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Benefit-Cost Assessment of a Maintenance Decision Support System (MDSS) Implementation: The City and County of Denver

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16. Abstract

The Federal Highway Administration, U.S. Department of Transportation, has established a Road Weather Management Program (RWMP) that seeks to improve the safety, mobility and productivity of the nation's surface transportation modes by integrating meteorology into transportation operations and maintenance. A central activity of the RWMP has been to develop and encourage the deployment of tools to support decision making by transportation operations and maintenance. One of those tools is the Maintenance Decision Support System (MDSS) that offers road maintenance managers guidance regarding efficient tactical deployment of road crews, equipment and materials with the expectation that the MDSS can save state and local Departments of Transportation money and time while also enhancing the safety and mobility of the traveling public. This report presents the results of a Benefit-Cost Assessment (BCA) of the use of an MDSS by the City and County of Denver, Colorado. The MDSS was used over two consecutive winters (2007-2009) and resulted in budget savings that exceeded costs of the system while maintaining the level of service on the road network. Most of those savings are attributable to more effective tactical crew deployment decisions. The nature of the small sized snow events and the local and arterial road system of the City of Denver resulted in limited ability to test the effects of the MDSS treatment module. Overall, the City and County of Denver management and staff were very satisfied with the utility and performance of the MDSS in supporting their maintenance decisions.

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Table of Contents

List of Figures

List of Tables

Acronym List

AADT	Annual Average Daily Traffic
AVL	Automated Vehicle Location
BCA	Benefit-Cost Assessment
C/C Denver	City and County of Denver
CDOT	Colorado Department of Transportation
DIA	Denver International Airport
DOT	Department of Transportation
ESS	Environmental Sensor Station
FHWA	Federal Highway Administration
GIS	Geographic Information System
LOS	Level of Service
MDC	Mobile Data Computer
MDSS	Maintenance Decision Support System
NCAR	National Center for Atmospheric Research
OT	Overtime
RITA	Research and Innovative Technology Administration.
RPP	Residential Plowing Program
RWIS	Road Weather Information System
RWMP	Road Weather Management Program
USDOT	United States Department of Transportation

Executive Summary

This report presents the results of a Maintenance Decision Support Systems (MDSS) evaluation conducted under a contract with the Federal Highway Administration (FHWA), U.S. Department of Transportation (USDOT), through the Road Weather Management Program (RWMP) and Research and Innovative Technology Administration (RITA). A long-term objective of the RWMP in encouraging deployment of an MDSS is to offer transportation agencies a tool that can help their maintenance operations become more efficient, productive, and cost effective while maintaining a high level of safety and mobility for travelers. This Benefit-Cost Assessment (BCA) examined the use of an MDSS by the City and County of Denver (C/C Denver) over two winter periods: 2007-2008 and 2008-2009.

Background

This assessment quantifies the benefits versus costs of the deployment of an MDSS by a city street maintenance division in a major metropolitan area. This BCA of the application of an MDSS by C/C Denver has been conducted in two phases. Phase I of the BCA involved working closely with C/C Denver to monitor and collect data on their use of the MDSS during the winter of 2007-2008. A Phase I report included a recommendation regarding the conduct of a complete benefit-cost evaluation during the winter of 2008-2009[1]. Based on the findings in this report, FHWA decided to continue with a full BCA over the following winter of 2008-2009. Thus, two winter seasons worth of data are available to support this assessment.

There are a number of pathways to achieving benefits from using an MDSS, including benefits to the implementing agency (such as labor, equipment and material savings), benefits to the traveler (travel time, safety, vehicle operating costs), and benefits to the environment (less run-off of materials, etc.). Figure ES-1 shows a benefit cost framework for focusing the evaluation of the BCA in terms of the primary pathways by which benefits and costs are expected to be experienced by C/C Denver. The area inside the red dotted box represents the costs and benefits specific to the agency, and these constitute the primary focus of this BCA.

This evaluation assesses the viability of the MDSS strictly from an agency perspective. In other words, can a local agency investing in an MDSS expect a positive return on its investment primarily on savings to its budgets while maintaining the same level of service to the travelers? If an agency can obtain a return on their investment through benefits (savings in staff time, equipment costs, and materials) absent negative impacts to travelers and the environment, the MDSS is an economically viable tool in the winter maintenance toolbox for the agency.

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[1] Battelle. (2008). *Evaluation of a Maintenance Decision Support System (MDSS) Implementation: The City and County of Denver.* Phase I Report, Submitted to the Federal Highway Administration, Joint Program Office. (September 29).

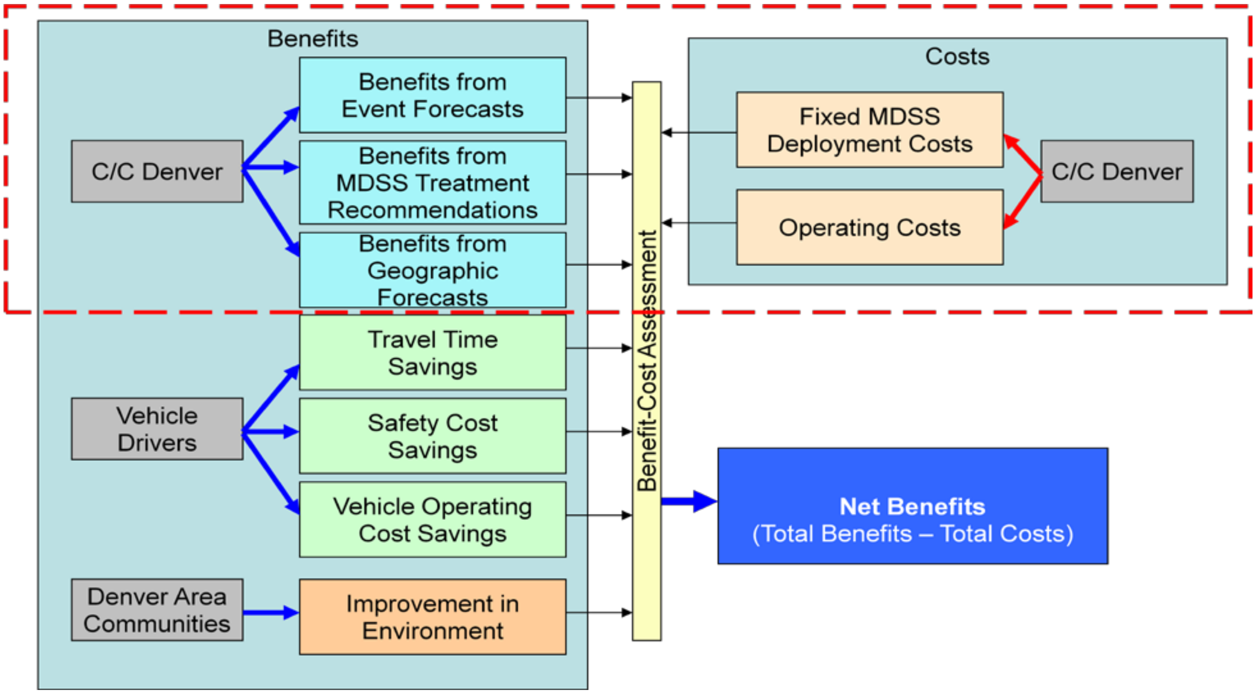

Figure ES-1. The BCA Pathways Framework

C/C Denver Snow Maintenance Activities

The Denver Public Works Department provides routine and emergency snow response services on non-interstate surface streets within C/C Denver across six districts. Most personnel are assigned to 12-hour shifts, beginning at either midnight or noon, and deployed crew levels are maintained as long as forecasts for snow remain in effect. C/C Denver maintains approximately 1,780 lane-miles within its jurisdiction. They have a fleet of equipment consisting of 68 trucks equipped with snow plows and deicing material distributors and spreaders. Prior to a forecasted snow event, C/C Denver superintendents hold a snow meeting to determine their maintenance strategy for the storm and to guide the initial call-in of their crews. They routinely access a variety of weather and road-weather forecasting services, including the MDSS, to support their discussions and decisions in the snow meeting and throughout the event. Their snow removal budgets range annually from $4.0 million to $5.5 million, which includes a discretionary portion of about $1.25 million, comprised of staff overtime ($250,000) and supplies and material costs ($1 million).

MDSS Use by C/C Denver

C/C Denver is currently using the functional MDSS prototype funded by the USDOT and being developed and refined by the National Center for Atmospheric Research (NCAR). The MDSS has three basic modules: weather forecasting, current and forecast pavement conditions, and treatment recommendations. The MDSS provides a probability of snow, rain or freezing rain for the C/C Denver operational area. The weather forecast module uses multiple data sources and forecast algorithms to form a weather forecast for a 48-hour period that includes the probability of moisture and the phase, accumulation, intensity, wind, temperature, and other important data for the road weather environment. The forecast module of the MDSS prototype is proprietary to NCAR; whereas, the other model components are available for any DOT, developer or other user to incorporate into their own systems.

The treatment module uses the forecast data in conjunction with existing weather-related pavement data. Having a prediction of the weather and expected pavement conditions for a 48-hour period is valuable in formulating a deployment plan for winter snow operations. C/C Denver has provided NCAR with the types of materials used and their standard procedures for snow removal operations. The MDSS takes this a step further in the treatment module by making recommendations of material application and timing throughout the course of a storm. The MDSS takes this information and recommends treatments throughout the event that should enable the greatest mobility and safety for travelers.

At the snow meeting held by the street maintenance managers between 12 and 24 hours prior to the expected start of the event, decisions are made about when and to what extent crews will be deployed. The MDSS forecasting module is an important part of these strategic decisions. The forecasting data C/C Denver watches the closest are the expected start time of the event, expected precipitation type and snow accumulation, and current and expected pavement temperatures. This information is used by management to decide when to call in crews or shift crews from daily assignments to snow shifts and whether anti-icing may be warranted. Once an event has started, C/C Denver uses the MDSS for tactical crew allocation and road treatment decisions. Forecasts are updated at three hour intervals. The short-term forecasting data (precipitation, wind, temperature) indicate when conditions may change and allow supervisors to deploy their crews as needed to cover anticipated conditions or accommodate schedule breaks.

Conduct of the Benefit-Cost Assessment

The evaluation was designed to be a “with-without MDSS” analysis intending to quantify the two benefit areas: those due to atmospheric and pavement forecasts and those resulting from treatment recommendations. The first benefit area examined tactical forecasts that are made prior to a storm event to indicate the expected start time of the storm and other attributes discussed further below. Many of these same forecast parameters are useful for teams planning how best to fight the storm during the actual event. Most of the tactical decision making is associated with deciding when to call in crews, how many are needed, what equipment and materials to deploy, whether or not to apply pre-treatment or anti-icing, and how best to make appropriate tactical adjustments during the storm event. While C/C Denver uses several weather services in addition to the MDSS, they believe the MDSS provides more actionable forecasts than the other available resources. Tactical decisions are initially made 24 to 48 hours before the event (at the snow meeting with the management staff) and during each shift.

> ***Evaluation Hypothesis #1*** ***- By using the MDSS forecasts as a tactical decision support tool, C/C Denver will achieve reductions in shift hours or eliminate shift call-ins, thereby reducing labor hours and associated costs for winter maintenance.***

Over the past two winters combined, 69 snow events were tracked and reported by C/C Denver. MDSS forecasts were used for 56 of those events. For 13 events in the past two winters, MDSS was not used either because computer server problems prevented access to MDSS information, or C/C Denver supervisors were not able to compile the information. In the previous winter, MDSS was used for all but three events.

A vast majority of these events have been fairly straightforward in terms of tactical decision-making, and no savings were attributed to the use of MDSS information. In other words, C/C Denver would have made the same decision without the MDSS forecasts based on the other available weather forecasting services.

However, for 10 events (5 in each year), MDSS provided information that C/C Denver was able to use tactically to deploy shifts more efficiently, resulting in labor hour savings. C/C Denver was able to eliminate weekend and overtime shifts by relying on MDSS information as opposed to other information. In both years, use of MDSS information did not result in any additional costs compared to other forecasts; that is, there was no event where differing MDSS forecasts resulted in decisions to call in shifts unnecessarily.

The magnitude of savings for the 10 events has been substantial for C/C Denver. The savings have resulted primarily from not calling in an extra shift or saving overtime hours for the five events in each year. Using average labor rates and number of staff on a snow shift, the value of these savings was computed. In 2007, savings for the five events were $66,222 (in 2009 dollars). In 2008, $124,495 (in 2009 dollars) was saved by avoiding overtime costs. On average, C/C Denver was able to save $95,359 per year in overtime costs. This alone has justified the investment in the MDSS for C/C Denver.

