

$$
\begin{aligned}
\text{minimize} \quad & \sum_{i\in I} e_i y_i + f \sum_{i\in I}\sum_{j\in J} n_{ij} + && && (6)\\
& m \sum_{k\in K} q^k \Big(\sum_{i\in I}\sum_{j\in J} s_{ij}^k + h \sum_{i\in I}\sum_{j\in J} z_{ij} + \rho \mathbf{V}^{\mathbf{t}}\bar{\mathbf{I}}^{\mathbf{k}} \Big) && && \\
\text{subject to} \quad & \sum_{i\in I} x_{ij} = 1, && \forall j \in J && (6a)\\
& x_{ij} \le y_i, && \forall i \in I, \forall j \in J && (6b)\\
& n_{ij} \le Q x_{ij}, && \forall i \in I, \forall j \in J && (6c)\\
& s_{ij} \ge \gamma o_{ij} n_{ij} + \gamma l_j x_{ij}, && \forall i \in I, \forall j \in J && (6d)\\
& \sum_{i\in I} x_{ij} l_j D_j - \sum_{i\in I} q n_{ij} \le D_j \bar{l}_j, && \forall j \in J && (6e)\\
& z_{ij} \ge u(l_j - \bar{l}_j) - (1 - x_{ij}) M && \forall i \in I, \forall j \in J && (6f)\\
& \sum_{j\in J} n_{ij} \le c_i y_i, && \forall i \in I && (6g)\\
& \sum_{j\in J} z_{ij} \le c^m y_i, && \forall i \in I && (6h)\\
& n_{ij} \in \mathbb{Z}_+, && \forall i \in I, \forall j \in J && (6i)\\
& z_{ij} \in \mathbb{R}_+, && \forall i \in I, \forall j \in J && (6j)\\
& y_i \in \{0, 1\}, && \forall i \in I && (6k)\\
& x_{ij} \in \{0, 1\}, && \forall i \in I, \forall j \in J && (6l)
\end{aligned}
$$

Notations

We documented the aforementioned parameters and decisions variables in the following table for the convenience of reference.

Table 8: Notations

		<u>Parameters</u>
e_i	$\triangleq$	Capital cost of setting up a snow truck station at candidate location i
f	$\triangleq$	Unit cost of purchasing/placing a snow truck
h	$\triangleq$	Unit cost of purchasing deicing materials
c_i	$\triangleq$	Capacity at location i for snow trucks
c_i^m	$\triangleq$	Capacity at location i for deicing materials
Q, M	$\triangleq$	A large positive integer number
c_i	$\triangleq$	Capacity at location i for snow trucks
o_{ij}	$\triangleq$	Distance from location i to the centroid of region j
l_i	$\triangleq$	Total road length in region j
D_j	$\triangleq$	Snowfall forecast for region j
γ	$\triangleq$	Travel cost parameter, converting travel distance to travel cost
q	$\triangleq$	maximum snow-plowing capability of a snow truck
$\mathbf{V}$	$\triangleq$	Vector of heavy commercial vehicles' Vehicle Miles Traveled(VMT) of all regions
ρ	$\triangleq$	Weighting parameter
q^k	$\triangleq$	The probability that scenario k occurs
m	$\triangleq$	The number of predicted snowfall events in a year
		<u>Decision Variables</u>
y_i	$\triangleq$	Whether to set up a snow truck station at candidate location i, binary variable
x_{ij}	$\triangleq$	Whether to assign snow trucks in location i to plow region j, binary variable
n_i	$\triangleq$	Number of snow trucks to be purchased for each station i, integer variable
n_{ij}	$\triangleq$	Number of snow trucks at facility i assigned to plow region j
z_i	$\triangleq$	Amount of deicing materials to be purchased for each station i, continuous variable
z_{ij}	$\triangleq$	Amount of deicing materials at facility i to be used for plowing region j
s_{ij}	$\triangleq$	Travel cost for the assignment of using station i's trucks to plow region j's roads
$\bar{\mathbf{l}}$	$\triangleq$	Vector of unplowed lane-miles for all regions

6 Case Study

Problem background

The state of Minnesota is a state who experiences long winter with annual average snowfall around 80-100 inches per year. In the winter of 2018-2019, the statewide snowfall average was 97.2 inches. Winter road maintenance, and especially snow plow and deicing is an critical responsibility for the state DOT. MNDOT currently plows a total of 30,426 lane-miles of road, operating more then 150 truck stations and over 800 snow plow trucks. The total cost for the winter of 2018-2019 amouted more than 133 million dollars. Any improvement of the current snow plow planning or operational strategy can greatly benefit the transportation agency. Therefore, we use the real network of Minnesota as a case study.

We chose the currently existing 156 stations across the state to be the candidate locations of the snow truck facilities. Figure 11 shows IDs and locations of these candidate locations. In the same map, the boundary of each of 87 counties were shown as well. These 87 counties were used as analysis zones (service regions). In the following case study, we set some restrictions on the task assignment variable (x_{ij}'s). That is, if the distance between the centroid of a service region and a potential snow truck station is over a given threshold, the snow plow task between the pair is disabled. This provides three advantages. First, this can significantly reduce the problem size because all the variables (including x, z, and n) for such a pair can be pruned beforehand. Second, from the operational perspective, it will not be practical to route trucks at a station to a service region that locates far away from it. The incurred transportation cost would be high and the snow-plow operations would not be timely either. Third, this gives the convenience of modeling snowfall events in that we can treat snowfall events across the state that happened in different times as if they had happened at the same time. In this case study, we use 50 mile as the threshold.

Parameters used in the case study is documented in Table 9. Capital costs for a snow truck stations were obtained from their insured value and a 50-year life cycle was assumed for all these stations. We converted the total capital cost to annual average cost. Their annual average cost range from $2,931 to $708,741 with the average being 83,608 and standard deviation 140,245. The capacities of these snow truck stations were estimated from the area of each facility. They range from 5 to 120 with an average of 25. The cost of a snow-plow truck is estimated to be around $200,000 and a life-cycle of 10 years was assumed leading to average cost of $20,000. The cost of the deicing materials per ton is estimated to be $75.0, which mainly includes the cost of salt and sand. The consumption of the de-icing materials is estimated to be 25 gallons per lane-mile. Transportation cost of snow trucks is assumed to be $ 20.0 per mile, which includes vehicle depreciation cost and fuel cost. The snow plow capability of a standard snow truck is 500 lane-mile-inch. Economic loss for per unplowed lane-mile was estimated to be around $100.0.

