Methods for Estimating the Benefits of Winter Maintenance Operations

Requested by:

American Association of State Highway and Transportation Officials (AASHTO)

Standing Committee on Highways

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Executive Summary

Winter maintenance operations play an important role in assuring the safety of winter driving. Maintenance agencies are continually challenged to provide a high level of service (LOS) and improve safety and mobility of winter roads in a cost-effective and environmentally responsible manner. Winter highway maintenance activities offer such direct benefits to the public as fewer accidents, improved mobility, reduced travel costs, and reduced fuel usage. Indirect benefits of snow and ice control operations include: reduction in accident claims, sustained economic productivity, continued emergency services, etc. As these examples illustrate, snow and ice control operations allow agencies to keep the highway system safe, mobile, reliable, and productive during winter weather. Nonetheless, the cost of such activities is such a major outlay that it demands close scrutiny. To minimize the adverse effects of winter storms on road users and society, state and local agencies spend significant amount of resources annually performing a variety of maintenance actions. There is a need to better understand and quantitatively estimate the benefits of winter road maintenance both at the national level and at the state level.

The work presented in this report sought to establish approaches to estimating the benefits of winter highway maintenance. A literature review was completed to identify the general benefits of winter maintenance, establish which ones were quantifiable, and determine if any methodologies or approaches existed that could be transferred to this work and general agency usage. It was found that these were limited in number and developed for specific applications and not directly transferable. The benefits which could be directly quantified using existing agency data included: safety improvements (reduced crashes), travel time savings, and fuel savings. Consequently, methodologies were developed to estimate each of these benefit components. Different issues and limitations with these methodologies were identified and discussed, and subsequently future research needs were identified and presented for consideration.

To estimate safety benefits, a Negative Binomial model was established to predict the number of crashes that could be expected to occur under different winter maintenance scenarios. The changes (ideally reductions) in crashes and the financial savings as a result of improved maintenance represent the benefits of winter maintenance on safety.

Travel time savings resulting from differences in travel speeds over road segments under different levels of winter maintenance were established as the method to estimate the second category of quantifiable benefits of winter maintenance. Once again, improved travel speeds on road segments where higher levels of winter maintenance were performed represent financial savings; in this case, through reductions in road user delay and in lost productivity.

Finally, the differences between vehicle fuel usage under storm conditions where maintenance is or is not preformed were established to estimate the fuel savings, the third category of quantifiable benefits of winter maintenance. This method is based on the concept that vehicle mileage per gallon (MPG) will decrease on roads with limited winter maintenance performed, whereas it will increase as the level of winter maintenance is increased. The differences between these levels of fuel usage can be used to estimate the financial savings in fuel usage accrued through winter maintenance.

Using 2001-06 winter season data from the Minnesota Department of Transportation (DOT) as a case study and following the above mentioned methodologies, the researchers estimated the quantified benefits of winter highway maintenance by the Minnesota DOT to be $201,656,553 per winter season. This represents a significant benefit. A review of each of the individual estimations is in order.

When analyzing safety benefits, it was found that the expected number of crashes that would have occurred had no winter maintenance been performed was 20,275, compared with the 15,675 that were actually observed under the Minnesota DOT maintenance conditions. This difference of 4,600 crashes, when multiplied by an average crash cost of $36,453 for Minnesota, indicated that winter maintenance activities on the entire highway system of Minnesota produced a financial savings of $167,683,800. This figure clearly indicates that winter maintenance produces a considerable benefit from reduced crashes, both financially, and to society as a whole.

The benefits of improved travel times from winter maintenance were estimated by comparing expected vehicle speeds under pavement conditions without winter maintenance performed to those where maintenance resulted in a prevailing pavement surface condition of "lightly slushy" (the most frequently observed condition in the available data). Results of calculations indicated that, for the 828 route segments, a benefit of $10,915,699 in travel time savings was achieved. This lower figure (relative to the value of safety benefits), was in part attributable to the difficulty in quantifying the extent of lost time of motorists because of different road conditions. Still, this figure illustrates that winter maintenance has a positive benefit on reducing delay to motorists.

The final benefit of winter maintenance that was quantified was fuel savings. For this estimate, fuel usage differences were compared between conditions where winter maintenance had been performed to those where only no (or very little) winter maintenance had been conducted. This approach to estimation was based on the logic that one would expect vehicle fuel efficiency (in MPG) to decrease under poorer road conditions where limited maintenance is performed. Estimation results found there is a substantial difference in the amount of fuel used and the resulting cost of that fuel between conditions where winter maintenance is and is not used. This is particularly true for passenger vehicles. The same applies to trucks, albeit to a lesser extent, given the lower number of vehicle miles traveled each day by this type. While developed on an assumed basis, the cumulative fuel savings of $41,057,063 for the 2005-06 winter season indicate that winter maintenance produces significant benefits via reduced fuel usage. Note that in reality the level of winter highway service is generally better than the worst-case scenario and the actual fuel savings of improved winter maintenance operations are thus lower than the numbers shown above.

The methodology illustrated in the Minnesota case study could be easily adopted by other states or local agencies, even though the stated assumptions may need to be modified to reflect the specific situation. In light of the data gaps identified in this study, this work also helps to shed light on data elements needed to enable a reliable cost-benefit analysis for winter maintenance operations by a specific agency or region. Another note of caution is that there are intangible benefits of winter maintenance operations, which could be substantial yet are difficult to quantify in monetary terms.

CHAPTER 1

Introduction

Purpose of Research

Winter maintenance operations play an important role in assuring the safety of winter driving. The United States spends $2.3 billion annually to keep highways clear of snow and ice; in Canada, more than $1 billion is spent annually on winter highway maintenance (*1*). Maintenance agencies are continually challenged to provide a high level of service (LOS) and improve safety and mobility of winter roads in a cost-effective manner while minimizing corrosion and other adverse effects to the environment. To this end, it is desirable to use the most recent advances in the application of anti-icing and deicing materials, winter maintenance equipment and sensor technologies, and road weather information systems (RWIS) as well as other decision support systems. Such best practices have been observed or are expected to produce significant quantitative and qualitative benefits, including improved effectiveness and efficiency of winter operations, optimized material usage, and reduced annual spending, corrosion and environmental impacts.

Winter highway maintenance activities offer such direct benefits to the public as fewer accidents, improved mobility, reduced travel costs, and reduced fuel use. In the state of Washington, it was found that "crash frequency in the presence of snow was five times the rate under clear conditions". A comparison of crash rates between winter and summer revealed that the month of January had 12 times the accidents as July (*2*). In addition, for Washington State, it was found that 8% of the accidents that resulted in injury or fatality during a five-year period (1991 to 1996) occurred on snowy, icy roads (*3*). In a case study in Iowa, it was found that during severe winter weather events, accidents increased by 1,300 percent and traffic volume decreased by 29 percent on a roadway segment 30 miles long (*4*). While this 30-mile segment is not representative of all winter roadways, the observations generally arrive at a similar trend of increasing accidents and decreasing average daily traffic volumes in the presence of snow and ice. Winter storms are also costly to the traveling public in terms of fuel economy. Studies in both Canada and the U.S. show that on average, winter driving requires 33% more fuel (*5*). Fuel economy decreases with colder temperatures, slick roads, and snow buildup on vehicles, especially around tires. It is estimated that a short winter trip may consume 50% more fuel than the identical trip driven in the summer (*6*).

Indirect benefits of snow and ice control operations include: reduction in accident claims, sustained economic productivity, continued emergency services, etc. In one study, it was found that costs associated with accidents decreased by 88 percent after deicing salts were applied (*7*). Investing in clear roads is essential and beneficial to the public as well as the economy, since the U.S. and Canadian economies cannot afford the risk of shutting down highways during winter storms. Society has grown accustomed to year-round travel on "bare pavement" conditions, and the economy relies on it. The cost of road closure is far greater than the cost of winter highway maintenance activities. From one economic study, it was found that "failure to get snowplows out and salt on the roads during a single day of a winter storm costs almost three times more in lost wages than the total annual costs for snowfighting" (*8*). An example of a winter storm hindering the U.S. economy occurred in 1996 when a blizzard shut down much of the northeastern U.S. for four days. The loss in production was estimated to be approximately $10 billion and the loss in sales was estimated to be $7 billion (*8*). Even these values do not account for accidents, injuries or other associated costs.

As these examples illustrate, snow and ice control operations allow maintenance agencies to keep the highway system safe, mobile, reliable, and productive. Nonetheless, the cost of such activities is such a major outlay that it demands close scrutiny. To minimize the adverse effects of winter storms on road users and society, state and local agencies spend significant amount of resources annually performing a variety of maintenance actions. In addition, we have known for a half century about the negative impact of snow and ice control materials (especially chemical deicers) on motor vehicles, transportation infrastructure, and the environment. While improvements in all these areas have been implemented, the benefits of these improvements are difficult to quantify effectively. There is a need to better understand and quantitatively assess the benefits of winter road maintenance relative to costs, both at the national level and at the state level. Additionally, there is a need to effectively communicate these benefits of winter maintenance operations to decision-makers and the general public.

Furthermore, benefit-cost analysis to evaluate operational effectiveness is critically important given the need to objectively formulate and prioritize maintenance budgets and the tendency to privatize maintenance operations. The costs and benefits of winter road maintenance are a function of relevant factors such as the target LOS, the winter traffic volume being managed, and the severity of winter weather experienced by the state or local agency. Typically the challenge is to find sufficient, reliable, and up-to-date data pertaining to specific benefits and costs to support the analysis effort, whereas such methodologies are much needed for agencies to deal with tradeoffs in the decision-making process and to achieve the best possible practices under the current fiscal and other constraints.

In light of these points, there exists a need to synthesize the existing work that has been completed with respect to the estimation, particularly through models, of the benefits of winter maintenance, develop new approaches if no reasonable or transferable ones exist, demonstrate the approach to estimating benefits, and determine what future courses of research are necessary to advance the practice of winter maintenance benefit estimation.

This research is a high priority given the annual spending associated with winter highway maintenance in the United States. In addition to the magnitude of the issue, there are also multiple dimensions to the winter highway maintenance activities and the implications are tremendous. It is believed that the approaches demonstrated through this study will help educate the public and decision-makers, promote and support best practices, and likely improve the image of the winter road maintenance industry as a whole. Benefit estimation methods are much needed for the agencies to conduct *"what-if"* simulations and to optimize their winter maintenance strategies within given funding and other constraints.

Research Objective

The overall objective of this research is to determine what methodologies presently exist for determining the benefits of winter maintenance operations, identify what data is required to apply those methodologies, demonstrate existing methodologies if transferable or develop new methodologies through a case study, and summarize the findings of the collective effort. The work presented in this report includes a comprehensive literature review to document the state of the knowledge and estimation methods regarding the benefits of winter maintenance operations. This includes identifying information related to tangible and intangible benefits (to the agency, road users, and the society), the types of data needed to support the benefit estimation methodologies, such as LOS data, traffic volume data, winter weather data, staffing/equipment/materials costs, and road safety records for the agency of interest. Subsequently, the research focuses on quantitatively modeling the relationship between winter maintenance benefits using key factors such as the LOS, winter traffic volume, winter weather severity, level of anti-icing, and their interactions through demonstrations of the methodologies. For instance, as the LOS increases, it is expected to indicate better pavement conditions and thus produce safety and mobility benefits. Yet such increase in the LOS may be derived from more agency investment (costs) in snow and ice control materials, equipment or staffing/training. As the winter traffic volume (e.g., vehicle-miles traveled) increases, the winter maintenance costs and benefits are both expected to increase. As the winter weather severity increases or the level of anti-icing decreases, the winter maintenance costs are bound to increase if other factors remain the same.

One way to calculate the benefits of winter maintenance is to examine cost savings to the maintenance agency as a result of better practices or reduced LOS. There can also be user benefits derived from improved LOS (and thus enhanced safety and mobility), or infrastructure and environmental benefits derived from reduced usage of deicers, anti-icers, or abrasives. Regardless of the benefit or method employed to estimate it, an important technical challenge is to attempt to "normalize" the demonstrated methods such that different agencies can employ the same approach to estimation with a minimum of data conversion necessary. This consideration was taken into account throughout the research effort.

Report Organization

The following chapter will discuss the results of the literature review conducted to determine the current state of knowledge regarding the estimation of winter maintenance benefits, as well as what models have been or are currently being developed to make such estimates. Chapter 3 outlines the methodologies and data needs employed to demonstrate the estimation of benefits. Chapter 4 provides an illustrated use of the estimation methods through a case study using data acquired from the state of Minnesota. Chapter 5 discusses future research and data needs, limitations to the methodology, as well as provides recommendations for the implementation of the demonstrated approaches by agencies. Finally, Chapter 6 provides a conclusion and summary of the research. References conclude this report.

CHAPTER 2

Literature Review

Overview

One of the primary tasks of this work was to identify and review current literature relevant to the estimation of the benefits of winter maintenance operations and the methods employed to determine them. The approach taken in completing this task employed a comprehensive literature search through sources such as the Transport Research International Documentation (TRID) database, state DOT websites, Federal Highway Administration (FHWA), winter maintenance consortia (e.g., Aurora, Maintenance Decision Support System), and other databases (e.g., Google Scholar). The literature review searched for peer-reviewed papers and journal articles, agency reports (published and unpublished) and agency survey results pertaining to the benefits of winter maintenance operations. Research conducted by international sources was also reviewed wherever available, along with the ongoing research of relevance to the proposed work. The focus of the review was on work which has resulted in the determination of quantified benefits (i.e. benefits which have been numerically established, either in terms of dollars or another metric), as well as qualitative benefits (i.e. those which cannot be assigned a numerical value).

Overview of Benefits

Winter maintenance operations allow agencies to keep the highway system safe, mobile, reliable, and productive. To minimize the adverse effects of winter storms on road users, state and local agencies spend significant amount of resources annually performing a variety of maintenance actions. While such actions can have negative impacts (especially chemical deicers) on motor vehicles, transportation infrastructure, and the environment, they also provide significant benefits. Unfortunately, those benefits have not typically been communicated to decision makers, the public and other stakeholders. This is, in part, the result of a lack of methods determine and estimate the benefits of winter maintenance operations.

Before moving to a discussion of the benefits of winter maintenance and the approaches to estimate them, it must be noted that the benefits of winter maintenance may be quantifiable or qualitative. Quantifiable benefits are those that a specific value can be assigned to. In some cases, the quantified value can take the form of a percentage; in other cases, it may take on a dollar value or other numerical form. Qualitative benefits are those which are non-quantifiable numerically, but still produce some tangible benefit. For example, the use of Automatic Vehicle Location (AVL) can reduce material use (agency benefit), but it may be difficult to assign a value (percent reduction, dollars, etc.) that this specific aspect of a winter maintenance tool contributes when used in combination with other maintenance operations (e.g., plowing). In order to understand the existing state of knowledge regarding the benefits of winter maintenance, a review was undertaken, the results of which are presented in the following sections.