Qualitatively, C/C Denver reported that MDSS forecasts not only saved money but also provided a degree of comfort in their decision making. The superintendents and the managers felt that MDSS forecasts were more actionable and helped them make better decisions. Trust in the MDSS forecasts is growing, and C/C Denver is becoming more adept and comfortable with using MDSS to delay or eliminate shifts.

> ***<u>Evaluation Hypothesis #2</u> - By using the MDSS updates and treatment recommendations, C/C Denver will experience a reduction in the amount and cost of material used and a decrease in the number of truck miles, and hence cost of fuel and maintenance, over the course of an entire winter.***

By using MDSS, C/C Denver hopes to reduce the overall material and equipment usage and thereby achieve cost savings per lane-mile due to MDSS-recommended treatments. Typically, budgets for materials and supplies are in the $1 million range for the winter. Not all events require material usage. In 2007-2008, 17 out of the 32 events had material applications, and in the last winter, 16 of the 37 events required material treatments. MDSS primarily influences treatment decisions through the treatment recommendation module. MDSS recommends the timing and the amount of material that is based on C/C Denver's standard practices used in snow operations and current and forecast conditions.

Recommended treatments are generated by the MDSS, and C/C Denver is able to review the recommendations, make adjustments as necessary, and select the treatment to be performed.

Recommendations are provided by the MDSS by combining atmospheric and pavement forecasting capabilities with the road treatment protocols provided by C/C Denver. As C/C Denver crews apply materials and plow the roads, the requirements for subsequent treatments need to be adjusted to account for the road conditions as they are affected both by the on-going weather event and by the actions of the road crews. Therefore, in order to properly "forward correct" the recommended treatments, C/C Denver teams need to provide feedback to the MDSS every three hours, and then the MDSS adjusts its next set of treatment recommendations accordingly.

The evaluation design for assessing the role of the MDSS in offering treatment recommendations was a "with-without" design based on identified experimental plow routes on which crews used the MDSS forecasts and treatment recommendations and a matched set of control routes on which C/C Denver conducted operations without the use of the MDSS. Several major routes were selected where C/C Denver would follow the MDSS treatment recommendations to the best extent possible without jeopardizing public safety. The condition of selected experimental route segments where the MDSS would be used to guide treatments would then be compared with control route segments where treatments were determined using the existing procedures based on driver and supervisor decisions.

The treatment assessment test was conducted three times during the winter of 2008-2009. While ideally an entire winter of testing was desired, C/C Denver was able to complete their standard operating procedures for the evaluation design by January 20th, 2009. Subsequent to that date, only 7 events occurred and most of them required primarily spot treatments and not extended material use.

Overall, the treatment recommendations had minimal and inconclusive effects on C/C Denver's treatment strategies. Three tests revealed three different results across the control and experimental districts.

Overall, the treatment recommendations from the MDSS do not offer C/C Denver implementable guidelines and have not provided measurable benefits to C/C Denver. More important to C/C Denver are the forecasts provided by MDSS which the supervisors feel are more attuned to their region. A superintendent indicated that "The MDSS is helping us save materials, not by the treatment recommendations, but by keeping us from treating blindly like we used to. In earlier winters, we'd wipe out half our magnesium chloride from pre-treating when we really didn't need to as the forecasts were wide-ranging."

Overall, the MDSS provided a net positive benefit/cost tradeoff for C/C Denver with the average annual benefits due to the tool exceeding the costs. For every $1.00 that C/C Denver spent on MDSS, it achieved $1.34 in return. C/C Denver gained a net positive benefit[2] of $24,304 per year from the use of the MDSS. Table ES-1 shows the overall net benefits of using the MDSS for C/C Denver. The costs and the benefits are in current (2009) dollars and are based on the calendar year in which they were incurred. Costs incurred in 2006 include one-time system setup, calibration, and hardware costs.

[2] Net Benefit = Total Benefit – Total Costs

Table ES-1. Net Benefit Calculation for MDSS

Net Benefit Calculation in 2009 Dollars		
System Costs incurred by Agency (Current $)	Year Incurred	Adjusted Dollars (2009 $)
		(2009)
$82,315	2006	$90,769
$60,828	2007	$64,970
$55,295	2008	$57,424
Average Annual Cost (in 2009 $)		**$71,054**
Savings per Calendar year due to MDSS (Current $)	Year Incurred	Adjusted Dollars (2009 $)
$62,000	2007	$66,222
$119,880	2008	$124,495
Average Annual Benefit (in 2009 $)		**$95,359**

The net positive benefit is a significant percentage of C/C Denver's discretionary overtime budget (10%) and can be applied as savings or provide additional resources for C/C Denver. As a percentage of their overall discretionary budget (which includes supplies, materials, and overtime), MDSS provided a positive benefit of 2%. While not insignificant, the percentage savings in supplies and materials is quite a bit less compared with the overtime savings.

Overall tactical benefits are expected to increase in future years as C/C Denver increases their reliance on MDSS forecasts and becomes more comfortable in making less conservative shift decisions based on localized and actionable MDSS forecasts. Realizing benefits due to treatment recommendations is subject to technological and institutional factors (providing improved information on current condition and treatment to the MDSS, either through mobile data computers (MDC) mounted on snow plows or increased communications between drivers and supervisors who feed data into the MDSS, or more route-level or driver-level material monitoring by C/C Denver), and MDSS changes (specifically more segment-based treatment recommendations and ability to incorporate compound treatments). Costs in the future for the MDSS are expected to vary depending on the vendor and system configuration selected by C/C Denver. Given the city's budget constraints, overall costs of the MDSS to C/C Denver are not expected to increase significantly.

Lessons Learned

C/C Denver worked closely with the evaluation team and with NCAR, the developer of the prototype MDSS, in their use of the MDSS over the past two winter periods to inform C/C Denver's road maintenance decisions and actions. While the benefits experienced during these past two years have been substantial and valuable, there remains room for improved usage that could help C/C Denver derive even greater benefits in the future. A number of useful lessons, based on their recent experiences working with the MDSS tool, are suggestive of various ways that the benefits could be further enhanced and are summarized below.

- The primary benefits from C/C Denver's use of the MDSS were experienced as a road weather forecasting and tactical shift planning tool.
- In order to take full advantage of the treatment module of the MDSS, agencies like C/C Denver need to have advanced communications capabilities in their trucks such as AVL and be able to provide direct access to the MDSS in the field to supervisors and drivers.
- The MDSS offered C/C Denver value before, during, and at the end of storm events.
- Notwithstanding the benefits already noted, the prototype MDSS is not optimally configured for providing route-specific or segment-specific treatment recommendations in the kind of urban setting covered by C/C Denver.
- The full benefits of using an MDSS result from combining the forecasting, tactical, and treatment guidance from the tool with the experience, skill, and judgment of the maintenance crews.
- On-going training and support are essential ingredients for a road maintenance operation to gain the most benefit from an MDSS.
- The precisely focused road weather forecasts of the MDSS are considered more actionable than the broad weather information offered by other services.

Conclusions

The MDSS tool has been available for about five years, and as of the end of 2008 it was being used to some extent by approximately 30 state and local agencies and fully integrated into maintenance operations by five agencies. Over the past year usage has likely expanded further. During this time the technology that drives the MDSS has also continued to evolve, and several private service providers are offering various configurations of the MDSS to transportation agency users. C/C Denver is one of the very few city agencies that are using the MDSS to support their road maintenance decision making, and they are under contract with NCAR who has been developing the federal prototype MDSS. NCAR has closely supported C/C Denver's use of this prototype MDSS over the past three winters.

C/C Denver agreed to participate in the RWMP benefit-cost assessment of their use of the MDSS over the past two winter periods (2007-2008 and 2008-2009). They offered a unique test bed opportunity to isolate and quantify benefits and cost savings attributable to both the front end forecasting and tactical decision support component of the MDSS as well as the treatment module that recommends the type, timing, and amount of materials to put down on the road before and during a winter storm event.

Overall, C/C Denver found the MDSS to offer them valuable guidance in their efforts to fine tune their maintenance decisions before and during storms, and they fully intend to continue their investment in the MDSS into the future. They recognize that the MDSS has more than paid for itself since they began using this tool, and they anticipate full cost recovery, and more, in the future. They have become increasingly comfortable with its use and confident in the accuracy of its road weather forecasts. The MDSS has indeed become an integral part of their snow management process.

As the last two winters progressed, C/C Denver reported an increased level of confidence in MDSS use. Agencies charged with winter maintenance typically take a conservative approach, not wanting to be caught unprepared for a winter event. With the MDSS, C/C Denver has been able to use more localized, actionable information to save weekend and overtime shifts with an increased level of confidence and comfort. With budget cuts increasing pressure to justify shift deployment decisions, C/C Denver anticipates the role of the MDSS growing substantially over the coming winters. This evaluation clearly reveals the benefits and the vital role an MDSS can play in tactical or strategic decisions prior to and during the storm. The BCA has identified an estimated net annual benefit (cost savings) of more than $24,000 per year based on data from the past two winters that is attributable to labor savings achieved by more efficient crew shift deployment decisions guided directly by the MDSS. This savings is equivalent to about 10% of C/C Denver's discretionary overtime budget for the year, and their management believes this more than justifies their investment in the MDSS. For one event in each of the past two winters, C/C Denver used the MDSS forecasts to support their recommendation to not call in crews for Denver's residential plow program, thus avoiding significant additional costs. However, because the decision to deploy the RPP is based on many external inputs and influences, these savings have not been included in the net benefit calculations.

A less tangible and more qualitative benefit of the MDSS to C/C Denver over this two-year period was attributable to the treatment module. The relatively mild but typical nature of the winter storm events in the 2008-2009 winter resulted in few opportunities to test this component of the MDSS. Also, the MDSS could not adjust its treatment recommendations to address the variability of street and intersection configurations in this urban setting, or account for the limited ability to track application rates applied differentially on these routes. Also, the inability of C/C Denver to track usage by route segment and communicate that information back to the MDSS for forward correction resulted in difficulties in following the MDSS-recommended treatment regime as the storm event unfolded. This resulted in treatment recommendations that C/C Denver could not directly implement in most of the storm event situations.

Overall, this evaluation revealed that the treatment recommendations per se do not provide implementable actions absent improvements in the MDSS as well as institutional changes at C/C Denver to track and monitor material usage at a route-specific or at least a driver-specific level. One of the challenges of MDSS use by local agencies is the relative lack of sophistication in terms of communications technology between the trucks and a back-office MDSS tool. While AVL and Mobile Data Computers (MDCs) are not required for an MDSS implementation, they surely provide a critical pathway to realize benefits from the treatment recommendations.

However, it is important to realize that treatment decisions are affected by more than the material recommendations offered by the MDSS. The atmospheric and pavement temperature trends and forecasts, coupled with wind, blowing snow, and frost advisories helped supervisors and operators avoid treating "blindly" and resulted in savings in materials (not easily measured under these circumstances) that they likely would have applied in the absence of the MDSS. As such, these savings need to be tracked closely, along with detailed monitoring of material usage next winter.

This BCA is the latest in a series of efforts over the past several years to quantify the benefits, and assess a benefit-cost ratio for the MDSS. Taken together, the findings point to a clear set of benefits, along with real cost savings, that strongly justify the value not only to state DOTs but also local DOTs of having an MDSS among the suite of tools and services they rely upon to support their road maintenance decisions. Although not directly assessed in this BCA, the benefits at the agency level that have been identified flow down to the traveling public in terms of the agency's ability to maintain the level of service on the roadways and thereby make them safer for travelers. Finally, this BCA provides an evaluation structure and insight into the effective uses of an MDSS in an urban setting that may be of value to other local agencies similar to C/C Denver.

I. Introduction and Background

This report presents the results of a study conducted under a contract with the Federal Highway Administration (FHWA), U.S. Department of Transportation (USDOT), through the Road Weather Management Program (RWMP) and the Research and Innovative Technology Administration (RITA). The long-term objective of the RWMP in encouraging deployment of a Maintenance Decision Support System (MDSS) is to offer transportation agencies a tool that can help their maintenance operations become more efficient, productive, and cost effective while maintaining a high level of safety and mobility for travelers. A Benefit-Cost Assessment (BCA) examined the use of an MDSS by the City and County of Denver (C/C Denver) over two winter periods: 2007-2008 and 2008-2009.