To incorporate snowplowing operation priority into the analysis, we used total vehicle miles traveled summarized by each county to reflect the relative urgency of plowing snow in one service region relative to others. In the following computational results, we weighted their relative importance using both heavy commercial vehicle miles traveled (HCVMT) and vehicles mile travelled (VMT) for all vehicles on the interstate, state and trunk highways. Based on either measure of VMT, 87 zones were classified into three priority levels, with 1 being the lowest, 2 being medium and 3 being the highest level. The number of service regions were made roughly equal for each priority level. See Figure 12 and Figure 13 for their priority level. This is essential the same measure of priority as was carried out using AADT in

Table 9: Parameter values used for preliminary tests

Parameter	Value
e	Insured value amortized with 50 years, data from MNDOT
f	20,000 (\$) (10 years of usage assumed)
h	75.00 (\$)
γ	20.00 (\$)
q	500 (lane-mile-inch)
V	{1, 4, 9}
ρ	100.0

Section 4.4, but this is summarized by service zone and to make them additive, VMT instead AADT is used to reflect the relative importance. In these experiments, the parameter V for each region is determined by its priority level: the relative importance is proportional to the square of its priority level. That is, the importance of a zone of priority level 3 is 9 times as large as the importance of priority-1 level zone. Similarly, the importance of a zone of priority level 2 is 4 times as large as the importance of priority-1 level zone.

Snowfall demand generation

According to the historical climate data for the state of Minnesota from 1980-2010 at 22 climate stations (see Table 4 and Table 5 for examples), we generated two data sets. The first data set was generated using the historical average snowfall data in January across all 22 climate stations. Each station has an average snowfall amount and variance snowfall amount. Based on the mean and variance-covariance matrix we generated 10 scenarios drawing from the corresponding multi-variate normal distribution. Refer to Figure 3 for the monthly average snowfall prediction for the entire state using the kriging method. The second data set was generated using the historical one-day maximum snowfall data, which represents the extreme cases that could happen in reality. In this case, only one scenario is used which is the one-day max amount of snowfall in record. Optimal solutions obtained by using this data set corresponds to planning for extreme snowfall events with extra snowplowing capability.

Computational results

We present the computational results applied on the state of Minnesota in this section. Results for average snowfall events using the first data set and for extreme snowfall events using the second data set were discussed separately. All MILP problems were solved using the commercial optimization solver GUROBI 8.1.1 running on a personal computer with Intel Core i5-4590S with 16GB of RAM.

Planning for average snowfall events

In Table 10, we documented computational-related information and optimal decisions varying the total number of snowfall events within a calendar year. The objective value, the total cost including captial and operational cost, monotonically increases with the increase of snowfall events. The same increasing pattern holds for the number of opened snow truck stations. However, even though the total number of snow trucks generally increases, the numbers are relatively rather stable ranging from 359 to 384. The maximum increase is only 15.6% from the case where $m = 10$ to $m = 50$. In contrast, the increase of total cost and number of facilities are 208.90% and 86.20%, respectively.

The drastic increase of snow truck stations and total cost compared with relatively stable number of snow trucks indicates that operational costs increases significantly when there are more snow events. By opening more snow truck stations, the system can get benefits from saving operational cost related to transportation and unplowed road incurred economic loss even though the capital cost increases. In order to validate this, we computed the percentage of capital cost in the total cost for $m = 10$ and $m = 50$. The capital cost was $5,786,833 and $7,426,927, respectively, and weighs 43.48% and 18.07% in the corresponding total cost. In addition, we computed the average travel distance from a station to the centroids of service zones that each station is responsible for. For the case $m = 50$, the average travel distance is 14.46 miles, while it is 25.35 miles for the case $m = 10$. Therefore, opening more snow truck stations is helpful in making savings on operational costs. This is also reflected by the reduced unplowed snowfall amount. When there are fewer snow truck stations, routing snow trucks to certain service regions can be costly and thus more lane-miles are left unplowed.

Number of snowfall events annually m	**Objective Value ($)**	**# of opened snow truck stations**	**# of snow trucks**	**Total unplowed lane-miles**	**Computational time (s)**	**MIP Gap (%)**
10	13,308,471	29	269	1566.37	2819.94	0.82
15	17,034,541	32	276	1395.82	4029.00	0.94
20	20,502,322	36	288	557.16	3106.03	0.20
25	23,990,045	42	294	402.70	3045.94	0.08
30	27,446,689	43	296	357.38	2108.72	0.01
35	30,898,737	45	298	323.94	1633.51	0.03
40	34,521,356	51	305	433.67	1302.36	0.05
45	37,844,770	50	304	296.59	1164.10	0.34
50	41,109,707	54	311	278.42	854.55	0.03

Table 10: Computational results of the planning for average snowfall using HCVMT for priority

We present the detailed optimal solutions for the case $m = 30$. In this case, 43 out of 156 candidate stations were selected to open, with a total number of 296 snow trucks to be placed at these 43 stations. The total cost is over 27 million U.S. dollars, unplowed lane-mile is around 296 that accounts for around 1% of the total lane-mile that MNDOT is responsible for. The capital cost is 6,722,493 accounting for 24% of the total cost. On average, each snow truck is in charge of snow plow operations for 2.02 service zones. Snow truck station 9 (locates in county 57, see Figure 11) is in charge of the most number of service regions. Its 5 services regions are 45, 46, 49, 50, and 52. In Figure 5, selected stations are marked and their optimal task assignments are denoted by solid blue lines. From the figure, service zones that are generally served by stations that are geographically close to them and if a stations services more than one regions, these regions are also geographically clustered together. We want to know how much capacity of the opened snow truck stations is actually used by snow trucks. Therefore, we computed the capacity utilization rate that is defined by the ratio of the the number of snow truck at one station to the capacity of the station. The capacity utilization ranges from 13.33% to 100% in this case with an average utilization rate of 56.31%.