Methods to Estimate Winter Maintenance Benefits

One of the foremost interests of this work was to determine what, if any existing methods might have been developed that could be demonstrated by this project in estimating winter maintenance benefits. To this end, the following paragraphs provide an overview and summary of such methods as identified by the literature review, along with the limitations that each method may have in terms of transferability.

Haber and Limaye used stochastic simulation to quantify the benefit of reduced delay times (*9*). Using this approach, if the mean and standard deviations of speeds under two levels of service were known (e.g., an old treatment LOS versus an upgraded LOS), random normal variates could be computed to represent the two speeds. If an average trip length was also known, the time saved or lost under a specific maintenance LOS could be computed, with a conversion to a corresponding dollar value. The translation of delay measures into comfort and convenience costs was made using functions developed by the Utah DOT (*10*, *11*).

Haber updated the Idaho project discussed by Haber and Limaye (*9*) to include yearly traffic volume and winter maintenance cost data in 1996 (*12*). The algorithm employed in the model calculated the benefits accrued from changes in winter LOS, similar to that of the earlier model. The benefits calculated included the value of time saved and the total change in delay for all vehicles on a segment. A simulation using two vehicle speeds as random variables was used to approximate the time saved for a segment. The value of time savings was calculated using the vehicle time saved data and an assumed hourly labor rate. Collectively, both stages of the model developed for Idaho represent basic approaches to estimating the general direct benefits of winter maintenance. However, their transferability to the present work is limited in the sense that they only incorporate the direct benefit of travel time/time savings rather than other metrics such as fuel savings or accident reduction.

McBride developed an economic model that determined the economic costs and benefits accrued by snow and ice control (*10, 11*). It employed five modules that incorporated the maintenance, traffic and safety, environment, structural deterioration and vehicle corrosion aspects of winter maintenance. The maintenance and traffic and safety modules produced costs on a storm and LOS basis, while the structural deterioration and vehicle corrosion modules yielded annual costs based on estimates (the environmental module only provided written statements of potential damages, as cost information on this aspect of maintenance was not available at the time [1977]). Consequently the model primarily produced benefit estimates via the maintenance module, where LOS goals, available material and equipment, requirements to achieve a specific LOS, traffic volume, highway type, and snow accumulation were used as input for cost analysis and comparisons. Using this information, probability delay functions were developed to determine delays for a given volume of traffic, which was then converted to cost values by using comfort and convenience, vehicle costs and lost wage values. The difference (savings) between these costs for different LOS was the benefit for that particular maintenance operation. Given the assumptions employed and computational and data limitations of the time (1977), the modeling approach developed by McBride was somewhat limited in its ability to accurately establish the benefits of winter maintenance.

Welch et al., examined the economic impacts of snow on traffic delays and safety. This work primarily consisted of a review of previous work, but it also presented detailed equations for calculating the mean delay during a storm and the expected value of lost wages due to delay (*13*). Such equations could be employed in the framework of an overall model for estimating benefits, although such a model framework was not presented by the researchers.

Adams et al., employed regression tree models to predict winter storm maintenance costs in Wisconsin (*14*). The regression tree approach to modeling was selected to account for the different variables of winter maintenance operations, such as service level, area size, overtime costs, etc. Although focused on estimating the maintenance resources required per storm in this application, the regression tree approach may also offer an adaptable method to estimate the benefits of operations for different maintenance levels and traffic inputs. However, as no such application has been developed to date, this would require more detailed additional investigation.

Hayashiyama et al. employed the contingent value method to quantify the indirect benefits of winter maintenance (*15*). The contingent value method uses an interviewer who asks respondents how much money they would pay to achieve a given improvement (willingness to pay) or how much compensation they would require if conditions deteriorated to a given point (willingness to accept). The researchers noted that the contingent value method was not well suited to cost-benefit analysis for winter maintenance activities, as it does not include travel time and cost metrics. However, it does offer a potential approach to estimating the value of winter maintenance operations for indirect benefits, albeit requiring a large sample of respondents to be interviewed (100+ for each category). The overall result of this work was the determination, via an extrapolation of survey respondent results to the population of Sapporo, Japan, that there was a willingness to pay between $17 and $23 million dollars for improved winter road maintenance during a storm and a willingness to accept compensation of between 180 and $200 million dollars if maintenance was limited and road conditions deteriorated. Collectively, these results underscore a sense on the part of the public that mobility is a valuable benefit derived from winter maintenance.

Hanbali examined the economic impacts of winter maintenance from a safety standpoint (*16*). The overall approach employed in evaluating the benefits of maintenance was to compare the savings accrued from a cleared road surface to the costs expended deriving it. Benefits were estimated by determining the accident rate reduction and resulting road user safety benefit (savings in injuries and property damage), the vehicle operating cost (reduction in operating cost because of improved speed), and travel time savings (reduced trip time). The data employed in estimating the benefits included before and after (expected) accident rates from an operation, the respective dollar values of different crash types, normal and snow-adjusted operating speeds on a segment, an average of vehicle mileage per gallon, the current gas price, average delay incurred because of snow and a time saving value. Hanbali presents the equations used in computing the respective benefits, which provides a straightforward approach to estimating benefits regardless of locale.

Ye et al., determined the cost benefits of weather information for winter maintenance (*17, 18, 19, 20*). The work developed a winter maintenance cost model of the direct costs of materials, labor and equipment (indirect costs not included in the model) at the maintenance unit level (shed, garage, yard, other). The researchers noted that material, labor and equipment use could be affected by many factors, which they presented as:

$$WMCk = f\,(LMk\,, LOSk\,, WSIk\,, WIk\,, AIk\,)$$

Where

- $WMCk$ = winter maintenance cost for the *k*th maintenance unit per winter season
- LMk = lane miles of roadway maintained by the maintenance unit
- $LOSk$ = level of service of the roadways maintained by the maintenance unit, often characterized by the pavement condition
- $WSIk$ = winter severity index for the area managed by the maintenance unit
- WIk = weather information usage (frequency and accuracy) by the maintenance unit
- AIk = level of anti-icing used by the maintenance unit

A two step methodology was employed to estimate the benefit of weather information. Sensitivity analysis was used to explore the effects of input variables on maintenance costs. Then, neural networks were used to model winter maintenance costs and evaluate the impacts of weather information. To determine the benefits of weather information, the maintenance costs of a base case were compared to those of alternative scenarios where different levels of weather information were used. The difference between the costs from each scenario to the base case was the benefit to winter maintenance. While the approach appears at first glance to focus on cost information, it ultimately generates estimates of the value of winter maintenance benefits. In this respect, it offers a statistical approach to determining the quantifiable benefits of other winter maintenance operations, singularly or in combination.

Miedema and Wright developed a methodology to calculate and evaluate the benefits of using additional weather information (RWIS, forecasts from providers, etc.) in initiating snow and ice control activities (referred to as "callouts") (*21*). The methodology consisted of six steps: 1) identify benefits and benefit types; 2) determine "callout" cost profiles; 3) compare decisions using old and new information sources; 4) quantify the direct benefits; 5) quantify the indirect benefits; and 6) expand the benefits statewide. Benefits were considered tangible if they could be associated with a dollar value and intangible if they could not be monetarily quantified. Of interest to this work were the approaches employed to estimate the direct and indirect benefits of using improved information in winter maintenance. Direct benefits were calculated as:

$$DBenefit_j = \sum_{i=1}^{n} \Delta Cost_{ij} \times \Delta F_{ij}$$

Where:

$DBenefit_j$ = direct benefit for sub-district j
i = deviation type (i.e. change in procedure)
j = sub-district number
n = number of deviation types
$\Delta Cost_{ij}$ = increased cost of call out by deviation type
ΔF_{ij} = change in frequency deviation type

Similarly, indirect benefits were calculated as:

$$TSave_j = \sum_{i=1}^{n} \Delta T_{ij} \times \Delta F_{ij}$$

Where:

$TSave_j$ = total time of hazardous roadway avoided
i = deviation type (i.e. change in procedure)
j = sub-district number
n = number of deviation types
ΔT_{ij} = increased hazard time for deviation type increased
ΔF_{ij} = change in frequency deviation type

Indirect benefits consisted of the volume of traffic affected by different changes to call out procedures. Collectively, this multistep approach generated different benefit values for winter maintenance operations based on changes to weather information. However, it did not take into account different changes to operations and treatment materials which also play a role in producing the different benefits of winter maintenance.

Shahdah and Fu used the INTEGRATION simulation model to represent driver behavior under specific road and weather conditions in order to establish the benefits of different levels of maintenance (*22*, *23*). The model was used to capture driver behaviors and their impacts on traffic operations by adjusting road, traffic and environmental conditions through changes to free flow speed, speed at capacity, capacity and jam density parameters. While this approach provided a general indication of the benefits to traffic flow that collective (through different levels of surface condition) winter maintenance operations may have, it does not appear to offer a mechanism to incorporate detailed changes to one or more maintenance parameters, such as the materials being used or changes in equipment. This work also did not examine the other benefits that may have accrued from winter maintenance, such as improved safety.

Fu et al. examined the effects of winter weather and maintenance treatments on safety (*24*). Daily accident data, weather conditions and maintenance operations data were examined for two provincial highways in Ontario, Canada. The researchers employed a Generalized Linear Model (GLM) to identify weather and maintenance factors that had a significant impact on crash frequency. It was found that anti-icing and prewetting operations improved safety on one study route (anti-icing was used on only one route), while sanding operations had a positive effect on safety on both routes. The researchers noted that the safety effect of plowing and salting operations could not be statistically confirmed by their work, noting that there could be an inter-dependency between maintenance operations and snow conditions, with more maintenance operations dispatched during more severe weather conditions. Consequently, the variation in these operations under a given weather condition may have been small (*24*). This work focused on determining only the safety benefits of winter maintenance treatments and did not examine what benefits may have accrued to other areas, such as traffic. However, it does offer a statistical approach to establishing the safety benefits of winter maintenance.

Usman et al., quantified the safety benefits of winter maintenance through an investigation of the association between accident frequency during snow events and road surface conditions, visibility and other influencing factors (controlling for traffic exposure) (*25*). The research did not consider specific maintenance operations directly in the models that were developed, as it was assumed that these operations were reflected in the measurements of road surface conditions (measured by the road surface condition index, or RSI). Exploratory analysis indicated that maintenance activities were correlated to RSI and were not statistically significant once road surface conditions were accounted for (*25*). Three event-based models were developed by this work, including a negative binomial, a generalized negative binomial, and a zero-inflated negative binomial, with the intention of determining which was most suitable to fit the available data. It was determined that the generalized negative binomial best fit the data, with the coefficient associated with the RSI indicating that a 1 percent improvement in this metric would produce a 2.28 percent reduction in expected crashes. The key limitation of this work is that it did not explicitly incorporate specific maintenance activities into the developed models, instead relying on the assumption that RSI accounted for them based on observations made during exploratory data analysis. Consequently, a determination of the specific contributions of maintenance practices and materials (e.g., salt, sand, and brine) was not determined.

Ongoing work being conducted by the Ontario Ministry of Transport, the University of Waterloo and the Aurora pooled fund is developing predictive models to estimate the relative benefits of different levels of winter maintenance (*26*). The model will employ simulation to analyze weather, snow cover condition and weather-related crash and traffic flow data to predict trends in crash occurrence and traffic operations under different types of conditions. Based on the model outputs, the relative effort and benefits associated with different levels of winter maintenance can be understood and compared. As this work remains ongoing, this modeling approach to estimating benefits, while promising, is not available for use in the present research.

Morisugi et al., evaluated the benefits of snow removal in the Tohoku region of Japan (*27*). The researchers estimated generalized traffic savings based on comfort and punctuality metrics provided by different levels of maintenance operations. These were specified by using stated preference (driver survey) data examined using a logit model with a linear utility function. While this approach offers a means to incorporate driver preferences/comfort regarding road conditions in determining the benefits of winter maintenance, it requires extensive survey data to be completed, which is not feasible in the scope of the present project.

The Swedish National Road and Transport Research Institute (VTI) developed a tool, named Winter Model, to estimate and put a value on the impacts of winter maintenance strategies and measures on road users, maintenance agencies and society at large (*28, 29, 30*). The collective model uses several submodels that estimate the impacts of maintenance on accidents, accessibility, vehicle costs (e.g., fuel and maintenance), environmental impacts and road management costs (impacts to infrastructure). All of these submodels rely on data from a central road condition model that calculates road conditions hour by hour based on weather, treatment and traffic data. A flowchart schematic of the overall model is presented in Figure 1.

The Winter Model offers the most comprehensive approach to estimate the values of benefits accrued from winter maintenance operations identified to date. However, this model presents two distinct drawbacks. First, has been developed for local Swedish conditions, and it is not clear how adaptable it might be outside of the country. Second, while the model has been coded in Visual Basic to automate the overall process of data entry and analysis, the user interface is in Swedish. The combined adaptation and translation of the model are not feasible for the current project, although an investigation of such transferability is strongly encouraged as part of future work.