The deployment of an MDSS by State Departments of Transportation (DOTs) and other transportation agencies is progressing steadily. Through various initiatives such as the MDSS stakeholder meetings and the Pooled Fund program, use of the MDSS is increasing both in terms of the number of agencies and the extensiveness of usage within agencies. MDSS usage has begun to extend beyond state DOTs to include local agencies. This is appropriate, considering that all local agencies combined spend more than all state DOTs on snow and ice removal activities. Figure 1 below summarizes data from the USDOT *Highway Statistics*[3] that not only show an increasing trend in local expenditures but also that in 2007, local agencies spent about 44% more than state agencies, or about $1.8 billion in snow and ice removal compared to $1.25 billion.

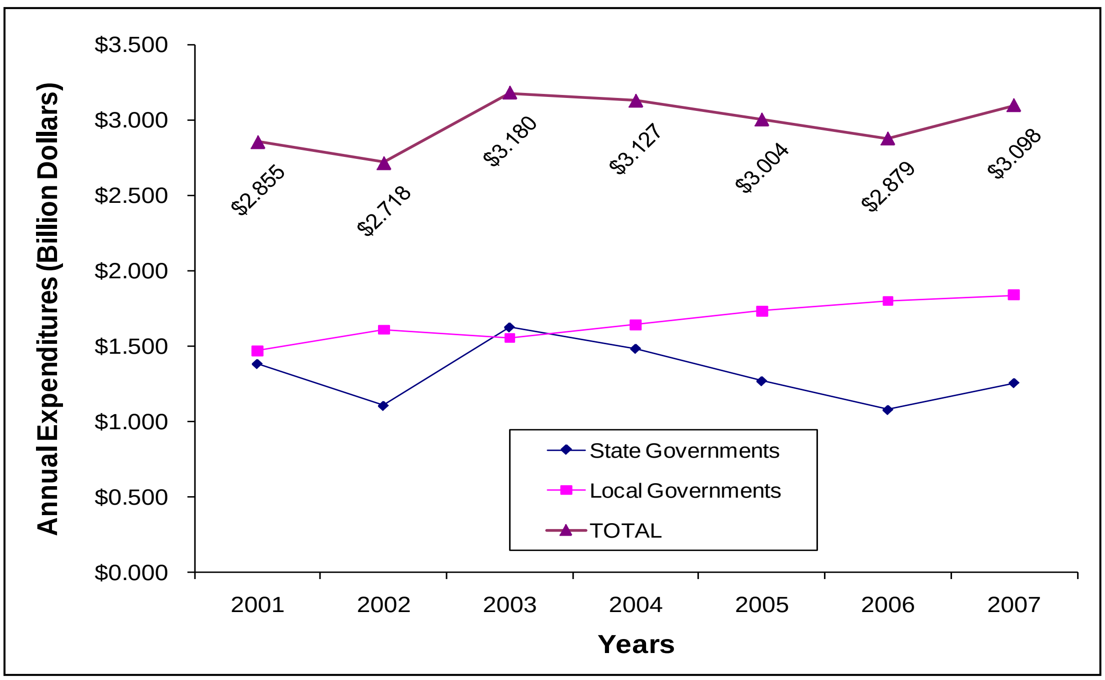

Figure 1. Snow and Ice Removal Costs

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[3] Data from USDOT, FHWA, Office of Highway Policy Information, Highway Statistics, multiple years, Table SF-4C and Table LGF-2. http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.cfm.

Typically, local agencies operate on much smaller budgets than state DOTs. Winter maintenance, usually part of the public works departments, is often not as technologically sophisticated and lacks funds to support large capital investments in vehicles and management systems.

This assessment quantifies the benefits versus costs of the deployment of an MDSS by a city street maintenance division in a major metropolitan area. C/C Denver faces many of the same challenges as other local agencies around the country, including budgetary and technological constraints. Nevertheless, their street maintenance division was eager to participate in an evaluation of their use of an MDSS and learn ways to enhance their winter operations and make better use of the MDSS tool throughout their jurisdiction. A Federal prototype MDSS is being used by C/C Denver as a tool to assist their maintenance operations in forecasting road-weather conditions in their area and providing treatment recommendations. This BCA of the application of an MDSS by C/C Denver has been conducted in two phases.

Phase I of the BCA involved working closely with C/C Denver to monitor and collect data on their use of the MDSS during the winter of 2007-2008. A Phase I report included a recommendation regarding the conduct of a complete benefit-cost evaluation during the winter of 2008-2009[4]. Based on the findings in this report, FHWA decided to continue with a full BCA over the following winter of 2008-2009. Thus, two winter seasons worth of data are available to support this assessment.

Evaluations of decision-support systems are complex, and the BCA for this MDSS is no exception. There are a number of paths to achieve benefits from using an MDSS, including benefits to the implementing agency (such as labor, equipment, and material savings), benefits to the traveler (travel time, safety, vehicle operating costs), and benefits to the environment (less run-off of materials, etc.). Figure 2 shows a benefit cost framework for focusing the evaluation of the BCA in terms of the primary pathways by which benefits and costs are expected to be experienced by C/C Denver. The area inside the red dotted box represents the costs and benefits specific to the agency, and these constitute the primary focus of this BCA.

There are two primary challenges in conducting the BCA as described by the above framework. The first challenge is in isolating the impact of the decision-support system from one winter to another. Ongoing research on winter severity promises to provide a way of normalizing winters so that a comparison of performance can be made. However, such methods are not mature or widely accepted. The second challenge is to understand the impact of the tool on achievement of level of service. Widely used level of service standards do not exist, and are specifically absent concerning the storm duration. The lack of such standards makes it difficult to quantitatively assess the improvements in traffic mobility and safety. The impacts of MDSS on traveler safety and mobility cannot be understated. However, they are very difficult to objectively measure with current standards.

[4] Battelle. (2008). *Evaluation of a Maintenance Decision Support System (MDSS) Implementation: The City and County of Denver.* Phase I Report, Submitted to the Federal Highway Administration, Joint Program Office. (September 29).

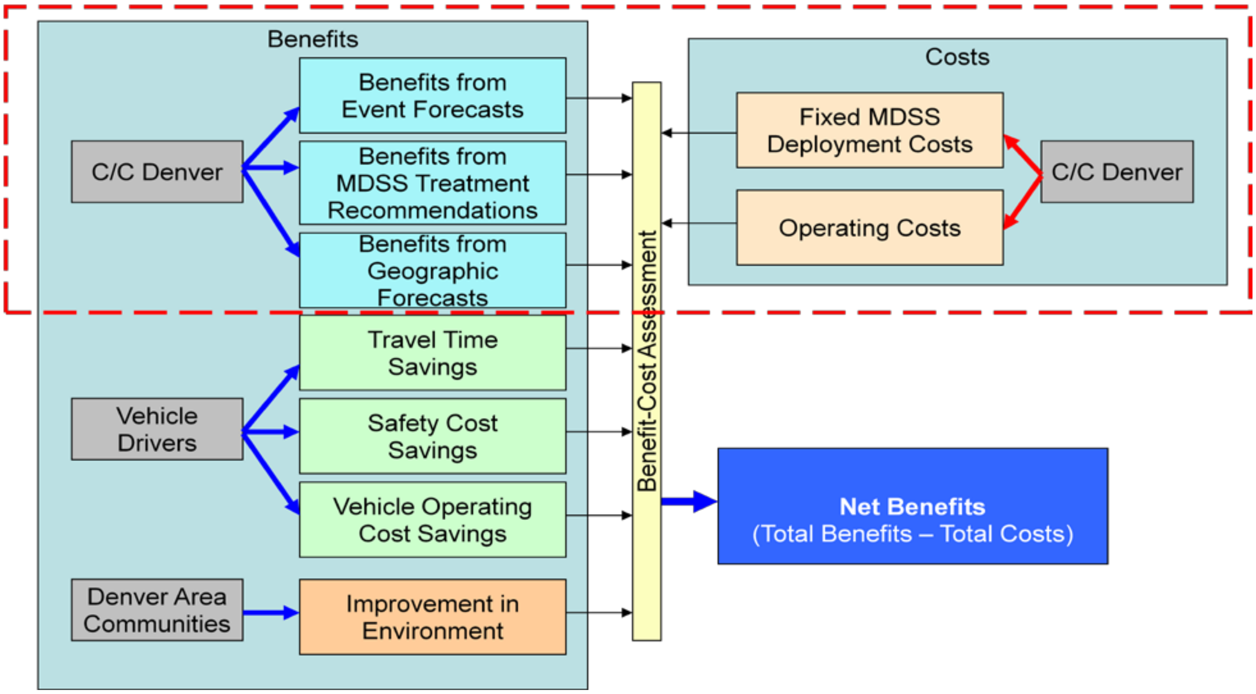

Figure 2. The BCA Pathways Framework

The above challenges place some unique requirements on the evaluation design. This evaluation was designed to be a "with-without MDSS" analysis that aimed to quantify the benefits over two consecutive winter periods, based on direct measurement of the benefits and costs experienced by C/C Denver (agency costs are shown in the area bounded by the dashed red box in Figure 2). Indirect costs to vehicle drivers and the communities are not considered in this evaluation.

This evaluation assesses the viability of the MDSS from strictly an agency perspective. In other words, can a local agency investing in the MDSS expect a positive return on its investment primarily on savings to its budgets while maintaining the same level of service to the travelers? If an agency can obtain a return on their investment through benefits (savings in staff time, equipment costs, and materials) absent negative impacts to travelers and the environment, the MDSS is an economically viable tool in the winter maintenance toolbox for the agency.

The rest of the report is organized as follows:

- Chapter II describes the winter maintenance practices and the use of the MDSS in winter maintenance by the C/C Denver
- Chapter III lists the two evaluation hypotheses for the study
- Chapter IV presents the results of the tactical (management) assessment over the past two winters
- Chapter V discusses the assessment of the MDSS treatment module
- Chapter VI presents the overall agency benefit cost assessment of the tool based on the results in chapter IV and V.

- Chapter VII presents the qualitative lessons learned based on interviews with C/C Denver staff
- Chapter VIII provides the summary and conclusions for this report.

II. Winter Maintenance and MDSS Use in C/C Denver

C/C Denver implemented a Public Works Integrated Emergency Snow Response Plan as of October 2007. That plan describes the winter weather conditions typically faced in Denver as follows:

> Contrary to popular belief, winters in Denver are actually quite mild. In January and February, the average daily high temperatures are in the mid 40s. Denver averages approximately 60 inches of snowfall per year, and most of the snowstorms are in the trace to 3-inch range. Only 50 miles west of Denver, however, annual snowfall in the 250 to 300 inch range is common. In upslope weather pattern locations, heavy snowfalls are possible. The significant number of sunny days that Denver experiences contributes to rapid melting of snow on city streets, reducing the cost of emergency snow response in comparison with other cities that experience similar snowfall amounts but different climate conditions.

The Denver Public Works Department provides routine and emergency snow response services on non-interstate surface streets within C/C Denver, excluding areas served by the Denver International Airport (DIA) in the airport service area (Peña Boulevard and other streets around DIA). They describe their emergency snow response activities as operating continuously during full deployment events "until all designated streets have been cleared and/or treated, and accumulation has ended."

C/C Denver Snow Maintenance Activities

Public Works personnel are assigned to non-residential snow plowing and direct support duties. Most personnel are assigned to 12-hour shifts, beginning at either midnight or noon. Deployed crew levels are maintained as long as forecasts for snow remain in effect.

During snow plowing operations, staff are deployed out of six work districts (Figure 3). Four districts are assigned to cover four quadrants of the city (NW, NE, SW, and SE Denver), one district is dedicated to serving streets in central Denver (the Central Business District and adjoining area), and one district provides services in Stapleton, Montbello, Green Valley Ranch, and Gateway in northeast Denver.