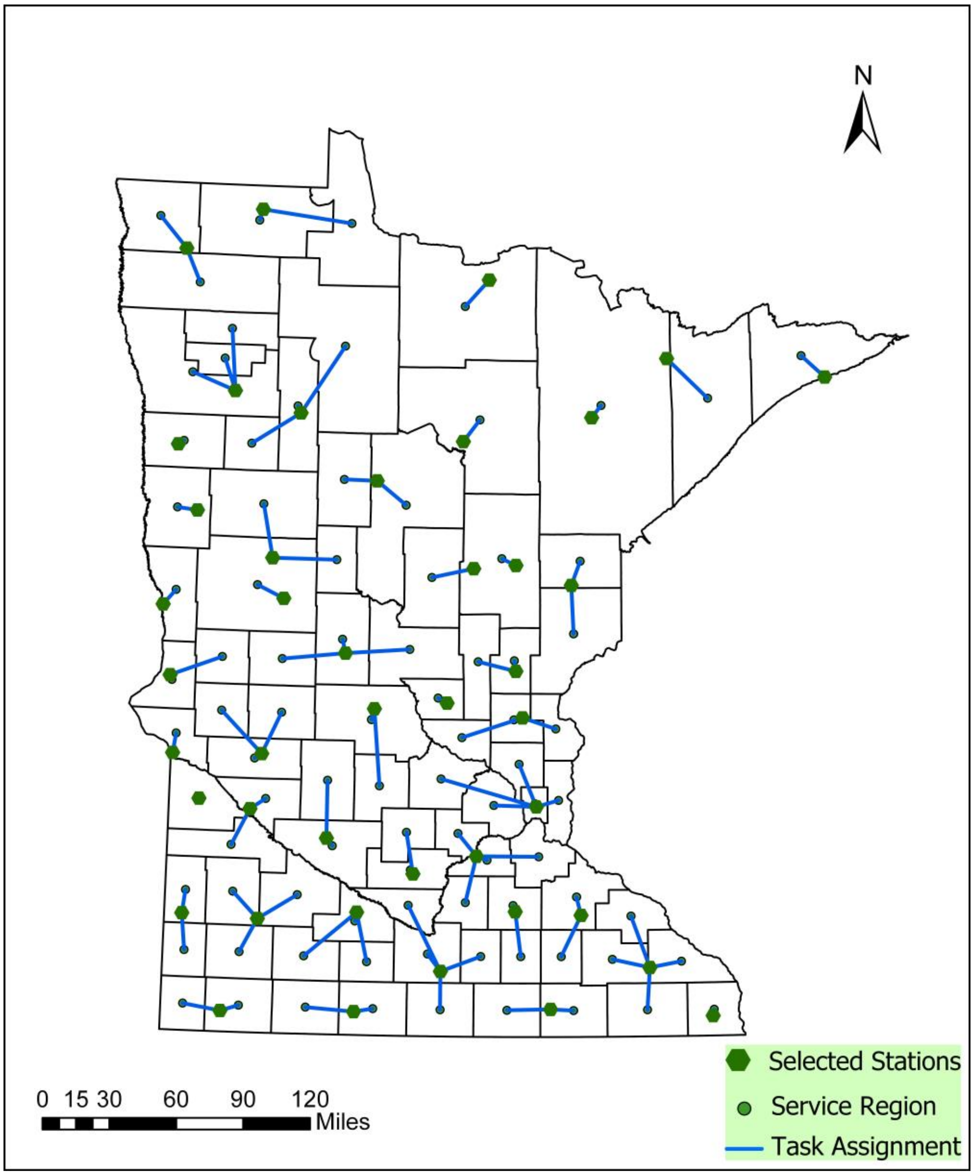

Figure 5: Optimal stations and snow plow task assignment for average snowfall using HCVMT for priority

Using the priority levels derived by VMT for all vehicles, we repeated the experiments whose results are documented in Table 11. The trends are much like the previous set of experiments: increasing total cost and snow truck stations, generally decreasing unplowed lane-miles, and relatively stable number of total snow trucks. The reason for these trends are the same as the aforementioned. For m = 10 and m = 50, the capital cost is $5,790,615 and $7,321,494, respectively, and accounts for 43.14% and 17.68% in the total cost. The average travel distance from a snow truck station to its corresponding service region is 25.86 and 14.38 miles, respectively.

Number of snowfall events annually m	**Objective Value ($)**	**# of opened snow truck stations**	**# of snow trucks**	**Total unplowed lane-miles**	**Computational time (s)**	**MIP Gap (%)**
10	13,422,054	32	272	2770.82	3297.02	0.85
15	17,109,574	33	279	1321.98	4451.04	0.57
20	20,761,034	37	293	1204.41	3417.14	0.71
25	24,211,962	39	297	889.67	2701.99	0.26
30	27,467,821	45	294	305.62	1950.41	0.10
35	31,146,693	45	304	493.90	1640.58	0.07
40	34,511,126	48	309	313.89	1220.26	0.04
45	38,234,111	52	320	379.63	850.35	0.73
50	41,394,260	52	320	244.98	668.32	0.13

Table 11: Computational results of the planning for average snowfall using VMT for priority

We present the detailed optimal solutions for the case m = 30. In this case, 45 out of 156 candidate stations were selected to open, with a total number of 300 snow trucks to be stored at these 45 stations. Capital cost is $6,716,691 accounting for 24.45% of the total annual cost. The total cost is over 27 million U.S. dollars, unplowed lane-mile is around 305.62 that accounts for 1% of the total lane-mile. On average, each snow truck is in charge of snow plow operations for 1.93 service zones. Snow truck station 19 (locates in county 58, see Figure 11) and station 121 (locates in county 8) are both in charge of the most number of service regions. Their 5 services regions are 54, 58, 59, 64, 65 and 8, 9, 12, 13, 16. The capacity utilization ranges from 20.00% to 100.00% in this case with an average utilization rate of 60.02%.