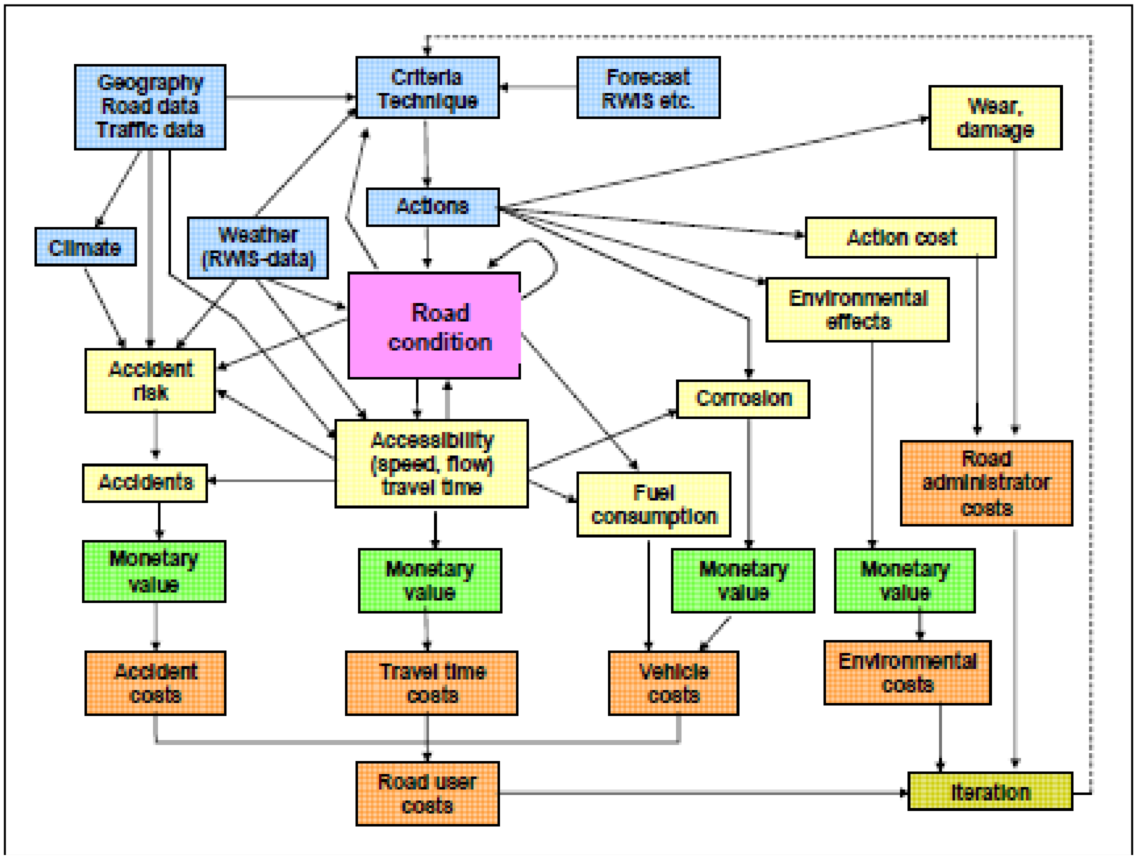

Figure 1: Schematic of the Winter Model (*28, 29, 30*)

Veneziano et al., developed a web-based toolkit to complete cost-benefit analysis of winter maintenance practices, equipment and operations (*31*). As part of the toolkit, estimates of quantified benefits were provided for individual items, including anti-icing, deicing, carbide blades, front plows, underbody plows, zero velocity spreaders, Maintenance Decision Support Systems, Automatic Vehicle Location and Geographic Positioning Systems, Road Weather Information Systems, and mobile pavement or air/pavement temperature sensors. In addition to quantified benefit values, the toolkit provided users with a list of non-quantified benefits for each particular item for reference purposes. Quantified benefit values were calculated based on parameters entered by the user that had been identified from published literature, as well as conservative assumptions as needed. While the toolkit did estimate winter maintenance benefits on an individual basis, it did not compute benefits in a collective manner. This limits its transferability to the current project, as the collective benefit of winter maintenance operations are of interest rather than the individual contribution of specific aspects.

General Benefits of Winter Maintenance

In addition to specific approaches that sought to estimate winter maintenance benefits, several past research efforts have estimated individual benefit values for one or more components of winter maintenance. These efforts are summarized in the following paragraphs.

Haber and Limaye analyzed the benefits and costs associated with winter maintenance activities in Idaho (*9*). The specific benefits that the researchers identified and used in their analysis were a reduction in accident rates, decreased travel delay, increased travel comfort, and reduced inconvenience (reduction in vehicle operating costs and reduction of business losses). The decreased delay, increased comfort and reduced inconvenience benefits were quantified by the researchers using stochastic simulation models to determine the impacts of changes in maintenance LOS on delay. Based on these changes, dollar values could be assigned to the reduced (or increased) delay, travel comfort and convenience (using functions to translate these from delay), resulting in quantified benefits. Given that the values for each of the identified benefits varied by LOS, trip length, etc., no specific quantified values were cited by this study.

Kuemmel, while primarily discussing the overall management of snow and ice control operations, did also touch upon its benefits. Specific benefits included reduced accident rates, economic/productivity benefits (decreased absence, increased productivity) and delay savings (*32*). This work did not produce specific quantified values for these benefits, although earlier work by the researcher, discussed elsewhere in this section, did develop values.

Welch et al., in discussing the economic impacts of snow on traffic delay and safety, identified different categories of benefits that accrued from different levels of maintenance (*33*). These included vehicle operating cost savings, travel time savings (or losses) and accident reductions, all varying by the level of maintenance provided. This work also provided general figures illustrating the costs of driver discomfort by time and lost wages per worker based on tardiness that were used by later researchers, such as Haber and Limaye (*9*).

Hayashiyama et al., classified the economic benefits of winter maintenance as being within the traffic market and outside the traffic market (*15*). Benefits within the traffic market included those accrued to road users, such as travel time and financial savings, and highway agencies and society, such as congestion mitigation. Benefits outside of the traffic market consisted of externalities, such as improved quality of life. The focus of the researchers was on the indirect benefits of winter maintenance, which were estimated based on the contingent value method, where an interviewer asked respondents how much money they would pay to achieve a given improvement (willingness to pay) or how much compensation they would require if conditions deteriorated to a given point (willingness to accept).

Hanbali classified the benefits of winter maintenance as being direct and indirect (*16*). Direct benefits included vehicle operating cost reductions, travel time reductions, and avoidance of property damage, injury and loss of life. Indirect benefits included availability of community services (police, fire, etc.) and maintenance of business operations. Hanbali noted that many of the benefits that fall under each of the categories are intangible. A notable result of this work was the conclusion that maintenance operations produced a direct savings (benefit) to road users of 45 cents per kilometer of travel on two lane highways and 20 cents per kilometer of travel on multilane freeways.

Although focused on the development of performance measures for snow and ice occurrence for Alberta, Falls identified the benefits of anti-icing operations (*34*). These were divided into a series of categories and subcategories, including:

- Mobility
    - Reduced road closures
    - Improved traveler information
- Safety
    - Reduced accidents
    - Decreased insurance claims
- Productivity

- Reduced maintenance costs (overtime, materials)
- Reduced clearance times
- Environmental Quality
  - Reduced impact on roadside environment
  - Improved air quality (reduced abrasives)
- Other/Indirect
  - Reduced asset damage (vehicles, equipment)

While some of these benefits are specific to anti-icing operations, others are applicable in general to winter maintenance operations, regardless of whether they are quantifiable or qualitative.

In discussing performance audit measures for winter maintenance, Thornes identified several benefits based on previous studies (*35*). The benefits identified included reduced accidents, reduced delay, improved emergency response and improved fuel economy.

A discussion paper by Environment Canada identified the direct and indirect benefits of using salt in winter maintenance and provided quantified values when available (in 2002 Canadian dollars) (*36*). Direct benefits included:

- Fuel savings – 33 percent reduction, translating into savings of $1.88 per 100 kilometers traveled
- Travel time savings - $11.00 per hour for car, $9.73 per hour for bus
- Avoided fatalities, injuries and property damage- savings of $1,594,412 per fatality, $28,618 per injury and $5,724 per property damage crash eliminated

Indirect benefits included:

- Reduction in tort liability claims
- Maintained economic activity – estimated at $27.00 per hour per employee
- Maintained access to social activities

The document notes that financial values for indirect benefits were not available and needed to be established through future research efforts.

Shi identified several benefits stemming from winter maintenance operations while discussing best practices, emerging challenges and research needs (*1*). Direct benefits included reduced accidents, improved mobility and reduced travel costs. Indirect benefits included sustained economic productivity, reduced tort claims and continued emergency services. It was noted that these benefits did not come without costs, which included materials, labor, equipment and impacts to vehicles, infrastructure and the environment.

Miedema and Wright identified several direct and indirect benefits to winter maintenance when examining the impacts that different weather information sources might have on response times (call outs) to storms (*21*). Direct benefits included decreased materials usage, equipment costs and labor costs. Indirect benefits identified included decreased accidents, travel time and fuel consumption. While direct benefits varied by location (in this case, sub-districts), general values for indirect benefits were developed. The benefit of reduced accidents was valued as $0.0748 per vehicle kilometer of travel on two lane roads and $0.0357 for four lane roads. The benefit of improved weather information on travel time was $0.0383 per vehicle kilometer of travel on two lane roads and $0.0162 on four lane roads. Finally, the benefit of reduced fuel consumption was determined to be $0.0007 per vehicle kilometer of travel on two lane roads and $0.0003 for four lane roads. The researchers noted additional benefits that could not be quantified, including reduced decision-maker stress, improved public perception and reduced environmental impacts.

Shahdah and Fu conducted a simulation-based analysis to quantify the mobility benefits of winter maintenance using a freeway segment near Toronto, Ontario, Canada (*22*, *23*). The simulation model was used to simulate traffic operations under a set of assumed snow storm events (low, medium, and heavy snowfall intensities) and maintenance scenarios (generalized extremes, either no maintenance performed or perfect road maintenance producing a bare, wet surface). The research results found that perfect road maintenance producing bare, wet pavement during low snowfall events could save a total travel time (compared with snow-covered scenario) of about 6 to 7 percent for volume/capacity (V/C) ratios from 0.35 to 0.60, 26 to 27 percent for V/C ratios of 0.70 to 0.75, and 10 to 11 percent for V/C ratios between 0.90 and 1.00. This travel time savings increased with snowfall intensity, with savings during heavy snowfall estimated to be between 7 to 11 percent for V/C ratios of 0.35 to 0.60, 29 to 36 percent for V/C ratios of 0.70 to 0.75 and 5 to 12 percent for V/C ratios of 0.90 and 1.00. Of course, the limitation to this work is that it did not examine the impacts of specific winter maintenance practices in a real world setting. Still, the results indicate that aggressive winter maintenance strategies result in improved operations.

A Strategic Highway Research Program (SHRP) report discussing the development of anti-icing technology provided estimates of the cost savings (benefits) that the technology might provide (*37*). These included labor, operational and material savings, as well as reduced accidents. The specific estimated savings per truck route and storm severity/number (in 1994 dollars) are presented in Table 1.

Table 1: SHRP Estimates of Anti-Icing Cost Savings (*37*)

Winter Storm Severity					
Storm Hours per Winter	100	300	500	700	900
Storms per Winter	5	12	18	25	30
Annual Agency Cost Savings ($)					
Labor	43	332	689	978	1,403
Vehicle Operations	40	312	648	920	1,320
Materials	3,160	9,673	16,251	22,764	29,406
Equipment	-1,977	-1,977	-1,977	-1,977	-1,977
Subtotal	1,266	8,340	15,611	22,685	30,152
Annual User (Motorist) Accident Cost Savings ($)	11,924	35,771	59,618	83,465	107,312
Total Annual Cost Savings per Truck Route ($)	13,190	44,111	75,229	106,150	137,464

Kuemmel and Hanbali performed a simple before and after analysis on the effectiveness of salting on safety in New York, Minnesota and Wisconsin (*7, 16*). The researchers found a significant reduction in crashes following salting operations, with an 87 percent reduction observed on two-lane undivided highways and a 78 percent reduction on freeways. As noted, a simple before and after approach was employed by this work which employed estimated traffic volumes based on historical data rather than observed counts. Weather-related factors, as well as the use of other winter maintenance operations (e.g., plowing), were not considered by this work either, which calls into question the true contribution of salting to the observed crash reductions. The researchers also performed a before and after analysis on the effectiveness of salting on vehicle operating savings (*38*). In computing user mobility benefits/savings, it was assumed that speed reductions of 10 mph on both two-lane highways and freeways resulted from weather. The researchers found that total direct operating costs for motorists fell from 7.3 cents to 6.1 cents per vehicle mile traveled on two-lane highways and 53.5 cents to 23.8 cents per vehicle mile traveled on freeways following maintenance activities. During the first two hours following maintenance, the direct road user benefits amounted to $6.50 for every $1.00 spent on two-lane highways and $3.50 for every $1.00 spent on freeways for maintenance. The direct costs of maintenance were offset once 71 vehicles and 280 vehicles had driven over a two-lane highway and freeway, respectively, with maintenance costs being paid for after approximately 35 minutes.

In a review of past work, Wallman et al. summarized the effects of winter road maintenance on safety, operations and corrosion (*39*). In their review, the researchers observed that accident rates in Europe ranged from 5 to 14 times higher before maintenance activities were carried out compared to after. Similarly, accident rates in the U.S. on two-lane roads were 8 times higher before maintenance compared to after.

Qiu and Nixon developed a method to measure the performance of a winter maintenance program with respect to the provision of safety and mobility to motorists (*40, 41*). The researchers noted that many past studies did not evaluate winter maintenance outcomes while accounting for factors including storm severity, road characteristics and maintenance efforts. To address this, a storm severity index was developed, with the effects of weather and winter maintenance on road surfaces estimated by Multinomial Logistic Regression (MLR). Multiple Classification Analysis (MCA) was applied to estimate the contributions of winter maintenance to safety, including the use of chemicals. Results of the MCA indicated that the chemical variable was a strong indicator of property damage only (PDO) crash probabilities; the impacts of specific chemical types were not broken out (*41*). However, winter highway maintenance operations collectively (plowing and chemical use) were found to be a weak predictor of crash severity. Overall, the researchers found that maintenance operations have no direct effects on safety when weather and road conditions were controlled, but did indirectly impact safety through reducing snow/ice surface conditions (*40*). The effects of maintenance operations on vehicle speeds and volumes were investigated. This involved investigation of the effects of weather and maintenance on Interstates and primary highways with different AADT levels and speed limits using Structural Equation Modeling. In general, the winter maintenance operations (plowing, chemical treatment) examined had positive effects on the speeds observed (i.e. speeds were higher where maintenance was employed at a higher priority level compared to a lower level). While plowing had a measureable impact, producing 2 to 3 mph higher speeds during the hour following plowing, chemical treatment did not have a pronounced effect (far below 1 mph higher speeds the following hour). Additionally, maintenance operations also had positive effects on traffic volume, with only a slight reduction in traffic volume observed during average winter storms for service routes that received a high level of maintenance.

Usman et al. developed disaggregate models for quantifying the safety effects of winter maintenance activities at an operational level (*42*). Two types of models were developed: a single level generalized negative binomial model and a multilevel Poisson lognormal model. The generalized negative binomial model did not account for within storm variation, while the Poisson lognormal model could account for hierarchical data (e.g., individual snow events and the individual hours within each storm). The models examined the link between winter road crashes and weather, road surface conditions, traffic exposure, temporal trends and site-specific effects. Hourly data from 31 highway routes in Ontario, Canada, were used in the analysis.

Model results indicated that factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, month of winter season and storm hour all had significant effects on safety. The work also allowed for a quantification of the benefits of maintenance operations and service standards in terms of expected crashes. This included identifying the safety benefits of combined plowing and salting versus a no maintenance condition and the timing of those operations (2 hours into event, 4 hours, etc.) and the time to bare pavement. For plowing and salting operations, the mean number of accidents expected following that operation are quite low, steadily rising back to the expected mean had no maintenance been performed over a period of hours following the maintenance. This is illustrated in Figure 2. An examination of the expected reduction in accidents from the models versus time to bare pavement indicated that, as one would expect, the sooner maintenance activities produce bare pavement, the greater the reduction in the percent of crashes. This is illustrated in Figure 3.

The use of chemicals on roads has effects on the environment by degrading water quality, soil quality, and ecosystems (*43*). While some effects are short-term and seasonally reversible, there are long-term effects, such as salt-contamination, that will take many years or decades to recover from (*43*).

Environmental Canada found that inorganic chloride road salts are harmful to the environment under the Canadian Environmental Protection Act (*44*). A national survey was conducted to rank the areas of environmental concerns of road salts, and the rankings (from high to low) were aquatic impacts (40%), air quality (27%), vegetation (20%), endangered species (13%), and other (1%). The survey also identified and ranked corrosion concerns, including concrete reinforcing (30%), vehicles (22%), concrete damage (20%), structural steel (16%), and roadside structures, utilities, and equipment (12%) (*44*).