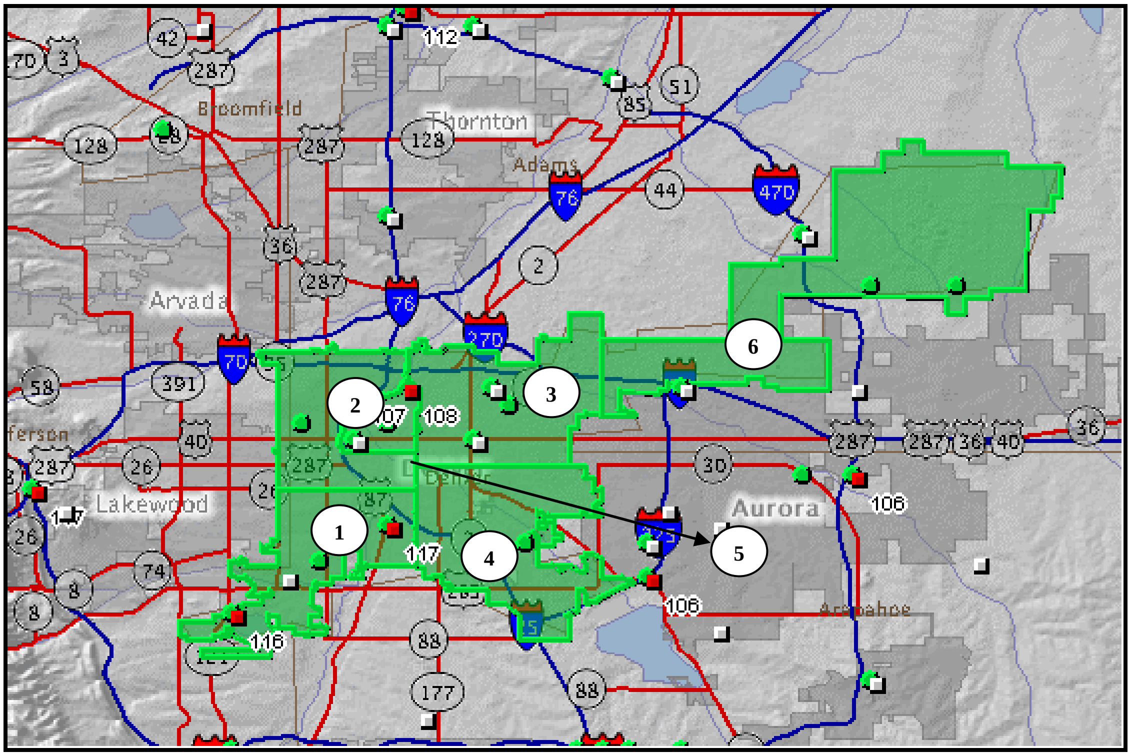

Figure 3. Map of Denver MDSS Study Area and Six Maintenance Districts

For each district, total snow route street mileage and traffic lane mileage are summarized by priority for route clearing in Table 1 below:

Table 1. Snow District Lane Miles by Maintenance Priority

Snow District	Priority A	Priority B	Total
1. Southwest	160.93	72.10	233.03
2. Northwest	163.25	61.70	224.95
3. Northeast	305.30	74.40	379.70
4. Southeast	233.19	92.60	325.79
5. Downtown	288.80	67.73	356.53
6. Northeast	202.69	57.37	260.06
Total	**1,354.16**	**425.90**	**1,780.06**

The city's fleet of snow plowing equipment consists of 68 trucks equipped with snow plows (Figure 4) and deicing material distributors and spreaders, classified as follows:

- 10 units with liquid material distribution tanks
- 18 units with dry material spreaders
- 40 units with a combination of liquid distribution tanks and dry spreaders

Photo by author, Chris Cluett.

Figure 4. C/C Denver Snow Plow Equipment

Each district has a maintenance camp with allocated equipment and crews. The planning group within C/C Denver holds a "snow meeting" that is attended by all the superintendents, usually from noon to 1:00 p.m. prior to a forecast winter storm event. C/C Denver operates a snow message line over the weekends, along with a pager system to notify crews. Once crews are called in, it takes about two hours to get the plows on the roads. The snow plows have radio communications but are not yet equipped with Automated Vehicle Location (AVL) systems. AVL deployment is planned for the near future.

Snow removal budgets are annually assigned and vary from $4.0 million to $5.5 million annually based on a calendar year cycle. The budget line items include regular staff pay, overtime, supplies and materials, and capital equipment purchases. Of the total budget, the discretionary portion, over which C/C Denver has operational control, is around $1.25 million, comprised of staff overtime ($250,000) and supplies and material costs ($1 million). Figure 5 shows the actual costs and the budgets for years 2005-2009. Substantial variations in actual costs can occur based on the severity of the winter. For example, the blizzard at the end of 2006 and early 2007 resulted in actual costs that exceeded the original and updated budgets.

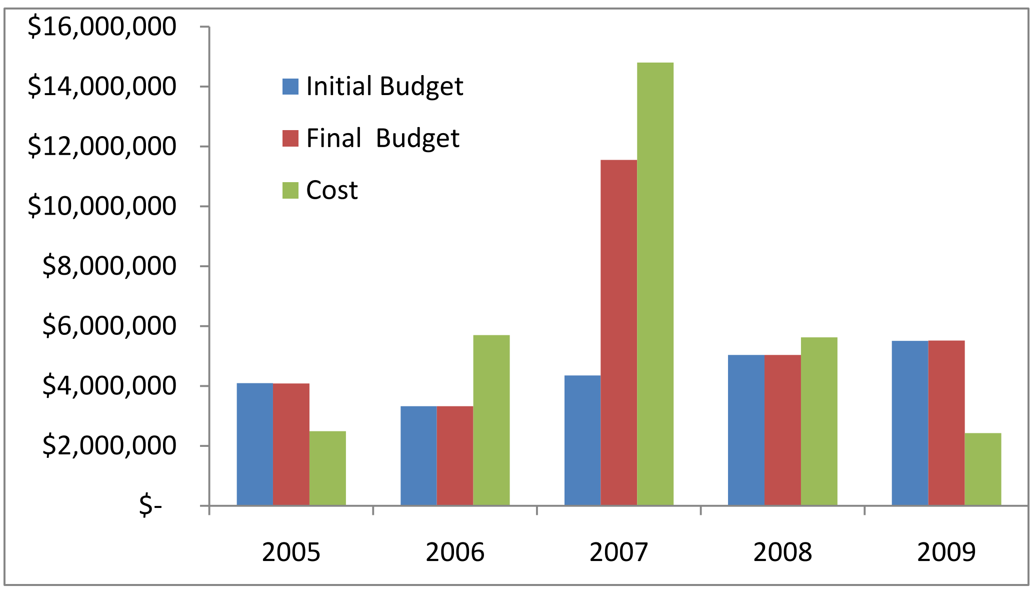

Figure 5. C/C Denver Snow Budgets and Costs

MDSS Use by C/C Denver

C/C Denver is currently using the functional MDSS prototype[5] funded by the USDOT and being developed and refined by the National Center for Atmospheric Research (NCAR). The MDSS has three basic modules: weather forecasting, current and forecast pavement conditions, and treatment recommendations.

The MDSS provides a probability of snow, rain or freezing rain for the C/C Denver operational area. If the conditional probability of snow (probability of snow given that precipitation is likely to occur) is 50% or greater, then a snow event is declared. If the conditional probability of rain is 25% or greater, then the MDSS declares rain. Precipitation (of any type) is declared when the overall precipitation probability reaches 20%. The system offers a 48-hour forecast horizon. The MDSS offers short term alerts online, and is updated hourly, for example, if the road temperatures fall below 32 degrees Fahrenheit and there is precipitation.

The weather forecast module uses multiple data sources and forecast algorithms to form a weather forecast for a 48-hour period that includes the probability of moisture and the phase, accumulation, intensity, wind, temperature, and other important data for the road weather environment. The forecast module of the MDSS prototype is proprietary to NCAR; whereas, the other model components are available for any DOT, developer or other user to incorporate into their own systems.

In the second module, the MDSS uses the forecast data in conjunction with existing weather-related pavement data (inputs are derived from the pavement temperature sensors ("pucks") deployed by C/C Denver, along with the Colorado Department of Transportation (CDOT) Road Weather Information System Environmental Sensor Stations (RWIS-ESS) to form a prediction of expected pavement conditions over the next two days). The city has provided NCAR with basic construction data for the pavements, and these are used by the MDSS to model latent heat and subsurface temperatures that will affect surface conditions.

Having a prediction of the weather and expected pavement conditions for a 48-hour period is valuable in formulating a deployment plan for winter snow operations. The MDSS takes this a step further in the third module by making treatment recommendations throughout the course of a storm. C/C Denver has provided NCAR with the types of materials used and their standard procedures for snow removal operations. The MDSS takes this information and recommends treatments that should provide the greatest mobility and safety for travelers. Within this module C/C Denver personnel are able to input alternative treatment programs that allow them to determine whether their own selected treatments will obtain results similar to the MDSS recommended treatments. One of the key features of the MDSS is its ability to "forward correct" its treatment recommendations for the next update cycle based on input of current treatment applied. While this allows the MDSS to tailor recommendations based on what is happening on the road surface, it does require the driver or the supervisor to enter this information.

[5] For a detailed description of MDSS capabilities and research program, see http://www.ral.ucar.edu/projects/rdwx_mdss/

When long-range forecasts indicate a weather event is approaching, C/C Denver managers begin monitoring weather forecasts based on multiple forecasting services, including the MDSS. When the storm is less than 48 hours away, they use the MDSS software to focus on a more detailed forecast of what to expect with the onset of the event. They have found that information offered by the MDSS in support of their decision making is more comprehensive and location-specific than information provided by the other weather services.

At the snow meeting held by the street maintenance managers between 12 and 24 hours prior to the expected start of the event, decisions are made about when and to what extent crews will be deployed. The MDSS forecasting module is an important part of these strategic decisions. The forecasting data C/C Denver watches the closest are the expected start time of the event, expected precipitation type and snow accumulation, and current and expected pavement temperatures. This information is used by management to decide when to call in crews or shift crews from daily assignments to snow shifts and whether anti-icing may be warranted. Once an event has started, C/C Denver uses the MDSS for tactical crew allocation and road treatment decisions. Forecasts are updated at three hour intervals based on the MDSS requirements. The short-term forecasting data (precipitation, wind, temperature) indicate when conditions may change and allow supervisors to deploy their crews as needed to cover anticipated conditions or accommodate schedule breaks.

III. Evaluation Hypotheses

The implementation of the BCA framework is shown in Figure 6. The evaluation was designed to be a “with-without MDSS” analysis intending to quantify the two benefit areas, those due to atmospheric and pavement forecasts and those resulting from treatment recommendations.

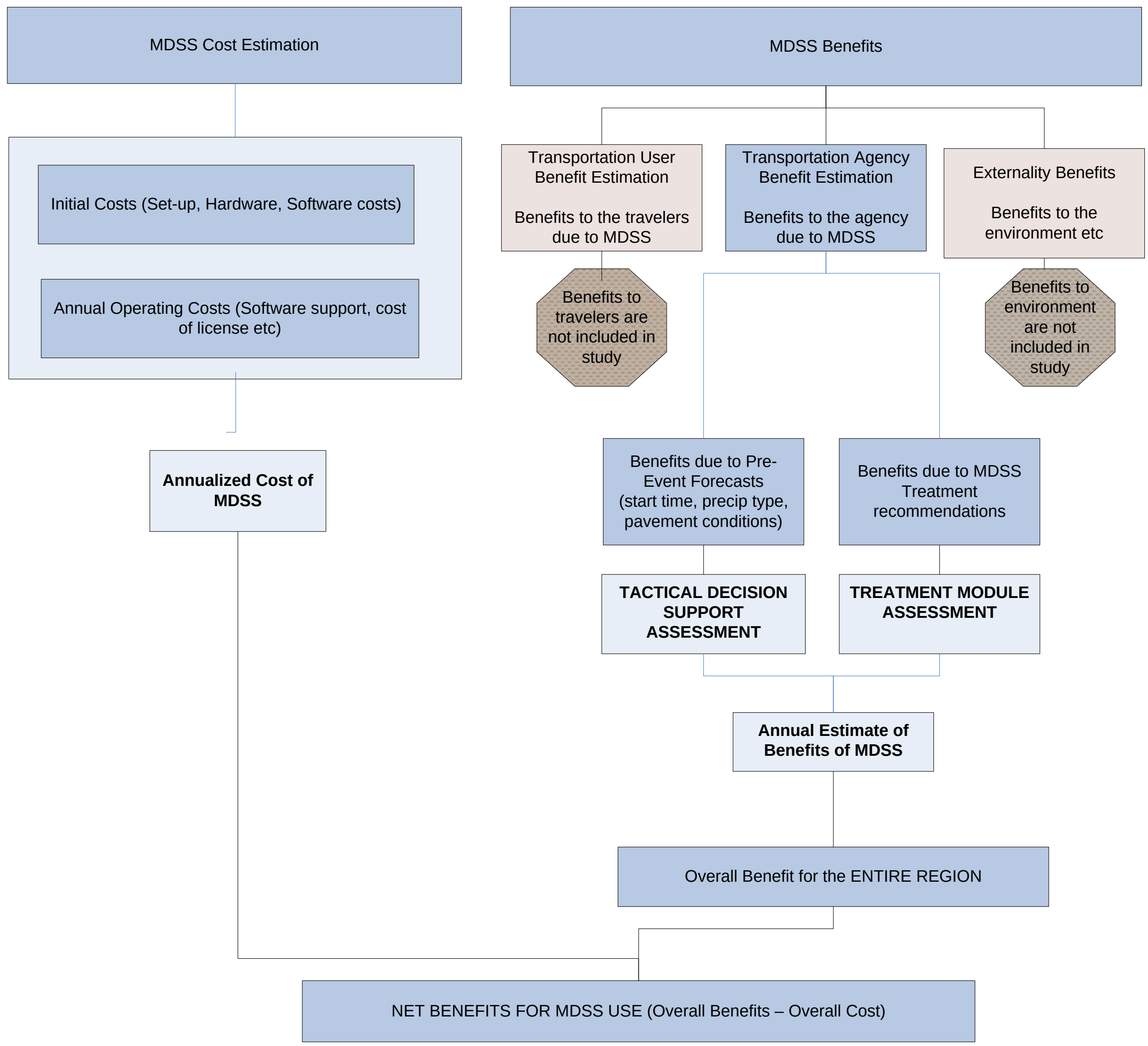

Figure 6. Implementation of the BCA Framework

The two benefit areas in Figure 6 are assessed by testing two key hypotheses.