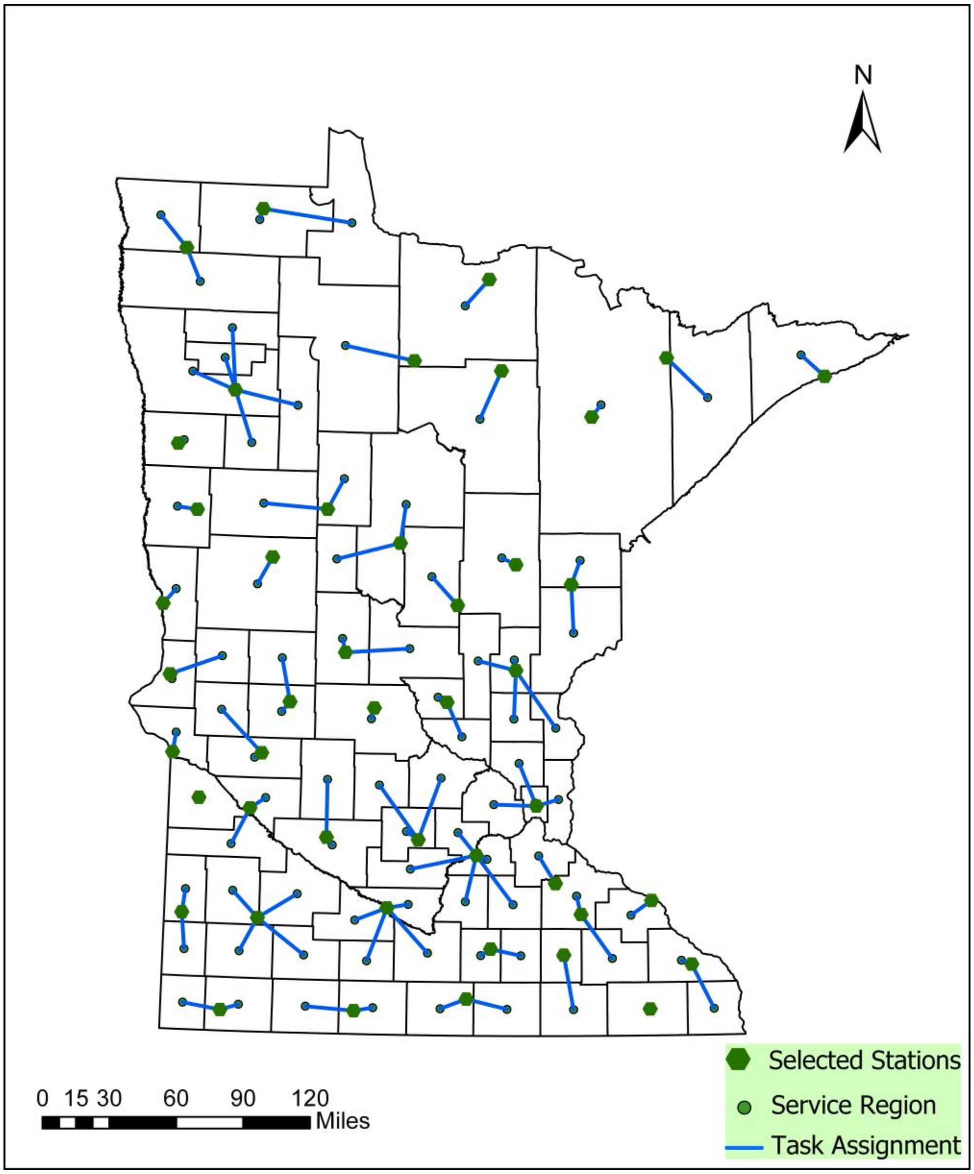

Figure 6: Optimal stations and snow plow task assignment for average snowfall using VMT for priority

Comparing the results of HCVMT and VMT priority classes

Comparing the results with HCVMT and VMT priority class for $m = 30$, their total costs are roughly the same. With around 295 snow trucks, they are capable of covering 99% of the road network in terms of lane-mile in the state of Minnesota. There are 43 opened stations with HCVMT priority class, and 45 with VMT priority class. Among these stations, 30 are common to both of them. One reason for this high similarity is that there is a high positive correlation between total VMT and HCVMT by service regions. One can see this by comparing Figure 12 and Figure 13 and note that the priority classifications for the two are rather similar even though they are based on different measures. Table 12 records the comparison details.

	HCVMT	VMT
# of stations	43	45
# of trucks	296	294
Total unplowed road (lane-mile)	357.38	305.62
Total cost ($)	27,446,689	27,467,821
Operational cost percentage (%)	76.00	75.55
Station capacity utilization (%)	56.31	60.02
Average distance between station and service region (mile)	18.62	15.97

Table 12: Comparison of the results for HCVMT and VMT priority class

Planning for extreme snowfall events

Using the historical one-day max snowfall data, we generated one extreme snowfall event across the entire state. Besides, for the experiments, we set m to 15. They were carried out with both HCVMT and VMT priority classes. For the HCVMT priority class, each opened station is in charge of 1.61 service regions on average. Station 66 has the most number of service regions that are 75, 76, 77, and 87 (see Figure 7). For the VMT case, the average ratio of service regions to stations is 1.59. The unplowed lane-miles for the VMT case doubled the number for the HCVMT case. Other than this, the number of stations, trucks, station capacity utilization, average distance between station and its service regions, and the total cost for the two cases are rather comparable (Table 13).

	HCVMT	VMT
# of stations	54	53
# of trucks	475	474
Total unplowed road (lane-mile)	506.30	1130.34
Total cost ($)	24,573,368	24,645,509
Capital cost	10,682,820	10,659,870
Operational cost percentage (%)	56.52	56.74
Station capacity utilization (%)	67.84	68.1
Average distance between station and service region (mile)	15.07	15.16