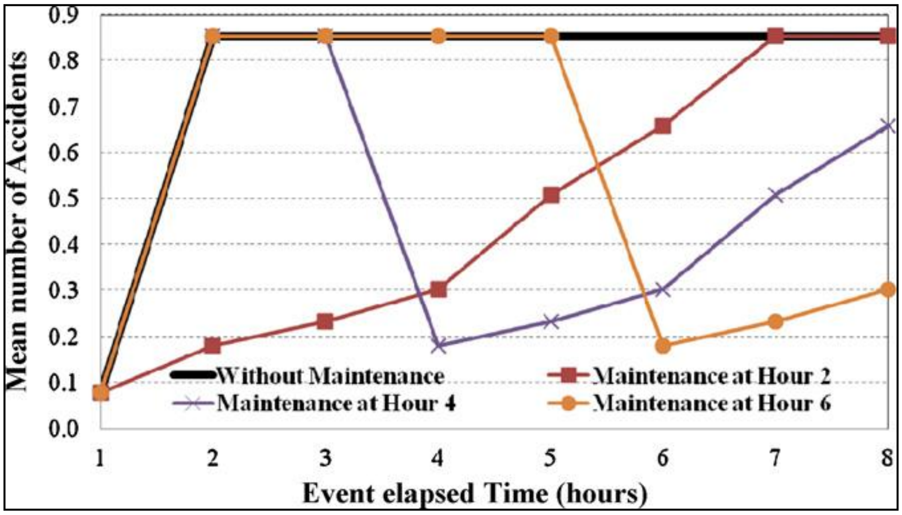

Figure 2: Safety Benefits of Plowing and Salting Operations Versus No Maintenance (*42*)

Figure 3: Effect of Time to Bare Pavement on Safety (*42*)

Chapter Summary

Based on the literature review of the benefits of winter maintenance operations and the methods employed to determine those benefits, a number of conclusions can be drawn. With respect to the benefits of winter maintenance operations, in general, both their direct and indirect benefits have been identified in a qualitative sense. In some cases, quantitative estimates (e.g., reduced crashes, reduced delay, fuel savings) have been developed. These estimates vary depending on the approach and specific metrics (e.g., traffic, safety and material usage) employed in estimation. With respect to estimation methods, more sophisticated approaches have been recently developed (Sweden) or are in the midst of development (Canada). However, these approaches have been developed for a specific locale or are still in development, and their transferability to the present work is limited. Aside from these specific examples, the estimation of winter maintenance operations benefits has focused on specific aspects (e.g., traffic operations and accidents) or individual components (e.g., weather information). Consequently, a comprehensive method to estimating the benefits of winter maintenance operations does not truly exist in a form that can be used “off the shelf”.

While no comprehensive “off the shelf” methods are available to estimate winter maintenance benefits, the literature review did provide useful references for estimating different types of benefits. For instance, the study by Haber and Limaye (*9*) provided a way to estimate travel time savings, which was used to compare traffic speeds under different LOS conditions; the GLM method used by Fu et al. (*24*) is a popular method for traffic safety analysis, and this method can be a good way to estimate safety benefits of winter maintenance.

Although it is known that winter maintenance has direct benefits (e.g., reduced crashes, travel time savings, fuel savings) and indirect benefits (e.g., reduction in tort liability claims, maintained economic activity, and maintained access to social activities), snow and ice control activities also cause negative benefits such as environmental degradation and infrastructure corrosion. Improving winter maintenance practices are important to reduce the negative impacts, but it must be noted that these will continue to exist in some manner for the foreseeable future.

Table 2: Summary of Winter Maintenance Impact Studies

Studies	Methods	Advantages and Disadvantages
Haber and Limaye (1990; 1996)	Stochastic simulation • Given mean and standard deviations of speeds under two LOS • Given traffic volume and average trip length	• Estimates travel time savings • Not able to estimate other benefits (e.g., safety)
McBride (1977; 1978)	Probability delay functions (Economic model) • Inputs include LOS goals, available material and equipment, traffic volume, highway type, and snow accumulation	• Estimates travel time benefits • Not able to estimate other benefits (e.g., safety)
Hayashiyama et al. (2000)	Contingent value method • Interviewed people about their willingness to pay and willingness to accept	• Estimates indirect benefits of winter maintenance • Does not include travel time and cost metrics
Kuemmel and Hanbali (1992); Hanbali (1994)	Before after study • Accident rates before and after (expected) winter maintenance	• Estimates safety benefits • Method is straightforward but lacks accuracy • Difficult to use for statewide evaluation that includes various types of roadways and associated characteristics

Studies	Methods	Advantages and Disadvantages
Ye et al. (2008; 2009)	Neural network method	• Evaluates sensitivities of variables to winter maintenance costs • Lack of transferability of the methodology to estimate safety and other benefits
Miedema and Wright (1995)	Direct Comparison • Determine snow and ice control activities • Compare decision using old and new information sources • Quantify direct and indirect benefits • Expand the benefits statewide	• Able to estimate statewide benefits (reduced accidents, reduced delay, and fuel savings) • Does not take into account different changes to operation and treatment materials
Shahdah and Fu (2009; 2010)	INTEGRATION Simulation model • Captures driver behavior through changes to free flow speed, speed at capacity, capacity and jam density parameter	• Estimates travel time savings • Does not offer a mechanism to incorporate detailed changes to one or more maintenance parameters
Fu et al.(2006); Usman et al. (2010)	Generalized Linear Model (Negative Binomial Model and Poisson Lognormal Model) • Develop safety performance functions	• Estimate safety benefits by examining crash frequency • Does not estimate other benefits, such as travel time savings
Morisugi et al. (2002)	Logit model with a linear utility function	• Extensive survey data are required to apply this method
VTI (2004; 2006)	Winter Model	• Submodels to estimate the impacts of maintenance on accidents, accessibility, vehicle costs, environmental impacts and road management costs • Developed for local Swedish conditions with user interface coded for Swedish users
Veneziano et al. (2010)	Web-based toolkit	• Estimate winter maintenance on an individual basis • Does not compute benefits in a collective manner
Qiu and Nixon (2008; 2009)	Multinomial Logistic Regression (MLR) and Structural Equation Modeling	• Investigates the effects of chemical usage on crash severities • Investigates the effects of winter maintenance on traffic speeds • Maintenance operations collectively found to be weak predictors of crash severity
Kuemmel (1994)	General evaluation (qualitative)	• Identify winter maintenance benefits including reduced accident rate, economic/productivity benefits, and delay savings • Focused on only one treatment type (salt)

Studies	Methods	Advantages and Disadvantages
Welch et al. (1977)	General evaluation (qualitative)	• Identify winter maintenance benefits including vehicle operating cost savings, travel time savings (or losses) and accident reductions
Thornes (2002)	General evaluation (qualitative)	• Identify winter maintenance benefits including reduced accidents, reduced delay, improved emergency response and improved fuel economy • Only identified benefits cited by past research, did not develop methods to estimate
Environmental Canada (2002)	No specific method was identified	• Direct (tangible) benefits include fuel savings, travel time savings, and improved traffic safety • Indirect (intangible) benefits include reduction in tort liability claims, maintained economic activity, and maintained access to social activities • While figures were provided, the approach taken to develop them was not discussed

CHAPTER 3

Methodology Development

Overview

Snow and ice control is a high priority during winter to maintain safety and mobility of traffic flow. It goes without saying that the major benefits of winter maintenance include safety improvements resulting from fewer winter crashes, travel time savings due to better road pavement conditions (or higher LOS) and fuel savings from reduced delay and improved roadway surface conditions. (Note: LOS in the context of this report refers to the actual pavement condition with respect to accumulation of liquid or frozen precipitate (*19*)). These three types of benefits should be emphasized when estimating the benefits of winter highway operations. Note that there are secondary benefits of winter maintenance, such as increased travel comfort and convenience. Such benefits are, however, difficult to observe and measure quantitatively, particularly with the datasets collected and maintained by transportation agencies. Thus, this section focuses on the methodologies and associated data elements for estimating statewide safety benefits, travel time savings and fuel use savings. The overall framework for data collection and the methodologies for estimating winter maintenance benefits are provided in Figure 4.

For benefit analysis, two scenarios of winter maintenance are defined:

- Base case (without winter maintenance). This scenario assumes no (or very little) winter maintenance activities are carried out. In the case study presented in the following chapter, this scenario corresponds to zero winter maintenance cost.
- Present case (with winter maintenance): This scenario corresponds to the actual winter maintenance activities conducted and effects achieved by an agency.

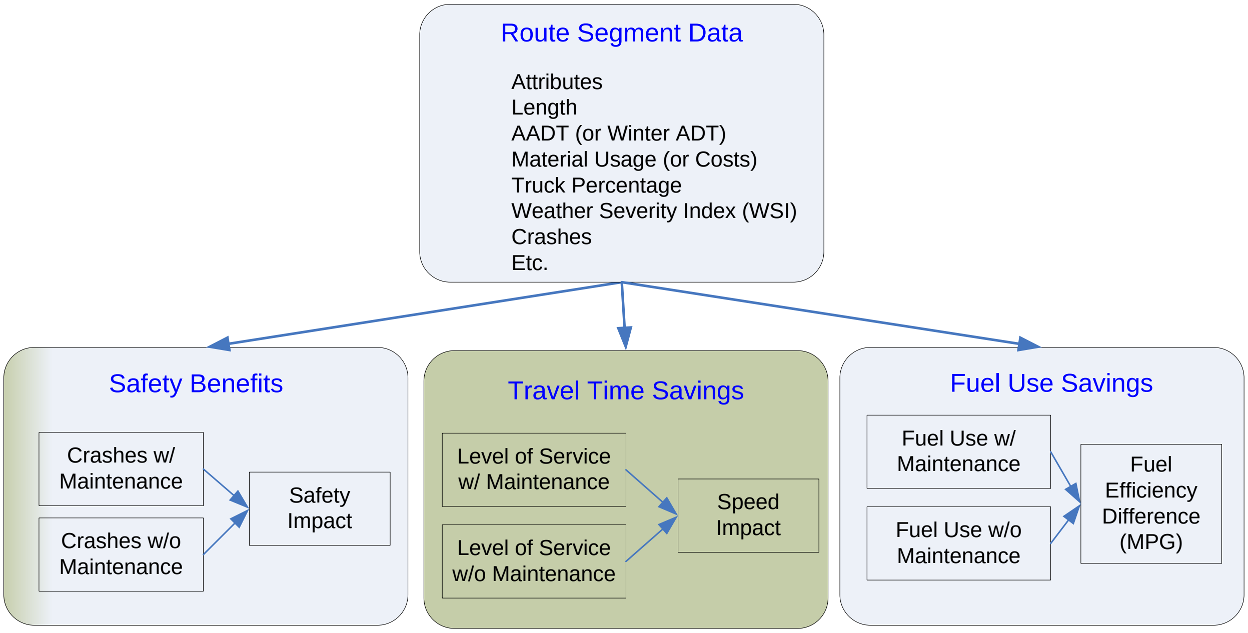

Figure 4: Overall Framework for Estimating Statewide Benefits

Route Segment Data Elements

The methodology developed by this work incorporated a number of data elements identified during the literature review as being included in other benefit estimation approaches. Recall that such approaches were not directly transferable for demonstration as part of this research effort but still offered useful insights and considerations for the development of estimation methodologies. Consequently, a database needed to be built for the processing and estimation of safety, travel time and fuel savings benefits. Such a database can be built as a spreadsheet with rows corresponding to the maintenance route segments within the State (see Figure 5). With the segments (rows) identified, the remaining effort consists of completing the columns of the spreadsheet with the requisite data. As shown in Figure 4, data collection should include the following elements for the methodologies discussed here:

- Attributes: the route (e.g., I-90) and district a maintenance segment belongs to, speed limit, number of lanes, maintenance job number, etc. These columns serve as the "primary key" which uniquely specifies a row (route segment).
- Length: the length (in miles) of a segment. It is usually calculated by obtaining start and end Mile Post (MP) data (or conversely, post miles, depending on the convention used by an agency). Length information will be used in the calculation of both safety benefits and travel time savings.
- Annual Average Daily Traffic (AADT) or winter Average Daily Traffic (ADT). Winter ADT data are preferred if available since the time period of investigation is during the winter season. Otherwise, conversion factors developed by an agency may be used to produce winter-specific figures. This information will be used for estimating safety benefits and travel time savings.
- Truck percentage: the percentage of trucks in the traffic stream. This information will be used for calculating benefits resulting from travel time and fuel savings. The need to obtain such information is that the Value of Time (VOT) for trucks is higher and fuel efficiency lower than that of passenger cars.

- Material usage (or costs): the costs or usage of materials for each winter season. If data are available for multiple winter seasons, multiple columns should be used to record usage or cost information. Material usage or costs will be used in estimating safety benefits.
- Crashes: the number of crashes that occurred during a winter season. If data are available for multiple winter seasons, multiple columns will be used to record crash information. The average cost of crashes can be calculated by the weighted sum *AvgC* of different crash types:

$$AvgC = \sum_{i=1}^{n} \frac{N_i}{N} \times C_i$$

  Where:

  N_i = the number of crashes for crash type i (e.g., fatal, injury, Property Damage Only - PDO),
  N = the total number of crashes
  C_i = the cost per crash for crash type i.
- Weather Severity Index (WSI). States may have developed their own WSI at the state, regional, and/or local level. Depending on the geographical level, a WSI value may be associated with multiple route segments. Road Weather Information System (RWIS) and the National Weather Service (NWS) are the common resources for collecting and analyzing weather data. Data collected from the NWS should approximate weather data in the road environment in a manner similar to RWIS.
- Other information can also be collected if such factor(s) may affect winter highway safety. Note that the inclusion of such data in the methodologies presented here and the means to do so will need to be made by the reader.

	A	B	C	D	E	F	G	H	I	J
1	Road Name	JOB_NUMBER	Clas	Length	Speed_Limit	No_Lanes	Crash	Material_Cost	Winter ADT	WSI
2	I 35	TP6R035T	UC	7.99	70	4	31	34386	16063	-12.49
3	I 35	TP6R0351	UC	5.26	70	4	28	29061	18643	-12.49
4	I 35	TP6R0352	UC	13.39	70	4	38	71674	18072	-12.49
5	I 35	TP6X0351	UC	15.97	70	4	75	61897	20298	-18.59
6	I 35	TP1AR101	UC	25.759	70	4	64	81163	19004	-12.02
7	I 35	TP1AR102	UC	21.136	70	4	45	91446	13956	-8.84
8	I 35	TP1AR107	UC	21.673	70	4	44	87103	14104	-10.27
9	I 35	TP1AR112	UC	6.3	70	4	22	59189	18297	-3.34
10	I 35	TP1CR205	UC	13.305	68	4	77	61536	25665	-8.26
11	I 535	TP1CR211	UC	1.541	45	4	12	38660	25420	-13.58
12	I 90	TP7PR102	UC	12.487	70	4	23	57369	8980	-7.81
13	I 90	TP7PR105	UC	14.139	70	4	19	54098	8709	-8.74
14	I 90	TP7PR108	UC	17.119	70	4	29	53897	8270	-8.74
15	I 90	TP7PR114	UC	13.989	70	4	13	45537	7136	-20.00

Figure 5: Example of Developed Spreadsheet

The data needs to estimate the three types of winter maintenance benefits are summarized in Table 3.