Hypothesis Associated with Tactical Forecasts

Tactical forecasts are those made prior to a storm event to indicate the expected start time of the storm and other attributes discussed further below. Many of these same forecast parameters are useful for teams planning how best to fight the storm during the actual event. Most of the tactical decision making is associated with deciding when to call in crews, how many are needed, what equipment and materials to deploy, whether or not to apply pre-treatment or anti-icing, and how best to make appropriate tactical adjustments during the storm event.

> ***Evaluation Hypothesis #1*** ***- By using the MDSS forecasts as a tactical decision support tool, C/C Denver will achieve reductions in shift hours or eliminate shift call-ins, thereby reducing labor hours and associated costs for winter maintenance.***

While C/C Denver uses several weather services in addition to the MDSS, they believe the MDSS provides more actionable forecasts than the other available resources. Tactical decisions are initially made 24 to 48 hours before the event (at the snow meeting with the management staff) and during each shift.

The MDSS forecasts include:

- **Start time of precipitation and precipitation type.** Knowing the start time of different types of winter precipitation is a critical component for determining an appropriate response.
- **Duration of precipitation**. This allows better crew scheduling and anticipation of the amount of chemicals needed.
- **Pavement temperatures**. The pavement temperature trends affect whether the precipitation will melt or begin accumulating on the pavement surface and whether icy conditions may occur during and/or after the event.
- **Precipitation rate**. The rate affects how fast after the precipitation onset the roads may become hazardous and will directly influence the response strategies.
- **Wind speed and blowing snow**. Blowing snow information can affect whether extra shifts will be required to maintain road conditions even after precipitation has stopped.
- **Road or bridge frost**. This information can support decisions on whether liquid anti-icing will be needed.
- **Refreeze**. Refreeze conditions may determine if extra shifts or chemicals will be needed.

This wealth of information offered by the MDSS enables C/C Denver to adjust their strategies pertaining to:

- The timing and size of their crew call-ups.
- When to reallocate crews from daily assignments to snow shifts.
- What deployment strategies to use.
- Whether anti-icing or pre-treatment may be warranted.

By using MDSS, C/C Denver expects to save labor hours by optimizing their shift call-ups over the course of each storm event and ultimately for the entire winter.

Hypothesis Associated with Treatment Recommendations

The MDSS combines its atmospheric and pavement forecasting capabilities with the road treatment protocols provided by C/C Denver, and the MDSS seeks to recommend the optimal amount and type of material for the conditions expected to be encountered during a storm event. As C/C Denver crews apply materials and plow the roads, the requirements for subsequent treatments need to be adjusted to account for the road conditions as they are affected both by the on-going weather event and by the actions of the road crews. Therefore, in order to properly "forward correct" the recommended treatments, C/C Denver teams need to provide feedback to the MDSS every three hours, and then the MDSS adjusts its next set of treatment recommendations accordingly.

> ***<u>Evaluation Hypothesis #2</u>* - By using the MDSS updates and treatment recommendations, C/C Denver will experience a reduction in the amount and cost of material used and a decrease in the number of truck miles, and hence cost of fuel and maintenance, over the course of an entire winter.**

Reducing the usage of materials and equipment, while maintaining the roadway level of service, offers an important incentive for C/C Denver to deploy and use the MDSS, as these reductions have direct impacts on their bottom line. In general, the timing and the amount of materials applied can be optimized based on better information and understanding of route-specific weather, prior treatments, and road surface conditions. Currently truck operators want to be certain they have applied sufficient materials to the road surface. By providing decision-making tools to the field crew based on current and forecast atmospheric and pavement conditions, reductions in material and equipment usage are possible. Using the treatment recommendations provided by the MDSS should result in optimal use of material and equipment (impacting the miles driven and fuel consumed).

IV. Tactical Decision Support Analysis

Potential benefits associated with adjustments to tactical decisions based on guidance from the MDSS are examined by testing hypothesis #1 defined in the previous chapter. Traditionally, shift deployment strategies used by C/C Denver, as with every other jurisdiction, tend to reflect caution in order to be assured that adequate coverage is available. However, when shifts can be eliminated, delayed or put on stand-by instead of a call-in, significant monetary savings may be realized, while continuing to have fully adequate coverage.

Discussions with C/C Denver revealed the wide variety of tools that are used to make tactical shift decisions about a snow event. In addition to the MDSS, C/C Denver routinely reviews several other freely available weather forecast services. Of key importance to this evaluation are events for which the MDSS provides a significantly different forecast than other weather forecasting services available to C/C Denver, as these events clearly isolate the impact of the MDSS on the tactical decision.

When the MDSS forecasts differ from other available weather services in the C/C Denver area, several outcomes are possible:

- If the MDSS predictions are trending towards lower precipitation amounts, later start times or lesser accumulation than other weather information sources:
    - C/C Denver can save labor hours by eliminating a shift or calling in a partial shift.
    - If the weather event starts earlier or is more intense than predicted by the MDSS, C/C Denver has to scramble to deploy resources to maintain acceptable conditions on the roadway. Such events will be carefully documented and reported as negative impacts to the traveler (not quantified).
- Conversely, it is possible that the MDSS may predict a higher snow accumulation than other providers, leading to increased shifts and labor hours. In such cases, C/C Denver will note whether the earlier shift call-up was warranted by actual event conditions.
    - If not, the extra shift cost would be considered a negative cost for C/C Denver.
    - If the earlier call-up was warranted, then the MDSS allowed C/C Denver to be better prepared to manage the weather event. In this case, while C/C Denver will face increased labor costs, they will be providing better service to the travelers (not quantified).

For the previous two winters, C/C Denver compiled records on all available forecasts, including the MDSS forecast, at the time of the snow meeting and at the end of each shift. For each winter event, the following data were collected:

1. Comparative forecasts used at the time of the snow meeting based on all available forecast data including the MDSS, in spreadsheet form. An example of the comparative forecast is shown in Table 2 (the MDSS forecast is highlighted).
2. Ongoing road weather forecasts during the storm event used to guide subsequent shift call-in decisions.
3. Actual event data – start time, precipitation type and amount, end time.

4. Deployment decision – subjective assessment by C/C Denver of their shift call-in decision and whether their shift call-in decisions were improved, were the same, or were worse due to the MDSS forecasts compared to what they would have decided without the MDSS.

Table 2. Comparative Forecasts at the Time of the Snow Meeting

Forecast Source	Forecast Start	Forecast End	High Temp 3/16	Low Temp 3/16	High Temp 3/17	Low Temp 3/17	Precip Proba-bility	Type/ Accumulation
MDSS	***Sunday Midnight***	***Monday Late***	***45***	***31***	***36***	***29***	***100%***	***Snow, trending down to 3"-4"***
Private Weather Service #1	Sunday Evening	Monday Afternoon	45	23	37	25	75%	rain/snow 5"-10"
Private Weather Service #2	Sunday Evening	Monday Evening	47	32	26	37	100%	rain/snow 4"-8"
Local Television #1	Sunday Afternoon	Monday Evening	49	28	36	28		rain/snow "enough to shovel"
Local Television #2	Sunday Evening	Monday Evening	50	26	35	23	85%	rain/snow 5"-10"
Local Television #3	Sunday Afternoon	Monday Evening	50	27	35	22		rain/snow 4"-8"
Local Television #4	Sunday Evening	Monday Afternoon	49	28	38	21		rain/snow 5"-10"

Tactical Decision Support Assessment Results and Findings

The results of the tactical assessment are shown in Table 3. Over the past two winters combined, 69 snow events were tracked and reported by C/C Denver. The MDSS forecasts were used for 56 of those events. For 13 events in the past two winters, the MDSS was not used either because computer server problems prevented access to the MDSS information, or C/C Denver supervisors were not able to compile the information. In the previous winter, the MDSS was used for all but three events.

Table 3. Tactical Deployment Assessment Summary Results

Winter Period	Total Events	MDSS Used	MDSS Resulted in Savings	MDSS Resulted in Costs	Missed Events BY ALL
2007-2008	32	22	5	0	1 (Late storm prediction by MDSS others missed entirely)
2008-2009	37	34	5	0	1
Total	**69**	**56**	**10**	**0**	**2**

A vast majority of these events have been fairly straightforward in terms of tactical decision-making, and no savings were attributed to the use of the MDSS information. In other words, C/C Denver would have made the same decision without the MDSS forecasts based on the other available weather forecasting services.

However, for 10 events (5 in each year), the MDSS provided information that C/C Denver was able to use tactically to deploy shifts more efficiently, resulting in labor hour savings (see Table 4). C/C Denver was able to eliminate weekend and overtime shifts by relying on MDSS information as opposed to other information. In both years, use of MDSS information did not result in any additional costs compared to other forecasts; that is, there was no event where differing MDSS forecasts resulted in decisions to call in shifts unnecessarily.

The magnitude of savings for the 10 events has been substantial for C/C Denver (Table 4). The savings have resulted primarily from not calling in an extra shift or saving overtime hours for the five events in each year. Using average labor rates and number of staff on a snow shift, the value of these savings was computed. In the winter of 2007-2008, savings for the five events were about $136,000. In the previous winter, $48,000 was saved by avoiding overtime costs. On average, per winter, C/C Denver was able to save $92,000 in overtime costs, which is about 37% of their overtime budget ($250,000).[6]

Table 4. Tactical Deployment Assessment – Value of Savings[7]

Year	Events with Savings	Type of Savings	Total Value of Savings ($)	Notes
2007-2008	5	2 Full Shift Savings 3 Partial Shift Savings (4 hours OT)	$136,000	1 event where RPP* might have been mobilized without MDSS
2008-2009	5	Partial Shift Savings (4 hours OT, standby versus bringing one crew in)	$48,000	1 event where RPP might be mobilized without MDSS
Average	**5**	**1 Full Shift, 3.5 Partial Shift Savings**	**$92,000**	

* RPP = Residential Plowing Program

Qualitatively, C/C Denver reports that MDSS forecasts not only save money but also provide a degree of comfort in their decision making. The superintendents and the managers feel that MDSS forecasts are more actionable and have helped them make better decisions. Trust in the MDSS forecasts is growing, and C/C Denver is becoming more adept and comfortable with using the MDSS to delay or eliminate shifts. A good example of the increasing trust in the MDSS is its use in deciding whether to call in the Residential Plowing Program (RPP), a

[6] This percentage reflects the total benefit and does not include the system costs of the MDSS. Net benefits are discussed later in this report and illustrated in Table 11.
[7] These figures cover each winter period for which the data were collected. For the benefit cost calculation in this report, the events are organized by the calendar year in which they occurred, and values are represented in constant 2009 dollars.

program instituted by the city to deal with extreme snow events. Twice during the evaluation period, MDSS forecasts were used to help justify not activating the RPP. The RPP involves private equipment being called into service through the Contractors Emergency Assistance Program. Private contractors make available graders and loaders, with operators, at pre-established rates. Each RPP deployment costs the city $120,000 per shift. However, the decision to deploy the RPP is often motivated by political and other factors and is not strictly a C/C Denver Street Maintenance decision. Consequently, while MDSS information was provided to the decision-makers, it is difficult to isolate the role the MDSS may have played in the decision to not deploy the RPP. As such, these savings were not included as part of the tactical assessment, though had they been included, the benefit-cost ratio would have been significantly greater for the MDSS.

V. Treatment Benefit Assessment

Hypothesis #2 addresses the effectiveness and benefits of the MDSS in reducing the amount of material used, number of truck miles traveled, and hence cost of fuel and maintenance, over the course of an entire winter.