Table 13: Results for planning for extreme snowfall events

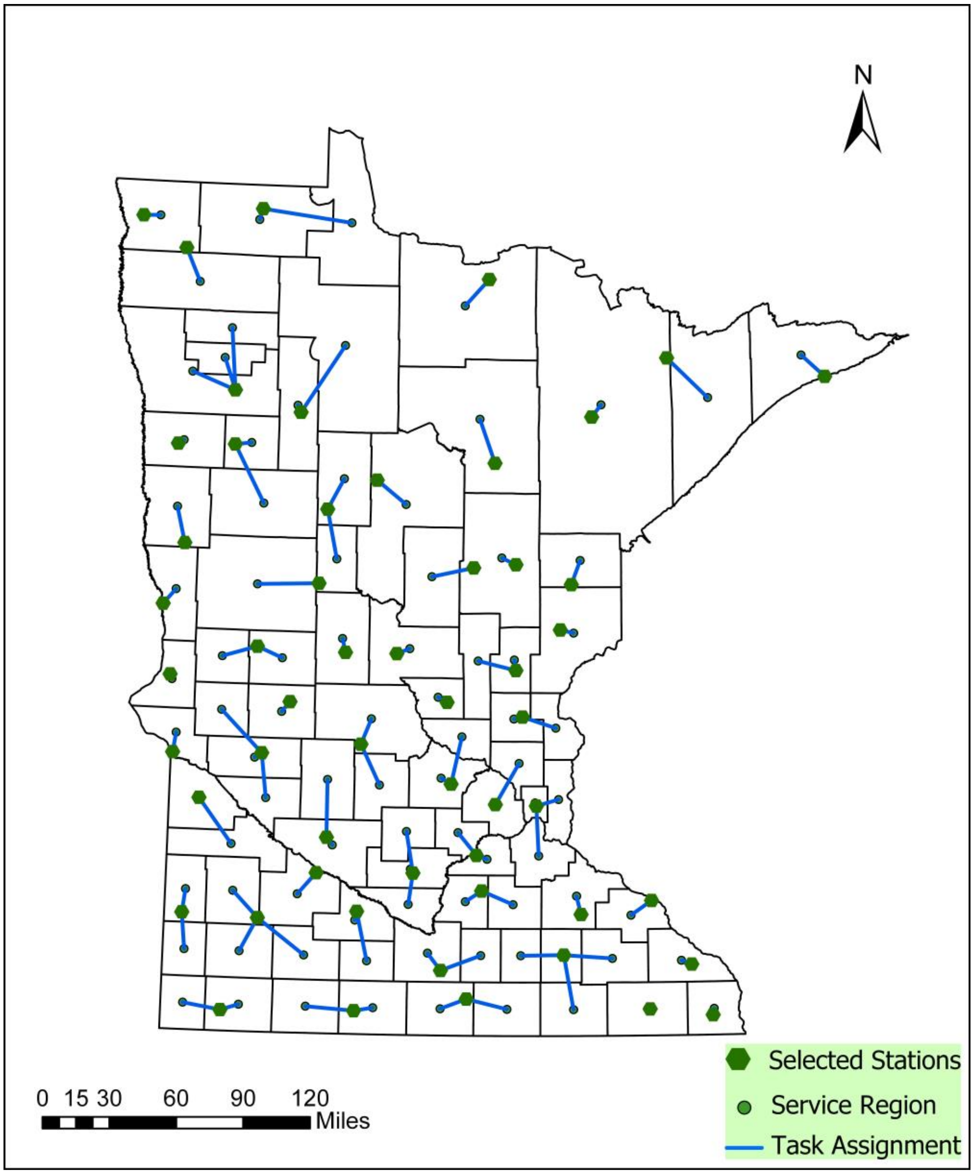

Figure 7: Optimal stations and snow plow task assignment for extreme snowfall using HCVMT for priority

Comparison of the planning for average and extreme snowfall

We compared the planning and operational decisions for extreme and average snowfall events using the HCVMT priority class. We selected two cases for the average snowfall case, $m = 15$ and $m = 30$. With $m = 15$, we can comparatively see how snowfall intensity affects the optimal decisions. The case $m = 30$ was selected because it resulted in roughly the same total cost as the planning for the extreme snowfall events. The number of truck stations, snow trucks, and the total cost were shown in the histogram in Figure 8.

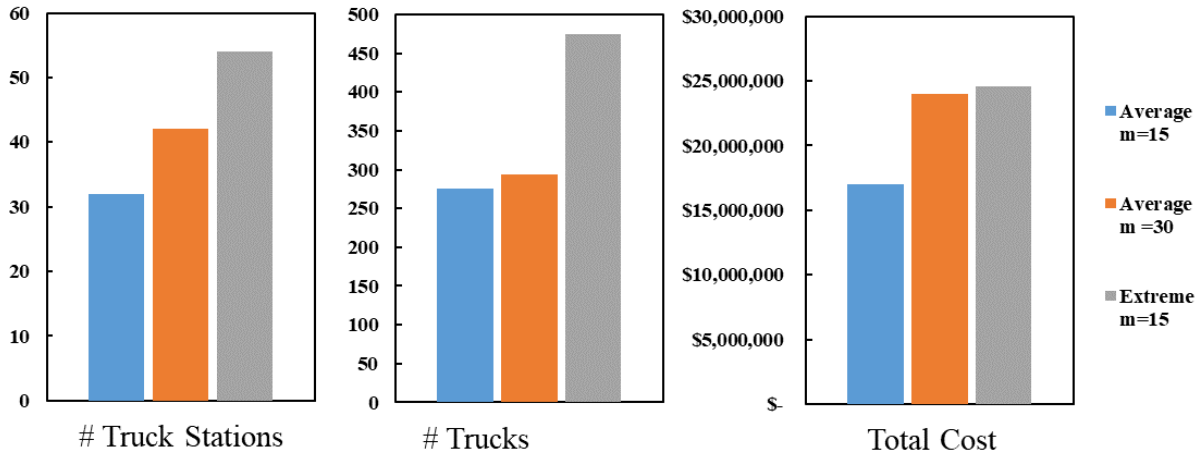

Figure 8: Optimal decisions and optimal value comparison between extreme snowfall case and average snowfall cases

It shows that with the same number of snowfall events, it needs to open more snow truck stations and have more snow trucks to carry out the snowplow operations. Because in the extreme snowfall case, the intensity of snowfall is greater than that of an average snowfall event, more snow trucks are needed to increase the snowplowing capacity. The number of snow trucks increase from 276 to 475, which is a 72% increase. Due to the fleet-size increase, more snow trucks should be opened to accommodate these snow trucks. Another reason for the increase of truck stations is that the increasing weight of the operational cost in the total cost urges the opening of more stations so that transportation costs from truck stations to service zones can lead to some saving. The number of snow truck stations increases from 32 to 54, which is a 69% increase. The total cost for extreme snowfall events with $m = 15$ is approximately the same as that of the average snowfall case with $m = 30$. Their planning decisions (the number of stations to open and trucks to purchase) are still quite different. It suggests that there is a lack of capability for even one extreme snow event if the system is only planned for coping with normal snow events.

7 Conclusion

Winter maintenance incurs large investment and costs for Department of Transportation (DOTs) in northern states of the U.S. Snow events create safety issues, road capacity reductions, and induce economic loss for both general traffic and freight transport. However, the effect of winter maintenance operations and severe weather conditions on freight fluidity has not been adequately investigated. Therefore, the objective of this project is to build a mathematical model that helps DOTs make both long-term planning and short-term operational decisions of winter maintenance, which lead to a much more efficient snowplow system with minimum capital and operation cost.

Three major research questions related to winter maintenance were addressed in this project. First, through a thorough review of related literature, the impacts of snow events on traffic safety, travel time, road capacity, and economic development were investigated, with special emphasis on freight transport. It has been found that snow generally has a positive correlation with crash rate, reduced speed, reduced road capacity. The negative impacts on these aspects are also related to snowfall intensity. Heavy snow generally leads to more severe negative impacts. The results of the first research question not only necessitate an efficient winter maintenance plan but also show that the decision support system should account for the variable snowfall that leads to different outcomes.

Second, we identified critical corridors and regions for freight and general traffic. This task mainly involves the spatial analysis of traffic volume and travel distance. With the data of AADT of interstate and state trunk highways, we classified road segments into three priority classes based on their AADT. To prioritize winter maintenance operations on the level of zone, we also used VMT summarized by zones to categorize their priority class. As a result, critical corridors and zones for freight traffic and general traffic were identified in GIS. Third, the winter maintenance decision support system was build by setting up a mathematical optimization problem. We formulated it as a two-stage stochastic optimization problem. Involving both long-term and short-term decisions together with uncertainty in snow, the adoption of the two-stage formulation is well suited for this case. The first stage makes long-term decisions, and the second-stage makes recourse decisions that compensate for unfavorable effects that might have been made in the first stage. The objective minimizes the total costs including capital cost and operational costs as well as economic loss due to unplowed snow. The solution determines the optimal geographic locations of stations, optimal fleet-size, task assignment, truck assignment, the amount of de-icing materials, and economic loss due to insufficient snowplow capability. We applied the model to the state of Minnesota. Ten scenarios of snow events based on the historical average snowfall were generated and used as input to the model to capture the stochasticity of snow events. Another scenario based on record-high snowfall was also generated for the planning for extreme snowfall events. For the plan for average snowfall events, we found the general trend that with more annual snow events, the weight of operational cost in the total cost increases even though the capital cost related to opening new snow truck stations and purchasing snow trucks increases as well. With a typical number of snow events of 30, the total cost was estimated to be about 27.5 million dollars. 43 out of 156 stations were selected and a fleet-size of 296 is needed. Selected snow truck station capacity utilization is about 56%. On average, one station is in charge of 2.02 service regions. For the plan for extreme snowfall events, the number of stations and fleet-size is significantly larger than that of the average case. With a number of snow events of 15, 54 stations are selected to open and 475 snow trucks should be purchased, which leads to a total cost of more than 24 million dollars. Station capacity utilization is about 57%. On average, each station is in charge of 1.59 service regions.