Table 3: Data Elements to Estimation Winter Maintenance Benefits

Benefits	Data Elements
Improved Safety	Route attributes (road name, speed limit, etc.) Segment length AADT Material usage (or costs) Crashes (Road) weather information
Travel Time Savings	Segment length AADT LOS of maintenance Truck percentage Snow storm duration
Fuel Savings	Segment length AADT Truck percentage Fuel efficiency for passenger cars and trucks Snow storm duration

Method for Estimating Safety Benefits

To estimate the safety benefits of winter maintenance, it is important to establish the relationship between safety (in terms of crash frequency in this study) and explanatory variables like AADT, maintenance costs, and WSI. This relationship is usually referred to as Safety Performance Function (SPF), as shown in Equation 1. The established SPF can be used to evaluate the effect of independent variables (e.g., winter maintenance in this study) on traffic safety.

$$Crash = f(Length, AADT, WSI, Costs, ...) \qquad (1)$$

In the past two decades, a variety of prediction methods have been developed to investigate factors that affect the likelihood of vehicle crashes. As summarized by Lord and Mannering (*45*), these methods include Generalized Linear Models (GLMs), Generalized Estimating Equation (GEE) Models, Generalized Additive Models (GAM), random-effect models, bivariate/multivariate models, Markov switching models, hierarchical/multilevel models, etc. Among these models, the GLM remains the most widely used method in highway safety, especially the Negative Binomial (NB, also referred to as Poisson-Gamma) regression model that can account for the overdispersion (variance greater than mean) characteristic of crash counts. Due to the heterogeneity of maintained routes (e.g., length, traffic volume, speed limit), crash data will most probably display the characteristic of overdispersion. The NB regression model is thus used for crash prediction. The structure of a NB regression model includes two parts: the distribution function and the link function, as shown in equations 2 and 3.

Distribution function: $Y_{it} | u_{it} \sim Poisson(u_{it})$ (2)

Link function: $u_{it} = f(X; \beta) \exp(e_{it})$ (3)

Where,

Y_{it} = the number of crashes at the *i*th entity and *t*th time period
u_{it} = the mean of the Poisson distribution

$f(\cdot)$ = function of the covariates or variables (X)
β = coefficients of the covariates
e_{it} = model error independent of the covariate.

The distribution function shows that the number of crashes (Y_{it}) at the ith entity (e.g., intersection, road segment) and at the tth time period, when conditional on its mean u_{it} $\mathrm{u_{it}}$, is assumed to be Poisson distributed. In the link function, it is assumed that exp(e_{it} $\mathrm{e_{it}}$) is independent and gamma distributed with a mean equal to 1 and a variance $1/\phi$ ($\phi > 0$)/. With this assumption, the probability distribution of Y_{it} Y_{it} is Poisson-gamma and the parameter ϕ f is the inverse dispersion parameter of the NB distribution (*46*), as shown in Equation 4. The mean and variance of Y_{it} are $E(Y_{it}) = u_{it}$ and $Var\ (Y_{it}) = u_{it} + u_{it}^2/\phi$.

$$\Pr(Y_{it} = y_{it}) = f(y_{it}; u_{it}; \phi) = \frac{\Gamma(y_{it} + \phi)}{\Gamma(y_{it} + 1)\Gamma(\phi)} \left(\frac{u_{it}}{u_{it} + \phi}\right)^{y_{it}} \left(\frac{\phi}{u_{it} + \phi}\right)^{\phi} \tag{4}$$

The functional form of the link function is usually given empirically. The results of crash data modeling will quantify the unknown coefficients (b) of the link function, which describes the relationship between crash frequency and explanatory variables.

Method for Estimating Mobility Benefits

Travel time benefits result from the savings of time traveling on maintained segments. For an ith vehicle, the savings of travel time to pass through a segment is calculated by:

$$TTS_i = L/S_{i1} - L/S_{i2} \tag{5}$$

Where:

TTS_i = travel time saving for the ith vehicle during storm events
L = segment length
S_{i1} = travel speed without winter road maintenance
S_{i2} = travel speed with winter road maintenance

From the above equation, it is important to know the speeds of vehicles traveling on roads with and without winter maintenance. Many research studies have been conducted to investigate the effect of pavement conditions (or LOS) on traffic speed. Ye et al. developed speed adjustment factors for 14 types of pavement conditions mainly based on past research (*47*). However, as winter storms have different impacts on the roadway environment and winter maintenance may have different levels of service, it is difficult to determine pavement conditions with/without winter maintenance at the micro level. Hence, the prevailing pavement conditions with/without maintenance are recommended to simplify the estimation of travel time benefits. For the case without winter maintenance, the pavement condition of “snowcovered” is used whenever snowfall occurs. The associated speed adjustment factor under “snowcovered” conditions is 0.84, based on the work of Ye et al. (*47*). The prevailing pavement condition with winter maintenance performed may be determined by the respective agency. For example, in the case study presented in this text, “slightly slushy” is used to represent the prevailing pavement condition, and the associated speed adjustment factor is 0.90 (*47*). By using this method, it is also necessary to know about the duration of storm events during the studied winter season(s). The speeds with and without winter maintenance will be the same if no snow storm occurs. It is assumed that Vehicle Miles Traveled (VMT) will not be decreased to reflect storm-related trip reduction, although in reality, such a reduction may occur. This method to calculate travel time benefits is conservative since the effect of snowfall is beyond the duration of the snow event itself if no maintenance activities have taken place (note that no travel time benefit calculation in this report has been made using the assumption of no maintenance performed).

Method for Estimating Fuel Saving Benefits

The final benefit of winter maintenance which can be estimated is fuel savings. This benefit is a function of the fuel consumption rate (mpg) on maintained and non-maintained road. Previous studies have found that winter maintenance reduced fuel use by varying degrees (*5*, *48*). Studies in Canada and the United States have shown that vehicles travelled on snow-packed and icy roads consume an average of 33% more fuel, and in some cases as much as 50% more (*48*). Thus, if the figure of a 33% increase in fuel consumption is used for the case of no winter maintenance, the fuel savings derived from winter maintenance can be also derived. The basic information for calculating fuel savings is the million vehicle miles traveled per winter season (ideally by passenger vehicles and heavy vehicles individually), an average vehicle MPG figure (again, by vehicle type) and an average fuel cost for the state/locale during the respective winter season being considered. With this information, it is possible to compute the estimated fuel usage for a no/limited winter maintenance condition (where vehicle MPG is likely reduced) and a condition where winter maintenance has been performed. The approach to calculating fuel use savings is outlined in the following.

For a "no maintenance" condition, fuel use for passenger cars is calculated as:

$$Fuel_{pcNM} = \frac{MVM_{pc}}{MPG_{pc} \times 0.67} \times \frac{Storm_{hrs}}{24} \times Cost_{Avg} \quad (6)$$

Where:

$Fuel_{pcNM}$ = 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

MPG_{pc} = an average passenger vehicle MPG figure

$Storm_{hrs}$ = total storm duration, in hours, per season

$\mathrm{Cost}_{\mathrm{Avg}}$ = 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.

Note that this same equation is used to compute heavy vehicle fuel use. To do so, the subscript of "PC" would become "”HV", with the appropriate data related to heavy vehicle MVM, MPG and fuel cost substituted in.

For the "winter maintenance" performed condition, fuel use for passenger cars is calculated as:

$$Fuel_{pcWM} = \frac{MVM_{pc}}{MPG_{pc}} \times \frac{Storm_{hrs}}{24} \times Cost_{Avg} \quad (7)$$

Where all variables are identical to Equation 6, except for the change of Fuel_{PCWM} to indicate fuel use for passenger cars when improved maintenance is employed is being calculated and the removal of the fuel use adjustment factor, as the use of winter maintenance would result in improved vehicle MPG. Once again, the substitution of “HV” for “PC” will result in the equation to compute heavy vehicle costs. These collective differences in fuel costs between the no maintenance and maintenance condition are computed as:

$$\Delta Fuel = (Fuel_{pcNM} + Fuel_{HVNM}) - (Fuel_{pcWM} + Fuel_{HVWM}) \qquad (8)$$

The result of Equation 8 is the difference in fuel costs between conditions where maintenance is and is not performed. Conceptually, the costs of fuel under the limited maintenance condition will be higher than those when winter maintenance is performed. This is shown to be the case in the following chapter.

This approach does have the limitation of not being precise regarding the true performance of vehicles under different levels of winter maintenance. For example, vehicle MPG under ideal winter maintenance may not be the same as under optimal (clear, dry and warm) conditions. However, no research has been conducted to date that establishes whether different MPG results from different road surface conditions (LOS) during a winter storm. However the above approach can be considered a starting point for the purposes of generally establishing the vehicle fuel savings resulting from winter maintenance.

Chapter Summary

This chapter has outlined the methodologies that will be demonstrated in the next chapter to estimate the benefits of winter maintenance operations. The three benefits of winter maintenance that can be readily quantified include the savings derived from reduced crashes, travel time savings, and fuel use savings. A number of data elements were identified as needed to estimate these benefits, including roadway attributes (speed limits, number of lanes, etc.), road segment lengths, daily traffic, percentages of truck traffic, material usage or costs, crashes, and a weather severity index.

To estimate safety benefits, a Negative Binomial model was established (with its application discussed in the following chapter) to predict the number of crashes that could be expected to occur under different winter maintenance scenarios. The changes (ideally reductions) in crashes and the financial savings as a result of improved maintenance represent the benefits of winter maintenance on safety.

Travel time savings resulting from differences in travel speeds over road segments under different levels of winter maintenance were established as the method to estimate the second category of quantifiable benefits of winter maintenance. Once again, improved travel speeds on road segments where higher levels of winter maintenance were performed represent financial savings; in this case, through reductions in road user delay and in lost productivity.

Finally, the differences between vehicle fuel usage under storm conditions where maintenance is or is not preformed were established to estimate the fuel savings, the third category of quantifiable benefits of winter maintenance. This method is based on the concept that vehicle MPG will decrease on roads with limited winter maintenance performed, whereas it will increase as the level of winter maintenance is increased. The differences between these levels of fuel usage can be used to estimate the financial savings in fuel usage accrued through winter maintenance.

CHAPTER 4

Demonstration of Methodologies

Overview

This chapter presents a demonstration of the methodologies developed to estimate the benefits of winter maintenance operations. Minnesota was selected as the case study state to estimate safety, travel time and fuel use benefits associated with winter maintenance. This state was selected based on the availability of comprehensive datasets encompassing the elements previously outlined as necessary for the methodologies, as well as the fact that it represents a comprehensive example of different winter storm conditions/severities over the course of a typical winter. The data collected for this case are first introduced, and then the results obtained by using the previously described methods are presented and discussed.

Data Collection and Preprocessing

Maintenance Routes

A spreadsheet containing information on Minnesota highway winter maintenance was obtained from the Minnesota Department of Transportation (Mn/DOT). The spreadsheet contained highway segment information such as route number, name of the plow route, maintenance job number, name of truck station, and start and end mileposts. This information is representative of that which is collected by most agencies for various purposes. The spreadsheet was used to establish the route segments employed in the analysis, with 888 maintenance segments distributed along 198 numbered highways (6 interstate highways, 19 US routes, and 173 state highways). These route segments covered 11,839 centerline miles. Ultimately, 828 segments were retained for analysis due to missing data for some route segments.

Speed Limit and AADT

A GIS shapefile was obtained from Mn/DOT and included milepost, speed limit, AADT, etc. information for the State. The data records in the shapefile were mapped to route segments in the spreadsheet discussed previously. It should be noted that a route segment consisted of one or more records in the shapefile that had the same route name and starting and ending mileposts. Thus, the speed limit and AADT data are actually aggregated information. For example, if a route segment was separated into n sub-segments and each sub-segment corresponded to a record in the shapefile, the aggregated speed limit (SP) for this segment can be calculated by:

$$SP = L / \sum_{i=1}^{n} \frac{L_i}{SP_i} \tag{9}$$

Where:

SP_i = speed limit of the ith sub-segment
L_i = length of the ith sub-segment

$$L = \sum_{i=1} L_i \text{ is the segment length}$$

The AADT for route segments were calculated in a similar way and included the years from 2001 through 2006. In addition, truck AADT were obtained from Mn/DOT records. Based on the AADT and truck AADT data, truck percentages in each year were calculated for the maintained segments. Further calculations were processed to estimate winter ADT and truck ADT. To make such estimates, a statewide seasonal adjustment factor was developed based on monthly data collected from 72 Automated Traffic Recorder (ATR) stations for the years of 2005 and 2006. The general process was to take a twelve month period, calculate the average daily traffic (ADT) volume during the winter months (November through March), and divide by the ADT over the entire twelve-month period, that is, the AADT. This generated a seasonal adjustment factor for each site. The average value (0.919) of the 72 adjustment factors (one value per station) was used and applied to all route segments, assuming that truck percentages remained the same during winter season as the whole year. Finally, the average data of winter ADT and truck ADT for the six winter seasons were used for the analysis of winter maintenance benefits.

Crash Data

Five winter seasons (from 2001-02 to 2005-06) of crash data were also obtained to determine the number of crashes on each segment. For simplicity, the average number of crashes during the six winter seasons was used to estimate an average crash rate (number of crashes per winter season), without considering any effects of changing traffic volumes on crash rates in a given year. The average crash count was 19 crashes per winter season per segment, and the standard deviation was 34 crashes per winter season. The total numbers of crashes by crash type (property damage only, injury, and fatality) were also calculated and later used to calculate an average crash cost.

Weather Data

Hourly weather data from 60 weather stations were obtained from Mn/DOT, and only winter season data were kept. The data included recorded precipitation, maximum and minimum temperature, snow depth, wind speed and direction, visibility, and dew point information. The approximate locations of these weather stations are illustrated in Figure 6. The collected data were first reduced to only include the winter seasons of 2001 through 2006. Those winter seasons missing more than 25 percent of the hourly observations were excluded. The reduced dataset was used to calculated Winter Severity Index (WSI) values.