Treatment Approach in C/C Denver

C/C Denver focuses their plowing and treatment priority on their "A" routes, then on the "B" routes, and they also have a third route type called "S" routes. Streets included in the priority route system are major arterials (A routes), minor arterials and collectors (B routes), and schools, hospitals, and nursing home areas (S routes). Most designated streets are plowed curb-to-curb and are treated with deicing agents during emergency snow response operations. On applicable streets, operators are instructed to plow the majority of the snow to the north side of the street to enhance melting after the storm. North/south running streets are generally plowed evenly in both directions. If conditions permit, plows pile snow toward open areas, parks, and large medians to minimize inconvenience to residents and businesses (see Figure 7).

Photo courtesy of Department of Public Works, Street Maintenance Division, Denver, CO.

Figure 7. Plowing Operations in C/C Denver

C/C Denver aims to keep each plow truck covering about 30 lane-miles, with 2 to 3 circuits during each shift. Plow drivers call in at the beginning and end of their routes. They receive pertinent information from their superintendents to help them decide how to deploy their trucks but determination of routes and treatments is made by the supervisors and the drivers. Communication between the supervisors and drivers is primarily through radio. The trucks do not have AVL or MDCs and do not report any data back to the supervisors during their routes.

The application of deicing materials depends upon the severity of the snowstorm. Some storms are effectively served by applying materials at intersection approaches, elevated structures, and traffic conflict points, minimizing materials used while providing adequate public safety. Streets may need to be plowed and treated for 12 to 24 hours after a storm has ended, depending on the severity of the storm.

C/C Denver primarily uses pavement treatment materials that include Ice-Slicer, a naturally-mined sand and magnesium chloride mixture, and Apex, a liquid commercial product. C/C Denver supervisors stated that a level of service (LOS) goal is to have streets cleared for the next rush hour on all arterials. Supervisors are on the roads an hour after the storm begins, tracking progress of pavement treatments and assessing road conditions. C/C Denver does not use anti-icing as a normal course of operations. However, if pavement temperatures and conditions indicate a need for anti-icing, C/C Denver uses Apex as their anti-icing chemical.

Table 5 provides the material usage for the last two winters. Typically, budgets for materials and supplies are in the $1 million range for the winter. Not all events require material usage. In 2007-2008, 17 out of the 32 events had material applications, and in the last winter, 16 of the 37 events required material treatments.

Table 5. C/C Denver Material Usage over the Last Two Winters

Winter Period	Events and Events Treated	Ice-Slicer (000s) lbs	Ice-Slicer Cost ($81/ton)	Apex (000s) gallons	Apex Cost (0.67/gal)	Total Cost	Lane Miles Treated	Cost/Lane Mile Treated	Cost/ Event requiring treatment
2007-2008	32/17	14,786	$598,822	370	$247,900	$846,722	121,473	$6.97	$49,807
2008-2009	37/16	13,109	$530,933	565	$378,550	$909,483	73,002	$12.46	$56,843
Total	69/33	27,895	$1,129,754	935	$626,450	$1,756,204	194,475		

MDSS Role in Treatment in C/C Denver

Currently, MDSS provides two types of decision-support to C/C Denver during a storm event – as a forecasting tool, and as a treatment recommendation tool.

First as a forecasting tool, MDSS provides several key pieces of information that enable supervisors to fine-tune their treatment strategy. Table 6 shows the role of MDSS forecasts on treatment approaches. MDSS forecasts are updated every three hours and are at a district-level.

Table 6. Role of MDSS Forecasts in Treatments

Role of MDSS Forecasts in Treatment	Impact on Material and Equipment Use	Treatment Approach
Pavement temperature trends	Affects whether the precipitation will melt or begin accumulating on the pavement surface and whether icy conditions may occur during and/or after the event. Might involve increased material application.	C/C Denver might put more material (especially Apex for anti-icing) if MDSS shows pavement temperatures trending down to freezing or below.
Wind speed and blowing snow	Some impact on the type of material used. Liquid materials might be used more if wind speed is a concern during treatment. Might involve increased plowing after the event has ended to account for blowing snow.	Supervisors might ask drivers to make more passes on specific sections of the district where blowing snow conditions may be present.
Road or bridge frost	Spot treatments might be necessary.	Drivers are made aware that certain spots on their routes have to be treated at a higher rate of chemical application.
Duration, precipitation type and accumulation	Depending on the duration, precipitation type and rate, the type and amount of material needed will vary.	C/C Denver may continue shifts if event duration increases. Precipitation type and accumulation influences the type of material used as well as plowing strategy. C/C Denver may decide to only plow and not apply material if significant accumulation was being recorded.

The second and more direct way that the MDSS can influence treatment decisions is through the treatment recommendation module. The MDSS recommends the timing and the amount of material that is based on C/C Denver's standard practices used in snow operations and current and forecast conditions. Figure 8 shows a treatment history screen for a storm event in March 2009. Recommended treatments are generated by the MDSS, and C/C Denver is able to review the recommendations, make adjustments as necessary, and select the treatment to be performed.

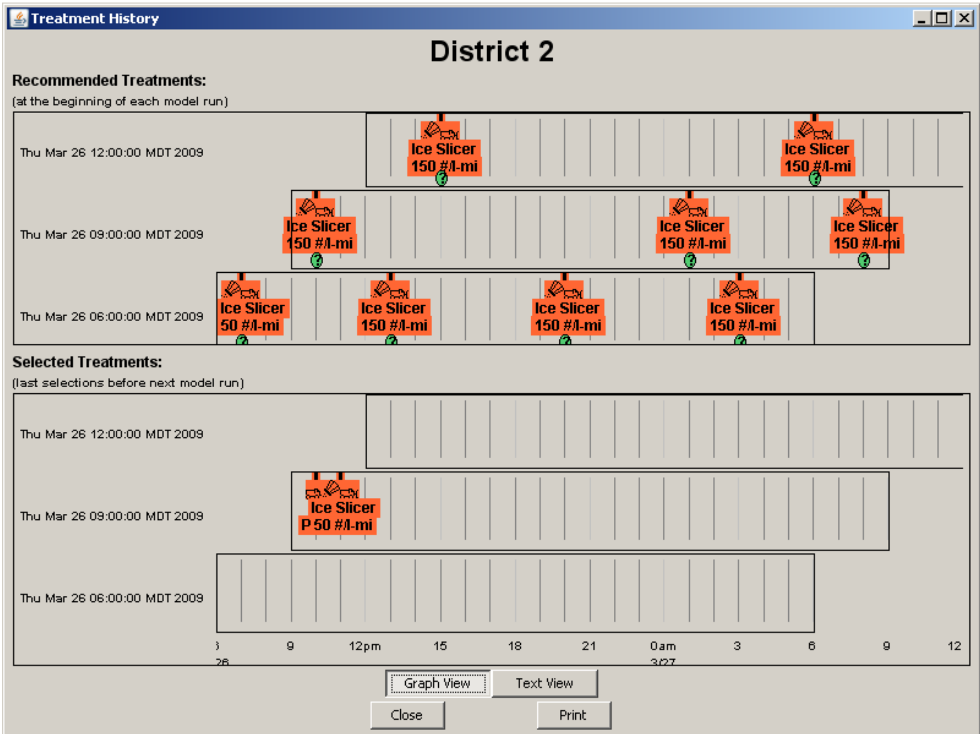

Figure 8. Treatment History for District 2 (March 26, 2009)

The treatment recommendations are at a maintenance district level, which poses a challenge to the supervisors on how to interpret the amount and timing across their region. Treatment recommendations provided over the two winter periods did not account for compound treatments (solid and liquid chemicals applied together) which is a practice followed by C/C Denver.

Evaluation Design for Treatment Tests

The evaluation design for assessing the role of MDSS in offering treatment recommendations was a "with-without" design based on identified experimental plow routes on which crews used the MDSS forecasts and treatment recommendations and a matched set of control routes on which C/C Denver conducted operations without the use of the MDSS.

Initially, the experimental and control sets were identified as maintenance districts, i.e., a district would be identified as an experimental district where MDSS would be followed and a corresponding control district where usual approaches would be used. After discussion with C/C Denver, the use of a district was judged infeasible because of lack of appropriately calibrated trucks that could follow the treatment recommendations. Meanwhile, the supervisors felt that routes in their districts varied widely and that a single treatment recommendation might not be appropriate for even a length of an entire arterial much less an entire district.

Therefore, a route-specific design was selected. Several major routes were selected where C/C Denver would follow MDSS treatment recommendations to the fullest extent possible without jeopardizing public safety. These selected experimental route segments where the MDSS would be used to guide treatments would then be compared with control route segments where treatments were determined using the existing procedures based on driver and supervisor decisions. For this analysis, four ‘A’ routes were chosen within four of C/C Denver’s six districts. The route in one district is the experimental route and the same route in the adjacent district is the control. Supervisors provide subjective assessments of the level of service. Table 7 and Figure 9 describe the locations of the experimental (red) and control (blue) routes on C/C Denver’s street system.

This allowed C/C Denver to assign selected drivers and properly calibrated trucks to the routes during the evaluation. Also, using the same arterials for both experimental and control helped to keep the pavement and traffic conditions as comparable as possible.

Table 7 provides details on the experimental and control routes for the treatment recommendations assessment. Figure 9 shows the geographic location of these routes.

Table 7. Experimental and Control Routes

Experimental Routes					
Street	**Route**	**Limits**	**Length**	**Lane mi.**	**AADT***
Colfax Ave.	30301/30302/30303	Downing St. to Yosemite St.	4.70	18.80	35,000
Federal Blvd.	10101	Alameda Ave. to Hampden Ave.	3.75	18.75	35,000
Colorado Blvd.	30101	6th Ave. to 52nd Ave.	4.50	22.50	50,000
Yale Ave.	10601	Federal Blvd. to Wadsworth Blvd.	3.00	6.00	10,000
Control Routes					
Street	**Route**	**Limits**	**Length**	**Lane mi.**	**AADT**
Colfax Ave.	20401	Federal Blvd. to Sheridan Blvd.	1.25	6.25	35,000
Federal Blvd.	20101	Alameda Ave. to 52nd Ave.	5.75	23.00	35,000
Colorado Blvd.	40101	6th Ave. to Hampden Ave.	5.00	30.00	50,000
Yale Ave.	40801/40802	Downing St. to Syracuse Way.	4.25	10.63	20,000

* AADT = Annual Average Daily Traffic

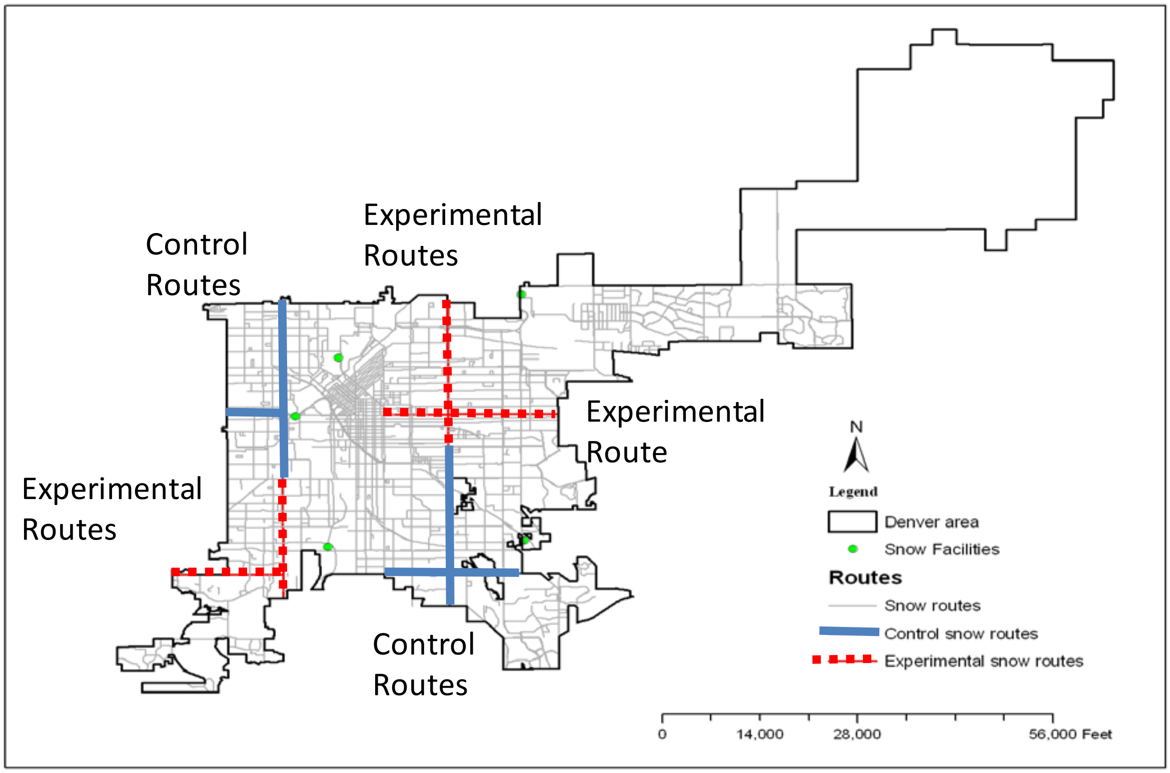

Figure 9. Experimental and Control Routes

Treatment Assessment Results and Findings

The treatment assessment test was conducted three times during the winter of 2008-2009. While ideally an entire winter of testing was desired, C/C Denver was able to complete their standard operating procedures for the evaluation design by January 20th, 2009. Subsequent to that date, only 7 events occurred and most of them required primarily spot treatments and not extended material use.