Taking into account the uncertainty of snow events in its intensity and space, the optimal decisions obtained from the developed mathematical model are robust. The proposed decision support system could benefit DOTs from a financial perspective by reducing winter maintenance operations cost and improving the efficiency in capital investment. The implementation of the decisions obtained from the proposed mathematical model benefit the freight industry by safe and efficient freight transport in winter.

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A Appendix

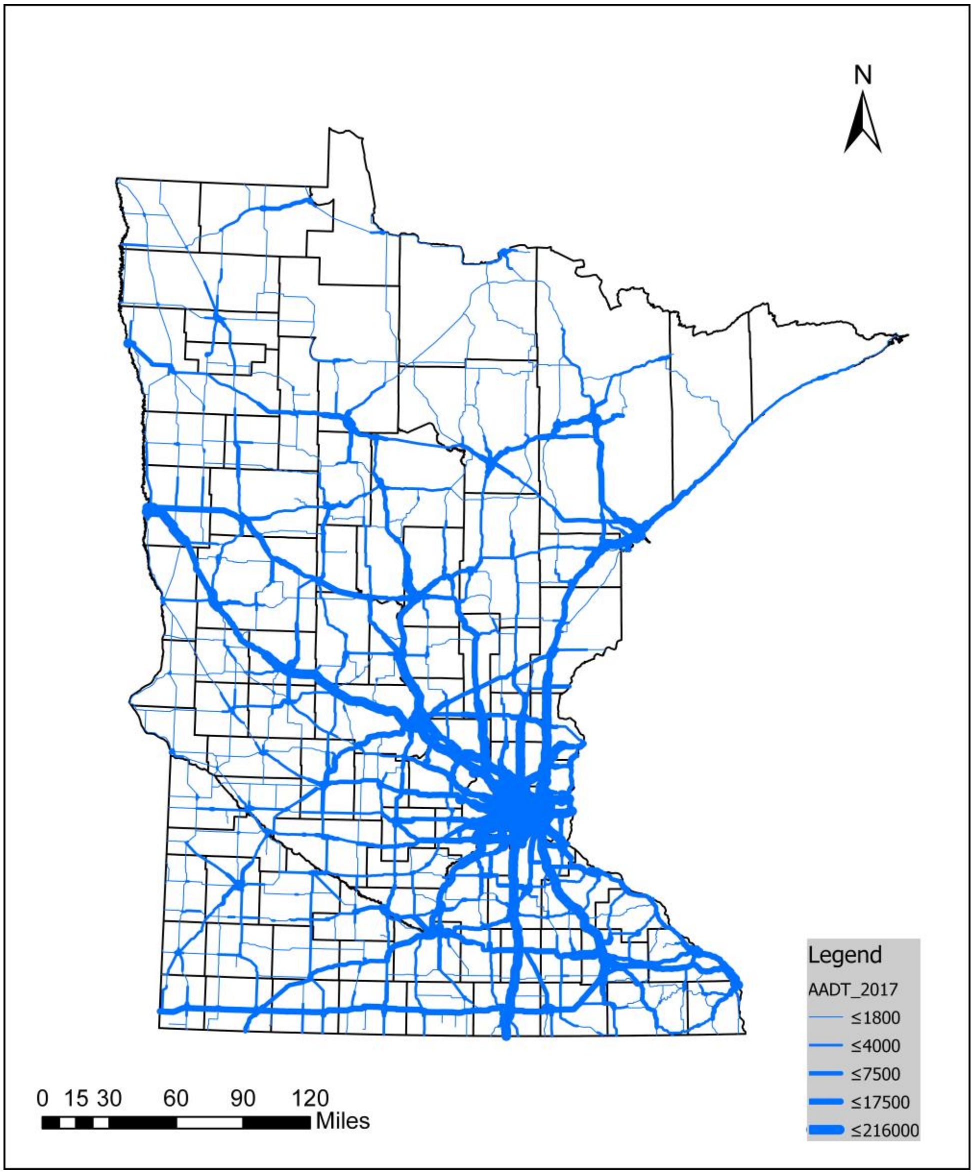

Figure 9: AADT map for interstate highway and trunk highway systems

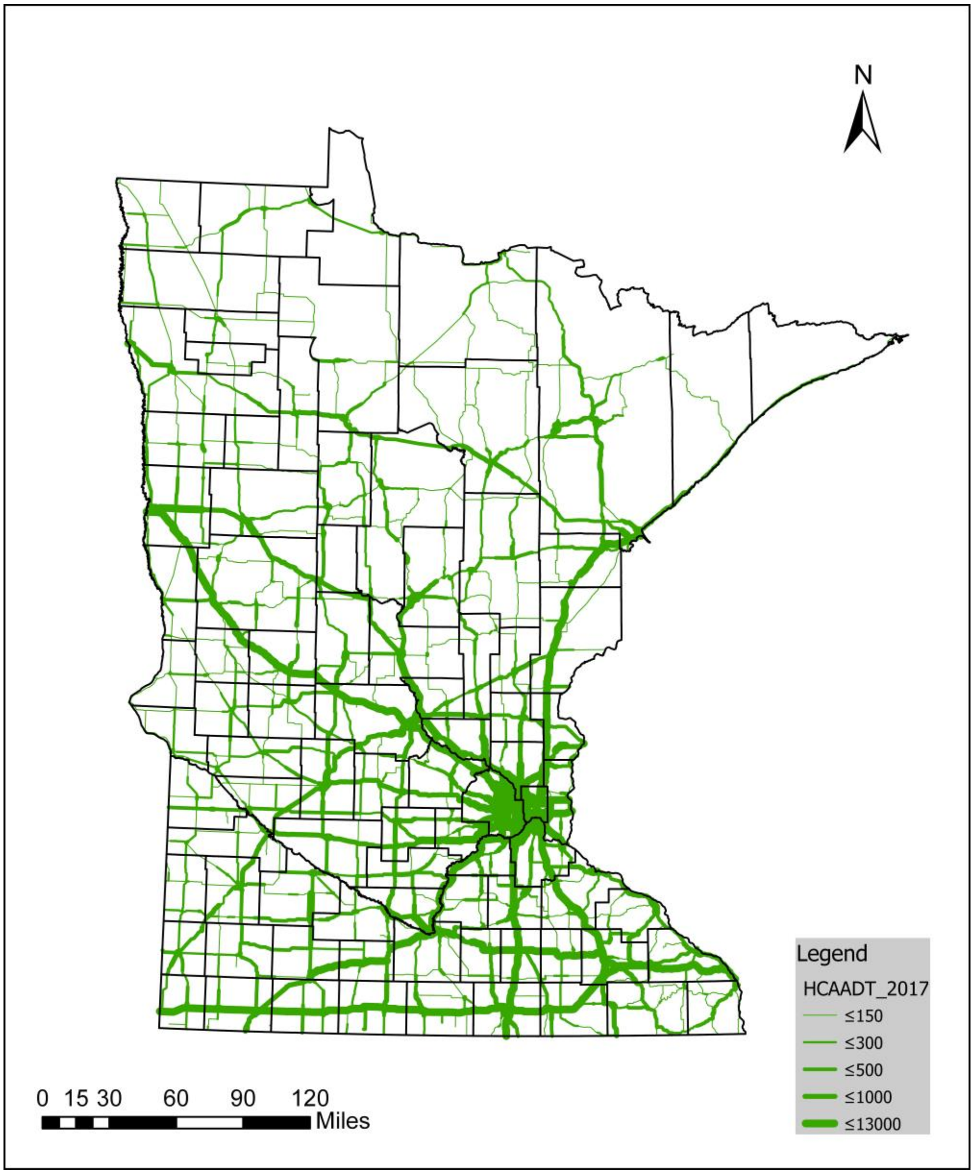

Figure 10: HCAADT map for interstate highway and trunk highway systems

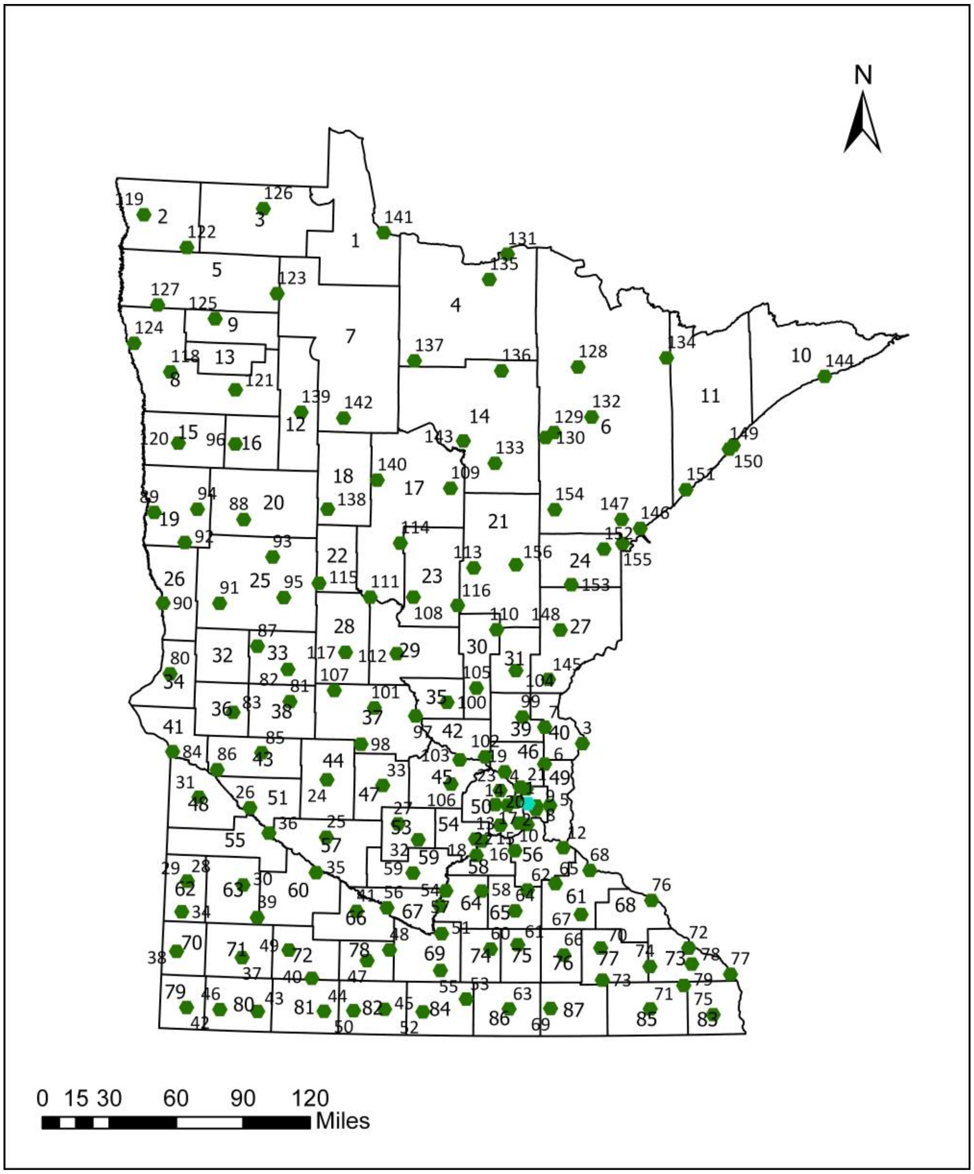

Figure 11: 156 candidate facility locations and 87 service regions in the state of Minnesota. Candidate locations are displayed by green dots with ID label. A service region is shown by its centered labeled ID and black boundary.