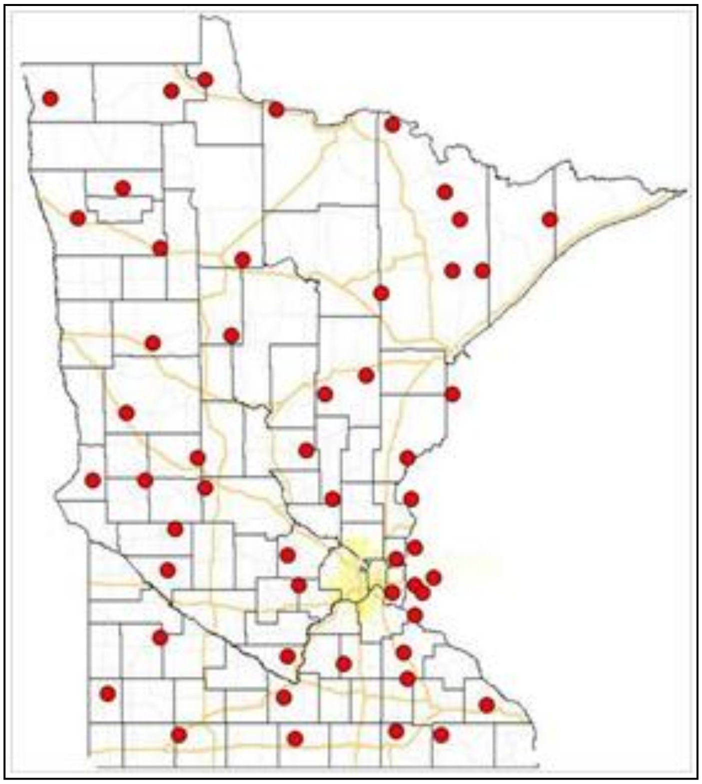

Figure 6: Weather stations in Minnesota

Currently, several indices may be used to measure winter weather severity (*49*). A commonly used WSI is the index proposed in the Strategic Highway Research Program (SHRP) study (*50*). This index is calculated based on the mean daily snowfall, and minimum and maximum temperatures averaged over the season, as shown in the following equation:

$$WSI = a\sqrt{TI} + b\ln(\frac{S}{10}+1) + c\sqrt{\frac{N}{R+10}} + d \qquad (10)$$

Where:

TI = temperature index. $TI = 0$ if the minimum air temperature is above 32^{0}F (0^{0}C); $TI = 1$ if the maximum air temperature is above 32^{0}F (0^{0}C) while the minimum air temperature is at or below 32^{0}F (0^{0}C); and $TI = 2$ if the maximum air temperature is at or below 32^{0}F (0^{0}C). The average daily value is used.

S = snowfall, using mean daily values in millimeters

N = mean daily values of number of days with minimum air temperature at or below 32^{0}F (0^{0}C), ($0 \le N \le 1N$).

R = the value of mean monthly maximum air temperature minus mean monthly minimum air temperature, in ^{0}C.

a, b, c, d = coefficients.

The values of the coefficients derived by the SHRP study (*50*) with reference to the U.S. climate were used ($a = -25.58; b = -35.68; c = -99.5; d = 50.0$) in this work to calculate WSI values. The WSI has a range from -50 (most severe weather and maximum level of snow and ice control), through 0 (not too severe weather and mean level of snow and ice), to 50 (warm weather and no need of snow and ice control).

The latitude and longitude information of each weather station were also gathered. The WSI value for a certain maintenance segment was determined by identifying the nearest weather station (in terms distance calculated by latitude and longitude). Thus, multiple segments could share a WSI value.

Winter Maintenance Data

Material costs for each route segment during the winter seasons of 2001-02 through 2005-06 were obtained from Mn/DOT. The average costs were calculated for the five winter seasons used in this case study. Minnesota used three types of materials - salt, sand, and brine - for highway maintenance during the study time period. The majority of material costs were from the use of salt, which contributed to more than 90 percent of total material costs. The majority of material costs were from the use of salt, which contributed to 93.4 percent of total costs. The average winter maintenance cost for the 888 segments was approximately $37 million dollars per winter season (in 2006 values). Other winter maintenance costs (e.g., labor cost, equipment usage costs) were not available for the winter seasons investigated.

Analysis of Safety Benefits

With the preprocessing of the collected data, the following variables were developed to support the analysis: crash = f(length; winter ADT; Material Cost; WSI). In this function, the crash, winter ADT, material cost, and WSI variables represent the average values for the five winter seasons (2001-02 through 2005-06). There were missing data (e.g., material costs, crashes) for some maintenance segments. In such a case, the maintenance segment was excluded from further analysis (60 segments were excluded). The final dataset included 828 maintenance segments.

To establish the crash prediction model, its functional form was defined as follows:

$$u_i = \beta_0 \times L_i \times ADT_i^{\beta_1} \times e^{\beta_2 \times C_i + \beta_3 \times WSI_i} \qquad (11)$$

Where:

u = crash frequency of the *i*th segment
L = length of the segment (mile)
ADT = winter ADT of the segment (vehicle/day)
C_i = material cost of the segment ($/winter season)
WSI_i = weather severity index of the segment
$\beta_0, \beta_1, \beta_2, \beta_3$ = coefficients

It is noted that if maintenance materials are broken into different types and cost information for each type of materials is available at the segment level, multiple material costs (as independent variables) and associated coefficients can be used in the functional form. In the case a different unit of measurement for costs (e.g., cost per lane mile, cost per centerline mile), the unit should be consistent for all route segments.

The 828 records were employed in the NB regression model, with the modeling results shown in Table 4. It can be observed that the coefficients of β_0, β_1, β_2 are significant at the level of 0.01, while β_3 is not. The results indicate that segment length, winter ADT, and material costs significantly contribute to the occurrence of accidents. The negative value of β_2 indicates that the use of winter maintenance materials reduced crashes. Conversely, segment length and winter ADT had positive effects on the number of crashes; that is, the number of crashes increase with the increase in segment length and winter ADT. Through the results of the NB regression, the functional form in Equation 11 becomes:

$$u_i = (9.487 * 10^{-5}) * L_i * ADT_i^{1.104} * e^{(-1.959*10^{-6})*C_i} \tag{12}$$

Table 4: Modeling Outputs of the NB Regression Model

Coefficients	Est. Value	Std. Error	*z* value	*Pr(>|z|)*
β_0	9.487e-06	1.626e-01	-56.957	< 2e-16
β_1	1.104	1.938e-02	56.974	< 2e-16
β_2	-1.959e-06	4.980e-07	-3.934	8.36e-05
b_3	-3.308e-03	3.781e-03	-0.875	0.382

Note: the dispersion parameter for the NB regression is 6.

The value of β_3 is negative, which makes sense since higher WSI values are associated with warmer weather. However, WSI is not a significant factor contributing to safety, which may be due to the following reasons. First, the weather stations may be not close to respective road segments and do not reflect road weather along those segments well enough. Weather data from Road Weather Information Systems (RWIS) are preferred if available as they are installed in the roadway environment. Secondly, it was found that there was a fair amount of missing data in the collected datasets. In some cases, there were no precipitation events recorded throughout an entire winter season (such datasets were removed from analysis). Finally, many segments had similar weather severities, which cancelled out the effects of weather severity on crashes. The average and standard deviation WSI values of the segments were -14.14 and 5.51, respectively. Table 5 shows the average snow amount at the district level over the 2001-06 period. It can be seen that the snow amounts of Districts 2 through 8 are between 40 inches and 57 inches per winter season, while District 1 had a much higher snow amount.

Table 5: Average Snow Amount of Districts (2001-06 winter seasons)

	District 1	2	3	4	5	6	7	8
Snow Amount (inches)	85	44	51	57	52	40	42	47

A goodness-of-fit (GOF) test for the crash prediction model was conducted to see how well the model fit the observations. The scaled deviance (G^2) was used for this purpose. The GOF value was equal to 742.08 and the degrees of freedom were 824. The p-value ($0 \leq$ p_value ≤ 1) of the GOF test was 0.99, which means that the crash prediction model has a strong fit of the observed data. Thus, the developed relationship between safety and associated independent variables (Equation 12) is reasonable for further use in evaluating the effect of winter maintenance on traffic safety on Minnesota roads.

To analyze the safety benefits of winter maintenance, the maintenance costs for all maintenance segments were set as 0, and the predicted crash values represented the number of crashes that could have been expected had no winter maintenance activities been carried out. For the 828 maintenance segments, it was predicted that 20,275 crashes (per winter season) would have occurred without winter maintenance.

Compared with the number of crashes (15,675) that happened with winter maintenance, it was found that winter maintenance reduced crashes by 29.4%. Given the average cost per crash ($36,453) as shown in Table 6, the safety benefits of winter maintenance were estimated to be approximately $167.7 million dollars per winter season.

Table 6: Average Crash Cost in Minnesota (in 2006 values)

	Cost (in year 2006)	No. of Crashes (in five winter seasons)
Fatal	$3,500,000	531
Injury	$49,000	14,480
Property Damage Only (PDO)	$2,700	59,870
Average Cost ($/crash)		$36,453

Analysis of Travel Time Benefits

A straightforward approach was employed to calculate travel time savings by determining traffic flow speeds with and without winter maintenance (Equation 5). In this study, it was assumed that for a given segment, normal (dry pavement conditions) vehicle speeds are set as speed limit (S_{sl}), and vehicle speeds without maintenance (S_{i1}) correspond to the speeds under "snowcovered" pavement conditions during snow storms, which is $S_1 = 0.84 * S_{sl}$ (*47*). In order to determine vehicle speeds with maintenance, pavement condition and snow storm duration data were gathered for the five winter seasons for a maintenance segment on I-94 in District 3, with mile posts starting at 156.229 and ending at 166.632 (10.333 miles in length). Mn/DOT has recorded snow storm durations at a district level, and the total snow storm duration for the five winter seasons was 1182 hours in District 3. Pavement conditions for this segment and associated speed reduction factors are summarized in Table 7. It was found that "Lightly Slushy" was the prevailing pavement condition during snow storms. The storm duration under this pavement condition was 1188 hours (71 percent), and is very close to the duration of snow storms (1182 hours). Thus, the vehicle speed with winter maintenance (Equation 5) was set to $S_2 = 0.90 * S_{sl}$.

Table 7: Pavement Condition and Associated Speed Reduction Factors

Pavement Condition	Duration (hrs)	Speed Reduction Factor
Chemically Wet	49	0.96
Compacted Snow	180	0.87
Deep Slush	4	0.84
Dusting of Snow	3	0.96
Icy	6	0.85
Lightly Icy	60	0.94
Lightly Slushy	1188	0.9
Lightly Snowcovered	7	0.89
Slushy	173	0.87
Snowcovered	2	0.84
Total	1672	

Note: speed reduction factors were from reference (*47*).

With the identification of vehicle speeds with and without maintenance during snow storms, travel time benefits for a given segment can be estimated through the following equation:

$$TTS = Dur \times (L/S_1 - L/S_2)(VOT_{PC} \times ADT_{pc} + VOT_{truck} \times ADT_{truck}) \quad (13)$$

Where:

TTS = travel time savings for a maintenance segment
Dur = duration of snow storms in a winter season (days). The average duration of snow storms at the district level are presented in Table 8.
L = length of the segment
S_1 = vehicle speed without maintenance under snow storms. In this case, $S_1 = 0.84 \times S_{sl}$
S_2 = vehicle speed with maintenance under snow storms. In this case, $S_2 = 0.90 \times S_{sl}$
VOT_{PC} = value of time for passenger cars. In this case, the value is assumed \$15.50 dollars per hour (in 2006 value) (*47*).
VOT_{truck} = value of time for trucks. In this case, the value is assumed \$26.30 dollars per hour (in 2006 value) (*47*).
ADT_{pc} = average daily traffic of passenger cars during the winter season
ADT_{truck} = average daily traffic of trucks during the winter season

Table 8: Average Snow Storm Duration in Minnesota (2001-06 winter seasons)

	District 1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Duration (hrs)	309	165	253	294	155	183	228	219

The results of calculations using Mn/DOT data and Equation 13 found that travel time benefits from maintaining the 828 route segments was \$10,915,699 dollars per winter season (in 2006 value). Compared to safety benefits (\$167.7 million dollars), this illustrates that the major benefits of winter maintenance result from reducing vehicle crashes. This is not surprising however, given that it is difficult to accurately quantify the true extent of lost time by motorists because of different road conditions throughout the highway network.

Analysis of Fuel Savings Benefits

The differences between vehicle fuel use under storm conditions where maintenance was or was not preformed was used to estimate the fuel savings benefits of winter maintenance. This method is based on the concept that vehicle MPG will be reduced when roads have limited winter maintenance performed, but MPG will improve/increase as the level of winter maintenance is increased. The differences between these levels of fuel use can be quantified to determine the financial savings in fuel use accrued through winter maintenance.

Studies in Canada and the United States have shown that vehicles travelled on snow-packed and icy roads consume an average of 33% more fuel, and in some cases as much as 50% more (*5*). For this work, it was assumed that a 33% increase in fuel consumption was the result of no/limited maintenance being used throughout the roadway system. Conversely, the normal, or average, MPG for the vehicle fleet is assumed to be the result of improved winter maintenance. Admittedly, these are less than ideal assumptions, and it is unlikely that the average vehicle MPG would be achieved even with the conduct of perfect winter maintenance on all roads. However, for the purposes of demonstrating this methodology and establishing an initial indication of the financial benefits in fuel savings resulting from winter maintenance, the average vehicle MPG was used. Note that a reader that chooses to perform their own calculations using this approach may incorporate a reduction in vehicle MPG for a high winter maintenance LOS condition by assuming their own reduction factor. For example, if it is assumed that even under ideal winter maintenance vehicle MPG is reduced by 10 percent, this factor may be incorporated into Equation 6 by replacing the 0.67 factor with 0.90.

For the case demonstrated here, vehicle miles traveled per day data for passenger cars and trucks (heavy vehicles), storm duration per year (in hours, and an average vehicle fleet MPG for the analysis year (from the Bureau of Transportation Statistics) (*51, 52*) were used. For 2006, the national averages for passenger cars was 27.5 MPG and 5.9 MPG for heavy vehicles (trucks). Similarly, average fuel costs by year are available for the U.S. (from the U.S. Energy Information Administration [EIA]) (*53*). For 2006, the average cost of gasoline was $2.62 per gallon, while diesel cost $2.71 per gallon. These figures include state and federal taxes, which should be deducted from the various calculations as they represent a fiscal transfer and not a benefit. In 2005-2006, the average state tax in Minnesota was $0.20 for gasoline and $0.20 for diesel (*54*). The 2005-2006 federal tax for gasoline was $0.184, while the tax for diesel was $0.244 (*55*). Subtracting these combined taxes from the average fuel prices for 2006 produces a gasoline price of $2.236 and a diesel price of $2.266. Note that, if available, local averages can be employed, as fuel costs typically vary from region to region. For simplicity, the annual average cost has been used here; however, a reader could also employ a more precise average from only the winter months of interest given that this level of detail is available from the EIA in some cases. Table 9 summarizes the data used to determine the fuel savings resulting from winter maintenance.