Overall, the MDSS treatment recommendations had minimal and inconclusive effects on C/C Denver's treatment strategies. Three tests revealed three different results across the control and experimental districts. Each of the three test cases is briefly described below.

Test 1- February 10th, 2009

For this storm event, MDSS recommended minimal application of material while no treatment was actually required. While 50 lbs/ln-mile was recommended at various times, no treatment was needed on the control routes. Table 8 compares experimental and control routes (control data are highlighted). Following MDSS recommendations across the entire C/C Denver A-Route system (1,354 ln-miles) for this storm would have resulted in 50 to 100 lbs/ln-mi material usage when not needed. Using 75 lbs/ln-mile at $81/ton as an average cost (excluding fuel and equipment costs) would translate to 101,550 pounds of material use at a cost of $4,112.

Table 8. Results of Treatment Test 1

Test 1- February 1st	Experimental				Control	
	MDSS Recommended Treatment				Actual Treatment	
Routes	**Lane-Miles**	**@1600 hrs**	**@1700 hrs**	**@1800 hrs**	**Lane-miles**	**Action Taken**
Colfax Ave.	18.8	50		50	6.25	No treatment
Federal Blvd.	18.7		50		23	No treatment
Colorado Blvd.	22.5				30	No treatment
Yale Ave.	6	50	50	50	10.63	No treatment

Notes - MDSS over-recommended material. No treatment was needed.

Test 2- March 26th, 2009

For this storm event, MDSS recommended earlier treatments compared to actual practice. MDSS recommended a treatment at 1100 hrs and again at 1600 hrs. Meanwhile, in the control districts, actual treatments were performed at 1600 hrs and at a higher rate at 2000 hours (Table 9).

Table 9. Results of Treatment Test 2

Test 2- March 26th	Experimental			Control		
	MDSS Recommended Treatment			Actual Treatment		
Routes	**Lane-Miles**	**@1100 hrs**	**@1600 hrs**	**Lane-Miles**	**@1600 hrs**	**@2000 hrs**
Colfax Ave.	18.8	150	150	6.25	100	200
Federal Blvd.	18.75	150	150	23	100	200
Colorado Blvd.	22.5	150	150	30	100	200
Yale Ave.	6	150	150	10.63	100	200

Upon review of the storm, superintendents felt the MDSS was recommending material use early when it was not needed based on their experience. They were reluctant to put down material when it was not yet needed on the roads. Higher pavement temperatures in the initial part of the event kept streets clear, confirming the superintendents' judgment. By afternoon, air temperatures had dropped, and storm intensity overwhelmed the latent heat. For about 2 hours most streets glazed over and were very slick. Crews were instructed to apply material at heavier rates at the next pass. Once the storm intensity dropped, latent heat in concert with material applications melted the ice, and streets were wet only for the duration of the event. Overall, the material usage was the same but the timing of the treatments varied between the MDSS recommendations and actual strategies.

Test 3- April 1st, 2009

For this storm, the MDSS experimental routes and control routes were consistent (Table 10). The storm petered out and required only spot treatments. One band of heavy snow passed over Districts 1 and 2 at 1600. Over about a 45 minute period, roughly one inch fell but latent pavement heat melted the snow on contact with very little accumulation on the pavement. Later in the evening, after precipitation ended some minor icing occurred in District 1, and spot applications of material were deployed.

Table 10. Results of Treatment Test 3

Test 3- April 1st	Experimental					Control	
	MDSS Recommended Treatment					Actual Treatment	
Routes	**Lane-Miles**	**@1800 hrs**	**@2000 hrs**	**@2200 hrs**	**@2400 hrs**	**Lane-Miles**	**Action Taken**
Colfax Ave.	**18.8**			Spot	Spot	**6.25**	Light spot application
Federal Blvd.	**18.75**	Spot	Spot		Spot	**23**	Light spot application
Colorado Blvd.	**22.5**			Spot	Spot	**30**	Light spot application
Yale Ave.	**6**	Spot	Spot		Spot	**10.63**	Light spot application

While more tests would have revealed patterns in MDSS treatment recommendations and actual treatment, the three tests are instructive on how MDSS treatments correspond to C/C Denver's usual treatment approaches.

Overall, the benefits of the treatment recommendations are still unrealized by C/C Denver. Primarily, they continue to face difficulties in following the treatment recommendations. Several reasons were identified by C/C Denver staff:

1. District-level recommendations are hard to follow. There is a need for route-specific recommendations so that drivers can be told exactly what treatment regime to follow.
2. Absence of AVL/MDCs on trucks. While there is constant radio communication between drivers and supervisors, information on exact material use is collected at the end of the shift. More accurate tracking of material use could provide C/C Denver with a better understanding of how effective their treatment strategy is.
3. Forward correction. Related to the above issue, the need to report back to the MDSS on what material is being put down on the road was a big challenge for supervisors and drivers. Supervisors typically are in the field driving around and checking road conditions, and they do not have access to the MDSS when they are away from their office.
4. The supervisors felt that the recommendations are more suited to interstates and highways. Arterials pose particular problems because of varying roadway types and urban street features like on-street parking, shaded areas, intersections, etc. In addition to just the roadway, typically, drivers would have to treat all four legs of an intersection.
5. Diversions along the route. Drivers frequently reported being pulled away from their assigned routes to help police in other locations or service other roads.

Overall, the treatment recommendations from the MDSS do not offer C/C Denver implementable guidelines and have not provided measurable benefits to C/C Denver. More important to C/C Denver are the forecasts provided by the MDSS which the supervisors feel are more attuned to their region. A superintendent indicated that "The MDSS is helping us save materials, not by the treatment recommendations, but by keeping us from treating blindly like we used to. In earlier winters, we'd wipe out half our magnesium chloride from pre-treating when we really didn't need to as the forecasts were wide-ranging."

VI. Overall Benefit Cost Analysis

This section builds upon the analysis in Chapters IV and V and provides an assessment of the benefits and costs of MDSS to C/C Denver.

Benefits were realized primarily by reductions in labor hours due to the tactical decision support offered by the MDSS. No benefits were realized by the MDSS in the treatment aspect. Costs include one-time set-up costs and annual contract costs for the MDSS. Benefits and costs were adjusted to constant 2009 dollars using inflation rates from the Bureau of Labor Statistics. The budget cycle for C/C Denver is based on the calendar year, so benefits and costs reported are for events in particular calendar years. Table 11 provides the net benefit calculation for C/C Denver.

Table 11. Net Benefit Calculation for MDSS

Net Benefit Calculation in 2009 Dollars		
System Costs Incurred by Agency (Current $)	Year Incurred	Adjusted Dollars (2009 $) (2009)
$82,315	2006	$90,769
$60,828	2007	$64,970
$55,295	2008	$57,424
Average Annual System Cost (in 2009 $)		**$71,054**
Savings per Calendar year due to MDSS (Current $)	Year Incurred	Adjusted Dollars (2009 $)
$62,000	2007	$66,222
$119,880	2008	$124,495
Average Annual Benefit (in 2009 $)		**$95,359**

Overall, the MDSS provided a net positive benefit/cost tradeoff for C/C Denver with the average annual benefits due to the tool exceeding the costs. For every $1.00 that C/C Denver spent on the MDSS, it achieved $1.34 in return. C/C Denver gained a net benefit[8] of $24,304 per year from the use of the MDSS.

The net benefit is a significant percentage of C/C Denver's discretionary overtime budget. They can save 10% of their overtime costs using the MDSS. These benefits can be applied as savings or provide additional resources for C/C Denver. As a percentage of their overall discretionary budget (which includes supplies, materials, and overtime), the MDSS provided a 2% savings per year. While not insignificant, the percentage savings in supplies and materials is slightly less when compared with the overtime savings.

Benefits due to the MDSS are expected to increase in the upcoming years as the MDSS is more widely deployed and used, and the level of trust in its forecasts and recommendations increases.

[8] Net Benefit = Total Benefit – Total Costs

Increasing funding constraints are expected to expand the role of the MDSS in shift deployment as a strategy to save costs. As the street maintenance budgets come under pressure, C/C Denver will rely heavily on the MDSS to make shift decisions. Tactical shift decisions, which C/C Denver used to make very conservatively due to the wide range of forecasts from different services, are being increasingly guided by the MDSS. Savings in overtime costs and weekend shift deployments before, during, and after storm events will continue to increase as superintendents find forecasts more actionable.

A largely untapped benefit is the potential reduction in treatment costs. In the short-term, treatment benefits are not expected to be a major component of the net benefits to urban users like C/C Denver. To realize benefits from the treatment recommendations, C/C Denver needs to make institutional as well as MDSS changes. Institutionally, C/C Denver can improve tracking of its material usage, especially at a route-level. While AVL and MDCs might serve as a long-term solution (with various other benefits), in the short-term, C/C Denver would need to properly calibrate their trucks and track salt usage by driver and routes. At a system-level, the MDSS software needs to be refined to provide segment or route-specific treatment recommendations rather than focusing at a district level.

Costs in the future for the MDSS are expected to vary depending on the vendor and system configuration selected by C/C Denver. Given the City’s budget constraints, overall costs of the MDSS to C/C Denver are not expected to increase significantly.

VII. Lessons Learned

C/C Denver worked closely with the evaluation team and with NCAR, the developer of the prototype MDSS, in their use of the MDSS over the past two winter periods to inform C/C Denver's road maintenance decisions and actions. While the benefits experienced during these past two years have been substantial and valuable, there remains room for improved usage that could help C/C Denver derive even greater benefits in the future. A number of useful lessons, based on their recent experiences working with the MDSS tool, are suggestive of various ways that the benefits could be further enhanced and are presented in this chapter.

The primary benefits from C/C Denver's use of the MDSS were experienced as a road weather forecasting and tactical shift planning tool.

The opinion of the superintendents and supervisors was that the MDSS did a good job across many different storm events of varying types and intensities in forecasting such critical parameters as start time, precipitation type and amount of precipitation, along with current and forecast pavement temperatures. The MDSS was perceived as generally more accurate and reliable when compared with the other weather forecasting services available to C/C Denver. The supervisors relied heavily on the MDSS during the storm to forecast their crew requirements from shift to shift. Their opinion was that the MDSS helped save them from calling in extra crews unnecessarily and that contributed to cost savings experienced during several storm events.

In order to take full advantage of the treatment module of the MDSS, agencies like C/C Denver need to have advanced communications capabilities in their trucks such as AVL and direct access to the MDSS.

The benefits of using the MDSS treatment module were less than the forecast module for C/C Denver over the past two winter periods, but that module added value, and its benefits could be enhanced by the addition of new technologies to C/C Denver's operations. Enhancements could include better vehicle-to-vehicle communications, AVL to help track the locations of all the equipment on the road in order to support better equipment allocation decisions during a storm event, technology in the plow trucks to monitor salt and liquid usage in much greater detail than is currently possible, and graphic communications capabilities that could allow MDSS information to be communicated directly into the truck cabs. This is both a technical and an institutional capability issue that, when implemented, could support smoother interactions between supervisors and truck operators and more accurate decision making based on precise data from the field during storm events.

The forward correction capability of the MDSS is critical to the ability of the MDSS to properly modify its on-going treatment recommendations and take into account the effect of the maintenance crew's actions on the condition of the roadway. The prototype MDSS used by C/C Denver requires the crews and supervisors to keep track of their maintenance actions and submit updates back to the MDSS every three hours so that the MDSS can issue modified treatment recommendations that account both for current storm conditions and the actions of the crews in treating the roadways. This is difficult to accomplish successfully in practice, in part because it requires access to a computer to provide the needed inputs. The crews are busy fighting the storm, and the supervisors are often not at their desks during the storm event and are certainly heavily occupied with trying to stay on top of the situation and guide their crews. Thus, providing the information needed for these forward corrections is difficult under the conditions faced in Denver and given the level of technology in the trucks at present. To fully take advantage of the capabilities offered by the MDSS, the forward correction process needs to be made easier for the supervisors and crews, and perhaps even automated to some extent. Part of the solution will involve more fully instrumenting the trucks with computer interfaces, AVL, and similar technologies that can facilitate this important aspect of the MDSS capability.