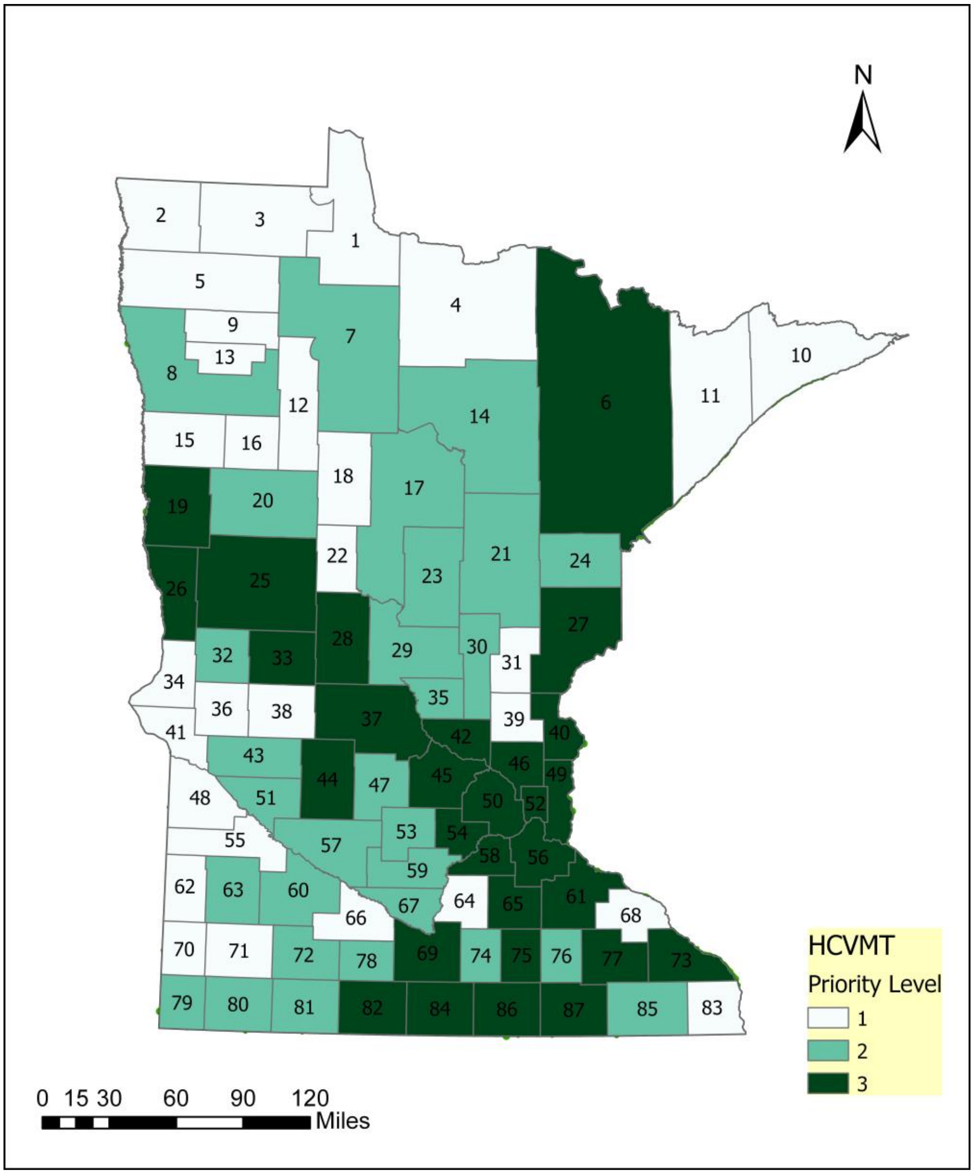

Figure 12: Service zone priority level based on heavy commercial vehicle miles traveled.

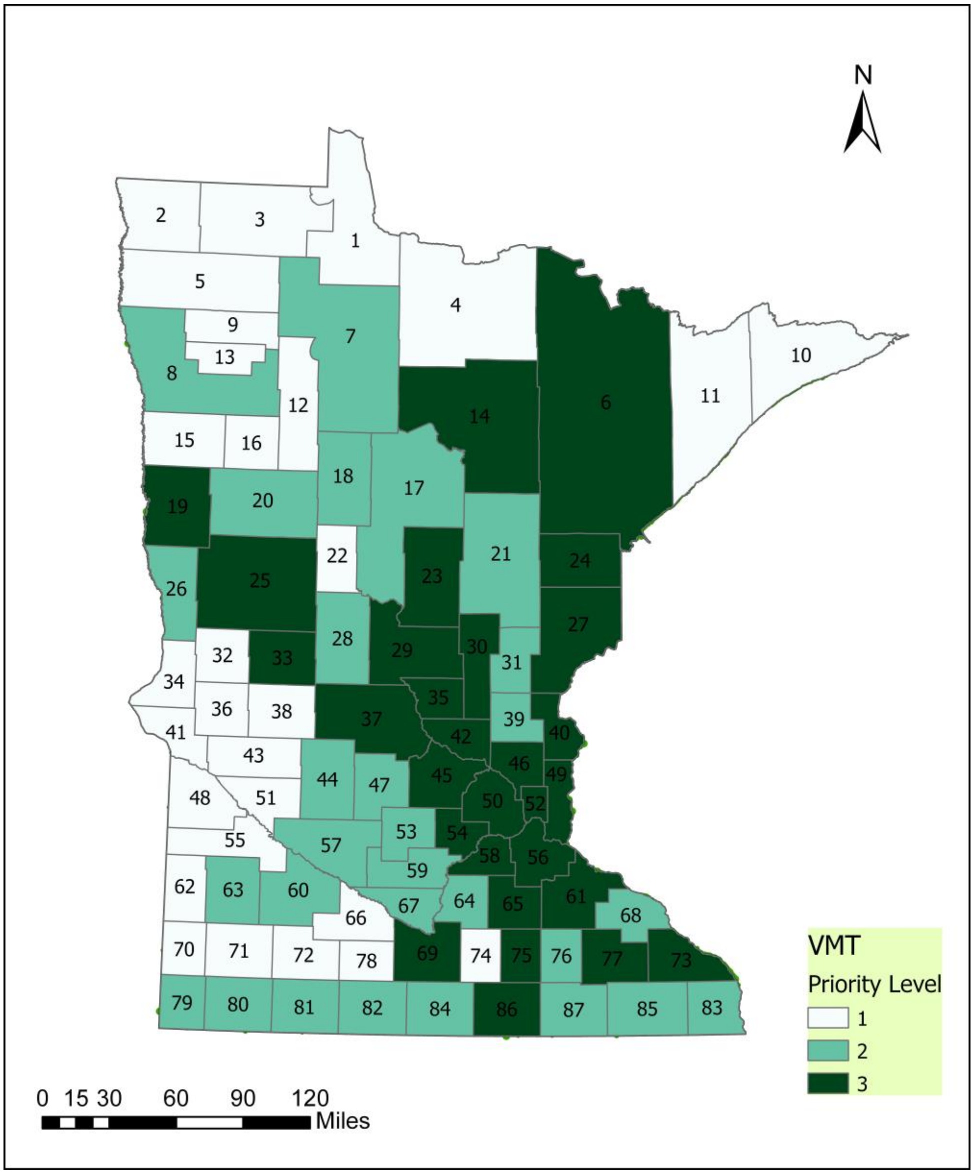

Figure 13: Service zone priority level based on all vehicles' vehicle miles traveled.