Table 9: Inputs for Calculating Fuel Savings of Winter Maintenance

Vehicle Miles Traveled per winter season	Passenger Car (million miles/day)	69.97
	Truck (million miles/day)	6.29
Average Fuel Efficiency (2006)	Passenger Car (mpg)	27.5
	Truck (mpg)	5.9
Average Fuel Price (2006)	Gasoline	2.236
	Diesel	2.266
Duration of Snow Storms per Winter Season (hrs)		236

Based on the calculations of Equations 6 and 7, the resulting costs of fuel associated with and without winter maintenance were estimated, with the results presented in Table 10. As these results indicate, there is a significant difference, particularly for passenger vehicles, in the amount of fuel used and the resulting cost of that fuel between conditions where winter maintenance is and is not used. The same is true for trucks, albeit to a lesser extent, given the lower number of vehicle miles traveled each day by this type. While developed on an assumed basis, the cumulative fuel savings of $48,404,214 for the 2006 winter season indicates that winter maintenance does produce significant benefits in terms of fuel use and financial savings. The total savings presented here are likely lower in practice, as the assumption of low levels of winter maintenance being performed on all roads does not reflect the reality of winter operations. Still, the fuel savings generated by winter maintenance are substantial, and likely represent a larger benefit than travel time savings, particularly outside of an urban environment.

Table 10: Fuel Savings from Winter Maintenance

Vehicle Type	Passenger Car	Truck
MVM/Day	69,970,000	6,290,000
MPG (w/o main't)	18.15	3.894
MPG (w/ main't)	27.5	5.9
Fuel cost	2.62	2.71
Storm Duration (days)	9.83	9.83
Fuel cost (w/o main't)	$84,763,290	$35,992,778
Fuel cost (w/ main't)	$55,943,771	$23,775,233
Fuel Savings	**$28,819,519**	**$12,237,544**
Fuel Savings Totals		**$41,057,063**

Chapter Summary

This chapter has presented a demonstration of the methodologies developed in Chapter 3 to estimate the benefits of winter maintenance. This included an estimation of the benefits to safety (savings from reduced crashes), travel time (motorist delay/lost productivity), and fuel cost (savings from reduced fuel consumption), as these represent the benefits of winter maintenance that can readily be quantified from existing data and are supported by part research findings. Data from the Minnesota DOT from the winter seasons between 2001-02 and 2005-06 were used in these demonstrations to provide real world estimates of the value of these benefits.

Using the data as a case study and following the above mentioned methodologies, the researchers estimated the quantified benefits of winter highway maintenance by the Minnesota DOT to be $227,003,713 per winter season. This represents a significant benefit. A review of each of the individual estimations is in order.

When analyzing safety benefits, it was found that the expected number of crashes that would have occurred had no winter maintenance been performed was 20,275, compared with the 15,675 that were actually observed under the Minnesota DOT maintenance conditions. This difference of 4,600 crashes, when multiplied by an average crash cost of $36,453 for Minnesota, indicated that winter maintenance activities on the entire highway system of Minnesota produced a financial savings of $167,683,800. This figure clearly indicates that winter maintenance produces a considerable benefit from reduced crashes, both financially, and to society as a whole.

The benefits of improved travel times from winter maintenance were estimated by comparing expected vehicle speeds under pavement conditions without winter maintenance performed to those where maintenance resulted in a prevailing pavement surface condition of “lightly slushy” (the most frequently observed condition in the available data). Results of calculations indicated that, for the 828 route segments, a benefit of $10,915,690 in travel time savings was achieved. This lower figure (relative to the value of safety benefits), was in part attributable to the difficulty in quantifying the extent of lost time of motorists because of different road conditions. Still, this figure illustrates that winter maintenance has a positive benefit on reducing delay to motorists.

The final benefit of winter maintenance that was quantified was fuel savings. For this estimate, fuel usage differences were compared between conditions where winter maintenance had been performed to those where only no (or very little) winter maintenance had been conducted. This approach to estimation was based on the logic that one would expect vehicle fuel efficiency (in MPG) to decrease under poorer road conditions where limited maintenance is performed. Estimation results found there is a substantial difference in the amount of fuel used and the resulting cost of that fuel between conditions where winter maintenance is and is not used. This is particularly true for passenger vehicles. The same applies to trucks, albeit to a lesser extent, given the lower number of vehicle miles traveled each day by this type. While developed on an assumed basis, the cumulative fuel savings of $41,057,063 for the 2005-06 winter season indicate that winter maintenance produces significant benefits via reduced fuel usage. Note that in reality the level of winter highway service is generally better than the worst-case scenario and the actual fuel savings of improved winter maintenance operations are thus lower than the numbers shown above.

Given that the material cost per winter season was $36.6 million dollars (for the 828 maintained segments), the benefit-cost ratio of winter maintenance was 6.0., without the consideration of other costs (e.g., labor, equipment). The specific figures used in calculating this ration are presented in Table 11.

Table 11 Benefit-Cost Analysis of Minnesota Case Study

Benefits	Safety (million dollars)	$167.7
	Mobility (million dollars)	$10.9
	Fuel (million dollars)	$41.0
Cost (million dollars)		$36.6
Benefit-cost Ratio		6.0

CHAPTER 5

Future Research and Recommendations

Overview

During the course of the research, a number of data and methodological issues and needs have been identified and that should be addressed through future research efforts. This chapter provides a summary and discussion of those findings, and provides recommendations for future research to enhance existing methodologies as well as address data and methodological gaps that exist. Finally, this chapter will provide recommendations for the implementation of the findings and methodologies developed as part of this research.

Issues

First, the methodologies developed by this research, and all methodologies developed to date (except for Hayashiyama et al., *15*), focused on direct benefits. This is understandable, given that they can be measured and quantified in some way. However, indirect benefits, such as the benefit of winter maintenance on continued emergency services, remain unaccounted for. The development of an approach to account for indirect benefits needs to be researched further for incorporation in future estimation activities.

Various data issues also exist which have varying impacts on the methodologies. First and foremost, the requisite data must be available, both in a collected and recorded form and a usable format. In some cases, an agency, particularly at a local level, may not have all of the data employed in the methodologies developed here available to them. This may be the result of not having collected that data to not having data in a usable format (e.g., electronic). In the latter case, paper logs of material usage are still common throughout the winter maintenance community, and such records will need to be converted to an electronic format (e.g., spreadsheet) in order to be used in estimating benefits.

Another data issue that needs to be considered when employing the methodologies is that different agencies may employ different pavement condition levels (or information). As a result, the reader may need to make conversions or adaptations of their scale to that used in the methodologies presented here.

The prior issue underscores a larger one that is present throughout the winter maintenance community, that of different approaches to performance measurement and the data being collected. Different agencies collect different information of interest to them, sometimes in a different format/scale/etc. than their counterparts. While there is nothing wrong with doing so, this creates a challenge in developing methodologies that are capable of employing different types or measures of data from different agencies in a common manner. Once again, the reader may need to make conversions or adaptations of their scale to that used in the methodologies presented here. In cases where data is collected and saved in an electronic format, conversions between one measurement scale and another may also be necessary, such as converting snowfall depths from inches to millimeters.

In some cases, general data may be available but not specific to the winter season, such as traffic. Many states/agencies provide conversion factors by month throughout the year to convert ADT and AADT data from the month the data was collected to remaining months of the year. However, these factors do not account for travel that occurs specifically during storms. Past studies have examined travel patterns during winter weather which should be consulted, and automated technologies such as Automatic Traffic Recorders (ATR) can also provide storm-specific information. However, the reader should bear in mind that certain data elements employed in the methodologies are localized and may require some individual collection or tracking via automated systems.

Data management is also an issue, particularly given the quantities of data used in the methodologies presented in this report (and also used by other approaches). Multiple years of data may be available to agencies, both in digital and paper format. The challenge is managing that data and formatting it in such a manner that it can be useful, both in the estimation of winter maintenance benefits, as well as in other reporting and analysis capacities. The approach used in setting up the database for analysis by the methodologies discussed here has been presented, and this may prove useful for consideration beyond the confines of benefit estimation.

The comfort level of winter maintenance professionals with the developed methodologies may be an issue. This is especially true of the safety data modeling methodology. While the approaches have been presented in this report in a manner to facilitate replication by different users, they may still be daunting. Not all agency personnel are familiar or comfortable with the statistical modeling of safety, nor is the time available to learn given their workload and available funding. Consequently, there is a need to automate the process in the longer term, which will be discussed later in this chapter.

While the methodology developed by this research incorporates the major aspects of winter maintenance benefits, it does not completely capture the complex interaction of different maintenance materials, equipment and operations, which can potentially vary from season to season (or even storm to storm). Some combinations of materials and equipment during one storm will produce benefits that may not necessarily be accrued in another storm, depending on the storm's characteristics. In this sense, the individual contributions of materials, equipment and operations separated but rather, are considered collectively.

An understanding of the changes to fuel use for different types of vehicles on roads with different winter maintenance LOS is also needed. No such information from any recent study was identified during the course of this work, which has resulted in the use of the assumptions incorporated in the fuel savings methodology. Once again, this is a research need that will be discussed in a later section of this chapter. Similarly, the speed changes during a storm used in the methodology will likely vary by locale, and additional, location-specific factors may need to be developed through data collection efforts.

Winter storms and the winter maintenance that goes on during them are never static. This results in the issue where an average LOS for a storm must be employed in estimating winter maintenance benefits. At present, it would be difficult to measure, let alone track the different LOS that may be present throughout the roadway system at a given time during a storm, but if this is possible in the future, it should be incorporated in estimation approaches.

Finally, the transferability of the developed methodologies may be an issue. While it was developed to use data that is commonly available in a general sense, not all agencies may collect the different data elements used. In this case, the methodologies may not be able to be used in their entirety. Furthermore, the methodologies are not in an automated program/software format, which may make their use daunting to some potential users. While other approaches discussed in the literature review are automated, these are also being developed for local entities using data and assumptions specifically from that locale. This represents a limitation to those methodologies.

Future Research

As a result of this work, a number of future research directions have been identified. These stem from the issues discussed in a previous section, as well as from general observations made during the course of investigating the benefits of winter maintenance. The following paragraphs present these future research opportunities.

The methodology developed by this research did not incorporate the indirect benefits of winter maintenance. This was the result of limited information pertaining specifically to those benefits. At present, they are generally known (e.g., continued emergency services during a storm and the resulting public benefit), but no detailed investigations have been made to quantify the value of these benefits. Future work should therefore attempt to fully identify and value such benefits. This will entail identifying the means of measuring such benefits and tracking them.

Additionally, the methodology that has been presented here, while presented in a step by step manner to facilitate application at other agencies, may still be somewhat daunting to staff. However, if converted to a software or web-based tool, estimation of winter maintenance benefits would likely be less daunting to users, as such approaches would require data input and complete estimation and analysis activities internally. Of course, the drawback to this approach is that it could potentially become a "black box" where information is fed in by the user and an answer churned out. In such a case, it may not be readily apparent to the user what calculations are being made, the assumptions employed, and so forth, although this concern could be minimized by adequate user manual documentation.

One of the notable current information shortcomings identified during this work was the lack of hard figures related to vehicle fuel use on roads with different LOS during a winter storm. This information is central to estimating the level of fuel savings that winter maintenance can produce, yet only generalized figures appear to be available. Consequently, there is a research need to identify the impacts on vehicle fuel efficiency (mpg) for different winter storm roadway conditions by vehicle type. Vehicle type is especially of interest, as it is reasonable to expect notable differences between passenger and heavy vehicles along the same roadway segment. The availability of such information will allow for more accurate estimates of the fuel savings generated by winter maintenance to be made.

Although more challenging to develop and implement, the possibility of standardizing the collection and recording procedures of data (and even establishing what data are collected) pertaining to winter maintenance should be investigated. While the need to record different data in different formats is partly driven by need (e.g., legislative reporting requirements), this can have a significant impact on estimating the benefits of winter maintenance. With a more uniform approach to data collection and recording, different agencies can begin to be "on the same page", so to speak, and able to develop estimates that can be directly compared to one another.

Recommendations for Transferability and Implementation of Developed Methodologies

The next step beyond this work may be the initial implementation of the methodologies discussed in this report by agencies. This would be an integral step in better understanding the benefits of winter maintenance on a larger scale. Agencies may complete the various calculations on a one year trial or for multiple years to have a better grasp of how the cumulative benefits of winter maintenance vary from year to year. In applying the methodologies discussed here, benefit figures will be derived in a common manner and allow comparisons to be made between agencies, based on metrics such as system mileage, average WSI, average LOS, and so forth. The following paragraphs provide some initial thoughts on how the work of this report may be implemented by agencies.

Implementation of the safety benefit methodology may be perhaps the most challenging for agencies. The approach which was employed involved the development of a Negative Binomial crash prediction model. The model presented in this report has been developed from Minnesota data and based on different conditions and variables from that state. Consequently, the specific model functional form (Equation 12) should not be considered directly applicable in other states. However, the general model functional form presented in Equation 11 can be employed by other agencies in developing a specific prediction model for their locale. The estimation of the model based on this form is not typically an activity that winter maintenance personnel are tasked with completing. However, at many agencies (particularly state departments of transportation), there is institutional experience with the type of safety analysis and modeling activity. In such cases, development of the safety model to estimate the number of crashes using the approaches presented in this report may be completed in cooperation with other agency personnel outside of the winter maintenance area, such as traffic safety engineers. The resulting model will provide an estimation of the crashes expected in the absence of winter maintenance that can then be compared to actual observed crash experience. From this comparison, the financial savings estimation can be made to arrive at the safety benefit of winter maintenance. The majority of the data used in the safety analysis are recorded directly by agencies; those elements that are not directly recorded can often be converted or estimated from complimentary datasets.

The travel time savings methodology should be straightforward to employ and can be completed by any agency personnel. The data elements employed by this approach are readily available from agency files in most cases (truck traffic levels may need to be estimated). Also, the value of time for different motorists (passenger cars versus trucks) may need to be assumed based on locale. Once the requisite data is collected, the application of Equation 13 is straightforward and can be completed in a spreadsheet environment. Using a spreadsheet, a number of different estimations can be made, including a system-wide benefit estimate, estimates at the region, district or garage/shed level, estimates for different roadway functional classifications, and so forth. Different estimates may be of interest for the comparison of performance between these different levels.

Finally, the fuel savings methodology is also expected to be straightforward and again completed by any agency personnel. The data elements used by this methodology are typically collected at most agencies, although some estimates may be needed to arrive at a figure for million vehicle miles traveled per day by trucks for example. Additionally, some assumptions may be necessary, such as averages for reduced vehicle fuel efficiency between different LOS. Once again, with the requisite data collected, the application of the methodology is direct using Equations 7 and 8. Equation 7 provides an estimate of passenger car and truck fuel costs under different maintenance conditions, while Equation 8 provides the approach to calculating the differences in the computed fuel costs to produce the resulting fuel savings. A spreadsheet may be used in completing these calculations, and in doing so, different levels of estimates may be completed for comparison purposes.