The MDSS offered C/C Denver value before, during, and at the end of storm events.

The MDSS offers decision support to maintenance teams both before and throughout a storm by looking ahead and providing operators and decision makers the detailed information on atmospheric and road weather conditions they need. During the storm the MDSS provided both tactical crew allocation decision support and material application support. As a storm event neared its end, the MDSS offered C/C Denver helpful forecasts of the timing of the end of the event and a sense of what would be required to clean up after the storm so that crews could be more efficiently assigned to that task.

Notwithstanding the benefits already noted, the prototype MDSS is not optimally configured for providing route-specific or segment-specific treatment recommendations in the kind of urban setting covered by C/C Denver.

There is a lot of variability across the roads in the six districts maintained by C/C Denver, along with variability in weather from one district to the next, and treatment strategies must adapt to these different needs. Conditions can change rapidly across this geography during a storm event, and maintenance crews need to be able to respond quickly to these changing situations. In addition, Denver's urban street environment is characterized by different road surface materials and subsurface structures, traffic intersections, usage patterns, and areas differentially affected by sun and shade, hills, and bridges of different construction. All these factors affect how the road surface responds to winter weather and applied materials, and implies a need for on-going adjustments to treatment strategies. Notwithstanding the complexities of their urban street setting and the limitations of the MDSS prototype in being able to represent these complexities, C/C Denver was able to take advantage of the atmospheric and pavement forecasts provided throughout storm events to make better informed judgments about treatment applications, namely, what to apply, when, where, and how much.

The amount of materials to use in treating the roads is a decision primarily made by the supervisors. There are no specific rules of practice to be followed; rather, the supervisors take account of weather and road condition information, inputs from the truck operators, and their own observations in making these decisions. Whether to use liquid or dry materials depends on a number of factors. For example, the downtown district is closely monitored for air quality and as a result the supervisors are particularly cautious of applying dry materials that may adversely impact air quality in that congested area. Some of the district supervisors have less experience with the liquid materials and therefore may be reluctant to apply liquids to the roads.

The full benefits of using an MDSS result from combining the forecasting, tactical, and treatment guidance from the tool with the experience, skill, and judgment of the maintenance crews.

As is the case with the tactical uses of the MDSS both before and during a storm event, the supervisors use the MDSS, along with their other forecasting services and real-time reports from the truck operators on the road, to support their treatment decisions. The more geographically targeted MDSS pavement temperatures and temperature trends provide particularly valuable information to be considered in making these treatment decisions. However, treatment decisions are not made solely based on the MDSS recommendations for materials, amounts, and timing. The MDSS is checked frequently during each storm event and supports fine tuning the treatment strategies. The lesson is not to follow the MDSS, or any other single weather service for that matter, blindly, but rather to use judgments and experience, along with guidance from the MDSS, to make fully informed treatment decisions.

Deciding how to manage and rapidly adjust winter treatments is perhaps as much art as science, and individual experience and skill count for a lot. These attributes become well imbedded into the culture of a road maintenance team over years of application under a wide variety of conditions. As one of the superintendants of C/C Denver said, "There is a culture here that says 'this is how we do snow.'" The lesson is that it is important to recognize and reinforce this experience base for making good maintenance judgments, and supplement this with new tools, such as the MDSS, that offer enhanced road weather information that add value to the decision processes. Supplementing and not replacing is the key lesson.

On-going training and support are essential ingredients for road maintenance operations to gain the most benefit from an MDSS.

Regardless of a crew's level of experience with winter road maintenance, they all seek the opinion of their fellow operators and supervisors when critical decisions regarding treatment need to be made. Having expert support available to help in interpreting weather information is particularly helpful, and C/C Denver superintendants and supervisors valued the advice provided by NCAR along with the MDSS. Where possible, it is important to offer MDSS users periodic training and consultation during storm events. This allows users to achieve the maximum benefit from the tool in support of their maintenance operations.

The MDSS has the ability to archive the details of its forecast and recommendations for each storm event, and C/C Denver found this valuable in providing factual storm reconstruction as backup and verification of their decisions and actions, protecting them from outside questioning of their performance after a storm event.

The precisely focused road weather forecasts of the MDSS are considered more actionable than the broad weather information offered by other services.

The MDSS is perceived as giving unequivocal and targeted information, compared with the often too broad and waffling forecasts from other services. The MDSS also provided operators with informative graphical representation of key event parameters such as atmospheric and pavement temperatures and trends. This level of detail, and the willingness to "tell it like it is" with the risk of being wrong, is viewed as a positive attribute of the MDSS that provides maintenance crews with more actionable guidance than other services typically offer.

Although a less significant benefit to C/C Denver than the MDSS's tactical forecasts, the tool has helped reduce the uncertainty associated with treatment decisions. The other weather services used by C/C Denver tend to provide broad-ranging weather forecasts for the Denver region; whereas, the MDSS provides more precise, focused forecasts specifically targeted for C/C Denver's maintenance districts. While the other services, compared with the MDSS, may be better protected by this approach from being wrong in their forecasts, C/C Denver maintenance staff appreciate the candor and focus of the MDSS forecasts. Even though the MDSS may miss the target and hence their treatment recommendations may be off from what the crews feel is appropriate under the evolving road weather conditions, they feel they are able to better avoid "treating blindly" with the MDSS. The superintendents said the MDSS has helped them actually save materials because they don't feel the need to put down materials to protect themselves when faced with a wide-ranging and uncertain forecast. Any inaccuracies in the MDSS forecast can usually be corrected by "catch up" treatments when needed, but avoiding unnecessary treatments more than makes up for these occasional forecast errors.

VIII. Summary and Conclusions

The MDSS tool has been available for about five years, and as of the end of 2008 it was being used to some extent by approximately 30 state and local agencies and fully integrated into maintenance operations by five agencies. Over the past year usage has expanded further. During this time the technology that drives the MDSS has also continued to evolve, and several private service providers are offering various configurations of the MDSS to end users. C/C Denver is one of the very few city agencies that are using the MDSS to support their road maintenance decision making, and they are under contract with NCAR who has been developing the federal prototype MDSS. NCAR has closely supported C/C Denver's use of this prototype MDSS over the past three winters.

C/C Denver agreed to participate in the RWMP benefit-cost assessment of their use of the MDSS over the past two winter periods (2007-2008 and 2008-2009). They offered a unique test bed opportunity to isolate and quantify benefits and cost savings attributable to both the front end forecasting and tactical decision support component of the MDSS as well as the treatment module that recommends the type, timing and amount of materials to put down on the road before and during a winter storm event.

Overall, C/C Denver found the MDSS to offer them valuable guidance in their efforts to fine tune their maintenance decisions before and during storms, and they fully intend to continue their investment in the MDSS into the future. They recognize that the MDSS has more than paid for itself since they began using this tool, and they anticipate full cost recovery, and more, in the future. They have become increasingly comfortable with its use and confident in the accuracy of its road weather forecasts. The MDSS has indeed become an integral part of their snow management process.

As the last two winters progressed, C/C Denver reported an increased level of confidence in MDSS use. Agencies charged with winter maintenance typically take a conservative approach, not wanting to be caught unprepared for a winter event. With the MDSS, C/C Denver has been able to use localized, more actionable information to save weekend and overtime shifts with an increased level of confidence and comfort. With budget cuts increasing pressure to justify shift deployment decisions, C/C Denver anticipates the role of the MDSS growing substantially over the coming winters. This evaluation clearly reveals the benefits and the vital role an MDSS can play in tactical or strategic decisions prior to and during the storm. The BCA has identified an estimated net annual benefit (cost savings) of more than $24,000 per year based on data from the past two winters that is attributable to labor savings achieved by more efficient crew shift deployment decisions guided directly by the MDSS. This savings is equivalent to about 10 percent of C/C Denver's discretionary overtime budget for the year, and their management believes this more than justifies their investment in the MDSS. For one event in each of the past two winters, C/C Denver used the MDSS forecasts to support their recommendation to not call in crews for Denver's residential plow program, thus avoiding significant additional costs. However, because the decision to deploy the RPP is based on many external inputs and influences, these savings have not been included in the net benefit calculations.

A less tangible and more qualitative benefit of the MDSS to C/C Denver over this two-year period was attributable to the treatment module. The relatively mild but typical nature of the winter storm events in the 2008-2009 winter resulted in few opportunities to test this component of the MDSS. Also, the MDSS could not adjust its treatment recommendations to address the variability of street and intersection configuration in this urban setting, or account for the limited ability to track application rates applied differentially on these routes. Also, the inability of C/C Denver to track usage by route segments and communicate that back to the MDSS for forward correction resulted in difficulties in following the MDSS-recommended treatment regime as the storm event unfolded. This resulted in treatment recommendations that C/C Denver could not directly implement in most of the storm event situations. Overall, this evaluation revealed that the treatment recommendations per se do not provide implementable actions absent improvements in the MDSS tool as well as institutional changes at C/C Denver to track and monitor material usage at a route-specific or at least a driver-specific level. One of the challenges of MDSS use at local agencies is the relative lack of sophistication in terms of communication technology between the trucks and a back-office MDSS tool. While AVL and MDCs are not needed for an MDSS implementation, they surely provide an easier way to realize benefits from treatment recommendations.

However, it is important to realize that treatment decisions are affected by more than the recommendations offered by the MDSS. The atmospheric and pavement temperature trends and forecasts, coupled with wind, blowing snow, and frost advisories helped supervisors and operators avoid treating “blindly” and resulted in savings in materials (not easily measured under these circumstances) that they likely would have applied in the absence of the MDSS. As such, these savings need to be tracked closely, along with detailed monitoring of material usage next winter.

This BCA is the latest in a series of efforts over the past several years to quantify the benefits, and assess a benefit-cost ratio, for the MDSS. Taken together, the findings point to a clear set of benefits, along with real cost savings, that strongly justify the value not only to state DOTs but also local DOTs of having an MDSS among the suite of tools and services they rely upon to support their road maintenance decisions.

Although not directly assessed in this BCA, the benefits at the agency level that have been identified flow down to the traveling public in terms of the agency’s ability to maintain the level of service on the roadways and thereby make them safer for travelers. Finally, this BCA provides an evaluation structure and insight into the effective uses of an MDSS in an urban setting that may be of value to other local agencies similar to C/C Denver.

IX. References

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X. Appendix A

Questions Asked in Interviews with the Two Daytime Shift and Two Midnight Shift Superintendants

1. How do you decide which materials and how much to apply in any given situation? Are their standard rules of practice you try to follow?

2. Has the MDSS changed how you do your job in any way? If so, explain how.

3. Did you encounter any unforeseen problems/issues in using the MDSS this past winter season? If yes, describe the problems/issues and describe how you addressed them.

4. How did test/control routes work?

5. Did you get adequate support (from NCAR; elsewhere) for using the MDSS? Discuss any problems working with the MDSS where you needed support.

6. How trustworthy do you find the information provided by the MDSS? Forecast accuracy? Appropriateness of treatment recommendations?

7. Is the MDSS easy/difficult to use? Explain.

8. Did you receive training on the use of the MDSS? Was your training adequate? Would you recommend any changes?

9. Are the treatment recommendations provided by the MDSS appropriate rarely/some/most/all of the time? What shortcomings have you observed?

10. In order to get the best results from MDSS treatment recommendations, it is important that crew actions be input to the MDSS at regular intervals. Does this cause problems? If so, describe. What would you suggest alternatively?

11. Do you think having an MDSS requires too much of a change in how C/C Denver manages its road network?

12. Would you say that C/C Denver’s maintenance decisions are made any more proactively than before, as a result of having/using the MDSS?

13. Is the MDSS very widely accepted among your colleagues? Do the drivers like it? Discuss.

14. Does the MDSS need refinements or improvements? Do you have any specific suggestions in that regard?

15. Do you think MDSS is ready for full deployment by C/C Denver? Are all the supervisors and crew ready for MDSS?

16. Are you comfortable with the idea of relying 100% for your decisions on what the MDSS is telling you? Comments?

17. Should other weather services be discarded and the MDSS relied upon exclusively for weather forecasts and treatment guidance? If not, why not?

18. In your own opinion, is it worth it to C/C Denver to pay to have the MDSS? How/why? Discuss the pros and cons.

19. What key messages would you want to offer other DOTs who may not yet have tried using an MDSS about what they should expect from the MDSS? What have you learned about using an MDSS that you think others should be aware of?

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