The methodologies presented in this report have been developed to make use of data which is typically collected in some form by agencies. Furthermore, the use of that data in estimating the travel time and fuel savings benefits of winter maintenance employs basic linear equations and requires no specific skillset. The application of the safety benefit methodology is more intensive, but this may also be completed through coordination with other agency staff, such as traffic safety engineers or others with experience in statistical modeling and evaluation. Because the methodologies presented in this report are straightforward, their implementation by agencies should not present a significant obstacle. Through implementation, a better understanding of the collective benefits of winter maintenance can be developed.

CHAPTER 6

Conclusion

Overview

The work presented in this report has sought to establish approaches to estimate the benefits of winter maintenance. A literature review was completed to identify the general benefits of winter maintenance, establish which ones were quantifiable, and determine if any existing methodologies or approaches existed that could be transferable to this work and general agency usage. It was found that these were limited in number and developed for specific applications and not directly transferable. Based on the literature review, it was determined that the benefits which could be directly quantified using existing agency data included safety improvements (reduced crashes), travel time savings, and fuel savings. Consequently, methodologies were developed to estimate each of these benefit components. Different issues and limitations with these methodologies have been identified and discussed, and future research needs based on these have been identified and presented for consideration. The following sections discuss the various work completed during the course of this research, as well as its results and findings.

Summary of Literature

One of the primary tasks of this work was to identify and review current literature relevant to the estimation of the benefits of winter maintenance operations and the methods employed to determine them. The focus of the review was on work which has resulted in the determination of quantified benefits (i.e. benefits which have been numerically established, either in terms of dollars or another metric), as well as qualitative benefits (i.e. those which cannot be assigned a numerical value).

A number of conclusions were drawn from the literature review regarding benefits of winter maintenance operations and the methods employed to determine those benefits. With respect to the benefits of winter maintenance operations, in general both their direct and indirect benefits have been identified in a qualitative sense. In some cases, quantitative estimates have been developed. These estimates varied depending on the approach and specific metrics (e.g., traffic, safety, and material usage) employed in estimation. With respect to estimation methods, more sophisticated approaches have been recently developed (Sweden) or are in the midst of development (Canada). Aside from these specific examples, the estimation of winter maintenance operations benefits focused on specific aspects (e.g., traffic operations and accidents) or individual components (e.g., weather information). Consequently, a comprehensive method to estimating the benefits of winter maintenance operations does not truly exist in a form that can be used “off the shelf”. The key result of the literature review was the identification of the quantifiable benefits of winter maintenance, including safety improvements, travel time savings and fuel use savings. Consequently, methodologies for estimating these benefits were developed.

Development of Methodologies

The three benefits of winter maintenance identified which could be readily quantified required the development of three estimation methodologies. A number of data elements were identified as needed to estimate these benefits, including roadway attributes (speed limits, number of lanes, etc.), road segment lengths, daily traffic, percentages of truck traffic, material usage or costs, crashes, and a weather severity index.

To estimate safety benefits, a Negative Binomial model was established to predict the number of crashes that could be expected to occur under different winter maintenance scenarios. The changes (ideally reductions) in crashes and the financial savings as a result of improved maintenance represent the benefits of winter maintenance on safety.

Travel time savings resulting from differences in travel speeds over road segments under different levels of winter maintenance were established as the method to estimate travel time benefits. Once again, improved travel speeds on road segments where higher levels of winter maintenance were performed represent a financial savings, in this case, a savings of motorist time through reduced delay and lost productivity.

Finally, the differences between vehicle fuel use under storm conditions where maintenance is or is not preformed were established to estimate the fuel savings benefits of winter maintenance. This method is based on the concept that vehicle MPG will be reduced when roads have limited winter maintenance performed, but MPG will improve/increase as the level of winter maintenance is increased. The differences between these levels of fuel use can be quantified to determine the financial savings in fuel use accrued through winter maintenance.

Benefit Estimation Results

Data from the Minnesota DOT were used to provide demonstration of the developed methodologies in estimating the value of winter maintenance benefits. The quantified benefits produced through the estimation methodologies are presented in Table 12. As indicated, the estimations produced for Minnesota for the 2005-06 winter season show that winter maintenance produces a financial benefit of $227,088,014. This represents a significant benefit, particularly when one considers the costs that were expended on winter maintenance operations including labor, equipment and materials, during that same season. A review of each of the individual estimations follows.

Table 12: Estimated benefits of winter maintenance for Minnesota in 2006

Item	Financial Benefit
Reduced Crashes	$167,683,800
Travel Time Savings	$10,915,690
Fuel Savings	$41,057,063
Total	**$19,656,553**

A Negative Binomial model was used to estimate the number of crashes expected to occur under a condition where no winter maintenance was performed. This figure was then compared to the actual number of crashes that were observed to occur (during the winter of 2006). When analyzing safety benefits, it was found that the expected number of crashes that would have occurred had no winter maintenance been performed was 20,275, compared to the 15,675 that were actually observed under maintenance conditions. This difference of 4,600 crashes, when multiplied by an average crash cost of $36,453 for Minnesota, indicated that winter maintenance activities produced a financial savings of $167,683,800. This figure clearly indicates that winter maintenance produces a significant benefit from reduced crashes, both financially, and to society in general.

The benefits of improved travel times from winter maintenance were estimated by comparing expected vehicle speeds under pavement conditions without winter maintenance performed to those where maintenance resulted in a prevailing pavement surface condition of “lightly slushy” (the most frequently observed condition in the available data). Results of calculations indicated that, for 828 route segments, a benefit of $10,915,699 in travel time savings was achieved. This lower figure (when compared to the value of safety benefits), was the result of the difficulty in quantifying the extent of lost time to motorists because of different road conditions. Still, this figure illustrates that winter maintenance has a positive benefit on reducing delay to motorists.

The final benefit of winter maintenance that was quantified was fuel savings. For this estimate, fuel usage differences were compared between conditions where winter maintenance had been performed to those where only no/limited maintenance had been conducted. This approach to estimation was based on the logic that one would expect vehicle fuel efficiency (MPG) to decrease under poorer road conditions where limited maintenance is performed. Estimation results found there is a significant difference, particularly for passenger vehicles, in the amount of fuel used and the resulting cost of that fuel between conditions where winter maintenance is and is not used. The same is true for trucks, albeit to a lesser extent, given the lower number of vehicle miles traveled each day by this type. While developed on an assumed basis, the cumulative fuel savings of $41,057,063 for the 2005-06 winter season indicates that winter maintenance does produce significant benefits in terms of fuel use and financial savings. The total savings presented here are likely lower in practice, as the assumption of low levels of winter maintenance being performed on all roads does not reflect the reality of winter operations.

Transferability and Implementation

The methodologies presented in this report have been developed to make use of data which is typically collected in some form by agencies. Furthermore, the use of that data in estimating the travel time and fuel savings benefits of winter maintenance employs basic linear equations and requires no specific skillset. The application of the safety benefit methodology is more intensive, but this may also be completed through coordination with other agency staff, such as traffic safety engineers or others with experience in statistical modeling and evaluation. Because the methodologies presented in this report are straightforward, their implementation by agencies should not present a significant obstacle. Through implementation, a better understanding of the collective benefits of winter maintenance can be developed.

Implementation of the safety benefit methodology may be perhaps the most challenging for agencies. The approach which was employed involved the development of a Negative Binomial crash prediction model. The model presented in this report has been developed from Minnesota data and based on different conditions and variables from that state. Consequently, the specific model functional form (Equation 12) should not be considered directly applicable in other states. However, the general model functional form presented in Equation 11 can be employed by other agencies in developing a specific prediction model for their locale. The estimation of the model based on this form is not typically an activity that winter maintenance personnel are tasked with completing. However, at many agencies (particularly state departments of transportation), there is institutional experience with the type of safety analysis and modeling activity. In such cases, development of the safety model to estimate the number of crashes using the approaches presented in this report may be completed in cooperation with other agency personnel outside of the winter maintenance area, such as traffic safety engineers. The resulting model will provide an estimation of the crashes expected in the absence of winter maintenance that can then be compared to actual observed crash experience.

Application of the travel time savings methodology should be straightforward and can be completed by any agency personnel. The data elements employed by this approach are usually available from agency files in most cases (truck traffic levels may need to be estimated). Also, the value of time for different motorists (passenger cars versus trucks) may need to be assumed based on locale. Once the requisite data is collected, the application of Equation 13 is straightforward and can be completed in a spreadsheet environment. Using a spreadsheet, a number of different estimations can be made, including a system wide benefit estimate, estimates at the region, district or garage/shed level, estimates for different roadway functional classifications, and so forth. Different estimates may be of interest for the comparison of performance between these different levels.

Finally, the estimation of the fuel savings methodology is also expected to be straightforward and again completed by any agency personnel. The data elements used by this methodology are typically collected at most agencies, although some estimates may be needed to arrive at a figure for million vehicle miles traveled per day by trucks. Additionally, some assumptions may be necessary, such as averages for reduced vehicle fuel efficiency between different LOS. Once again, with the requisite data collected, the application of the methodology is direct using Equations 7 and 8. Equation 7 provides an estimate of passenger car and truck fuel costs under different maintenance conditions, while Equation 8 provides the approach to calculating the differences in the computed fuel costs to produce the resulting fuel savings. A spreadsheet may be used in completing these calculations, and in doing so, different levels of maintenance scenarios may be completed for comparison purposes.

The methodology illustrated in the Minnesota case study could be easily adopted by other states or local agencies, even though the stated assumptions may need to be modified to reflect the specific situation. In light of the data gaps identified in this study, this work also helps to shed light on data elements needed to enable a reliable cost-benefit analysis for winter maintenance operations by a specific agency or region. One final note of caution is that there are intangible benefits of winter maintenance operations, which could be substantial yet difficult to quantify in monetary terms.

Communication with Decision Makers and Stakeholders

A key need for estimating the benefits of winter maintenance is to establish and communicate such information to decision makers and stakeholders. Such decision makers may include other agency managerial staff, as well as state and local legislators/government officials. All of these parties play a role in making decisions regarding the funding of winter maintenance operations. Consequently, any information that can aid winter maintenance managers in justifying their budgetary needs can go a long way in producing appropriate funding to maintain and/or improve existing maintenance levels of service. In the case of this research, the mechanisms for quantifying the benefits of winter maintenance can be one such informational aid, as the resulting data can be used to show exactly how winter maintenance operations directly benefit the traveling public and as a result, the larger local/regional/state economy.

While the mechanisms to estimate the benefits of winter maintenance were the focus of this work, the conveyance of the resulting information by winter maintenance managers is equally important. The question is how the analysis results that can be produced by the methodologies outlined in this report be used to influence decision makers? A discussion of possible communication processes is outlined in the following paragraphs to provide some answers to this question.

One strategy for providing information to decision makers is at various points during the annual budgeting cycle. Agency flowcharts and documents that outline this process will vary, but in general, winter maintenance managers should initially focus on conveying the information generated by the methodologies in this report to the management of their agency (e.g., division or DOT directors). The information would be provided at the early stage of the process of developing the overall agency budget request. As the overall budget for an agency is developed, information can once again be presented or expanded on to further justify the needs of winter maintenance. The information would move up the chain of command as high as necessary in order to ensure that it is incorporated into the budget request as well as presented to the next set of decision makers/stakeholders, those being legislators or general government officials charged with funding overall agency budgets. In presenting the facts about the benefits directly accrued by that particular state or locale, an agency can justify their budget needs to maintain or potentially enhance winter maintenance operations. Once again, additional information regarding the benefits of winter maintenance can be provided or expanded upon as the budget is developed and debated by legislative bodies.

In addition to providing initial benefit information during the budgeting process, it may also be necessary to present such information once again at a point during the winter season should requests for additional funding become necessary. As winter maintenance managers can attest, not all winters are the same, and in some cases, additional financial resources may be necessary during a severe winter. In such cases, having quantified benefit information available to demonstrate the need to fund additional winter maintenance operations at an adequate level should provide a strengthened case for the budget request.

In addition to conveying the benefits of winter maintenance to decision makers, it is also advisable to highlight the information generated by the analysis to the general public. This can be accomplished in a number of ways. For example, many transportation agencies have dedicated sections of their websites that discuss winter maintenance. This would be an ideal location to present information developed specifically by the agency using the methodologies of this report to quantify the benefits produced by winter maintenance specific to that agency. In this manner, the public would learn how they locally benefit from winter maintenance. Additionally, such a webpage would provide a location to point decision makers to during various stages in the budgeting process for further information. Agency-specific information can also be presented to local media for television, radio and print stories. These mechanisms would provide the public with a better understanding of how they directly benefit from the use of tax dollars in the funding of winter maintenance.

Research Highlights

While a number of benefits are provided by winter maintenance, including direct (fewer accidents, improved mobility, reduced travel costs and fuel usage) and indirect (reduction in accident claims, sustained economic productivity, continued emergency services), there is a need to better understand and quantitatively assess these benefits relative to costs at the national level and at the state level. Additionally, there is a need to effectively communicate these benefits to decision-makers and the general public. In light of this, the research discussed here determined what methodologies presently exist for determining the benefits of winter maintenance operations, identified what data is required to establish them, develop new methodologies through a case study, and summarize the findings of the collective effort.

The components of the research included the following tasks to determine and quantify the benefits of winter maintenance:

- Literature review to document the state of the knowledge and estimation methods regarding the benefits of winter maintenance operations.
- Development of a Negative Binomial model to predict the number of crashes that could be expected to occur under different winter maintenance scenarios.
- Development of a methodology to estimate the travel time savings resulting from differences in travel speeds over road segments under different levels of winter maintenance.
- Development of a methodology to determine the difference in fuel use between different levels of winter maintenance.

Data from the Minnesota DOT were used to demonstrate the developed methodologies in estimating the values of winter maintenance benefits. The quantified benefits produced through the methodologies are presented in the table below. As these figures illustrate, the financial benefits of winter maintenance are substantial.

Estimated benefits of winter maintenance for Minnesota in 2006

Item	Financial Benefit
Reduced Crashes	$167,683,800
Travel Time Savings	$10,915,699
Fuel Savings	$41,057,063
Total	**$219,656,553**

The next step beyond this work may be the implementation of the methodologies by agencies. This would be a step in understanding the benefits of winter maintenance on a larger scale. The methodologies were developed to make use of data which is typically collected by agencies, and the methodologies primarily use basic linear equations and require no specific skillset. The application of the safety benefit methodology is more intensive, but this may be completed through coordination with other agency staff, such as traffic safety engineers. Because the methodologies are straightforward, their implementation should not present a significant obstacle.

The methodology illustrated by the Minnesota case study could be easily adopted by other states or local agencies, even though the assumptions used in some cases may need to be modified to reflect the specific situation. In light of the data gaps regarding the benefits of winter maintenance, this work also helps to shed light on data elements needed to enable a reliable cost-benefit analysis for winter maintenance operations by a specific agency or region. Another note of caution is that there are intangible benefits of winter maintenance operations, which could be substantial yet are difficult to quantify in monetary terms.

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